TRANSPORTATION RESEARCH RECORD 670

Air Quality Analysis in Transportation Planning

TRANSPORTATION RESEARCH BOARD

COMMISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1978

Transportation Research Record 670
Price $5.00

mode
1 highway transportation

subject area
17 energy and environment

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Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Air quality analysis in transportation planning.

(Transportation research record; 670)
1. Automobiles–Motors–Exhaust gas–Congresses. 2. Air–Pollution–Mathematical models–Congresses. I. Title. II. Series.
TE7.H5 no. 670 [TD886.5] 380.5'08s [614.7'12] 79-720
ISBN 0-309-02809-4

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Oxidant Modeling Status

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Mathematical models that relate pollutant emissions to ambient air quality through the theoretical treatment of the chemical and physical processes of the atmosphere are reviewed. An evaluation of currently available models is presented and various shortcomings of state-of-the-art models are discussed. The program to verify the model for the St. Louis Regional Air Pollution Study is outlined and a discussion of the approach is presented.

Pollutants emitted into the atmosphere are transported, dispersed, transformed, and deposited via complex physical and chemical processes. Mathematical models provide a unique technique for evaluating the impact of anthropogenic emissions on air quality and will prove to be formidable tools in implementing the mandates of the Clean Air Act of 1963 and its amendments. Air quality simulation models (AQSM) provide the most fundamental approach to relating emissions to air quality through mathematical descriptions of the physical and chemical processes operating in the atmosphere.

The chemical mode of an AQSM is either nonreactive or reactive. Models that only consider inert pollutants or pollutants whose chemical transformation can be expressed by a first order reaction rate are nonreactive. Typical nonreactive pollutants are total suspended particulates, sulfur dioxide (SO_2), carbon monoxide (CO), and sulfate ($SO_4^=$). Reactive models, the subject of this review, are termed here as photochemical air quality simulation models (PAQSM). This is because of the major role played by photolytic reactions in the atmospheric transformation processes of pollutant species. Pollutants typically considered in PAQSM include reactive hydrocarbons (HC), CO, nitric oxide (NO), nitrogen dioxide (NO_2), and ozone (O_3).

MODEL FORMULATION

The development of a mathematical relation for simulating the transport, dispersion, transformation, and disposition of pollutant emissions into the atmosphere can assume varied ranges of complexity and scale, depending on the application under consideration. The need for practical PAQSM for describing the physical and chemical dynamics of the atmosphere necessitates the development of simplified approaches for treating reactive species in the turbulent planetary boundary layer. The basis of all PAQSMs is the equation of conservation of mass, which, with certain simplifying assumptions, reduces to the so-called atmospheric diffusion equation (1):

$$\begin{aligned}(\partial\bar{c}_i/\partial t) &+ [\bar{u}(\partial\bar{c}_i/\partial x)] + [\bar{v}(\partial\bar{c}_i/\partial y)] + [\bar{w}(\partial\bar{c}_i/\partial z)] \\ &= (\partial/\partial x)\{[(K_H\partial\bar{c}_i)/\partial x]\} + (\partial/\partial y)\{[(K_H\partial\bar{c}_i)/\partial y]\} \\ &\quad + (\partial/\partial z)\{[(K_z\partial\bar{c}_i)/\partial z]\} + [R_i(\bar{c}_i \ldots \bar{c}_n, T)] \\ &\quad + [\bar{S}_i(x,y,z,t)] \qquad (1)\end{aligned}$$

where

$\bar{c}_i$ = ensemble mean concentration for species i,
x, y, z = Cartesian coordinates,
$\bar{u}$, $\bar{v}$, $\bar{w}$ = ensemble mean velocities,
K_H, K_z = horizontal and vertical eddy diffusivities,
$\bar{S}_i$ = rate of injection (or removal) of species i by a source (or sink),
R_i = rate of production (or consumption) of species i through chemical reactions,
T = temperature, and
t = time.

The set of equations described by Equation 1 can be solved numerically to provide the theoretical mean concentrations of species i as a function of location and time. The model equations require (a) input information for initial and boundary concentrations of each of the pollutant species considered; (b) meteorological data for prescribing the wind field, turbulent diffusivities, solar radiation, and mixing height; and (c) source emissions as a function of location, time, and composition. Spatial scales may range from micro to synoptic and can be classified by the following four functional modeling domains (note that H = mixing height and PBL = height of the planetary boundary layer):

Scale	Domain	Dimension
Local	Micro	200 m x 200 m x 100 m
Urban	Sub-meso	50 km x 50 km x H
Regional	Meso	1000 km x 1000 km x PBL
Continental	Meso-synoptic	3200 km x 2400 km x PBL

Historically, the development of PAQSM has focused on the urban scale, where the O_3 problem was thought to originate and reside. Recent field programs indicate that O_3 and its precursors are not confined to the urban complex but in many instances are transported over hundreds of kilometers and time periods of several days. Based on these findings, development work in regional PAQSMs has begun. Given that the majority of research and development has concerned the urban problem, most of this review and evaluation will focus on that scale. Three basic approaches to photochemical air quality simulation modeling have evolved over the past several years. They are

1. A grid model based on numerical solution of the coupled atmospheric diffusion equations in three spatial dimensions on a grid over the region of interest,
2. A trajectory model based on simulating chemistry and vertical transport in air column advection with the local mean wind velocity, and
3. A box model based on simulating chemical processes in a well-mixed region in which no spatial inhomogeneities are assumed to exist and within which emissions are mixed instantaneously throughout the region.

Status of Urban Oxidant Models

A synopsis of air quality simulation models for photochemical oxidants is given below. The models considered are a representative sample of the current state of the art, limited to urban scales, and deterministic in nature.

1. Three-dimensional grid model based on numerical solution of the atmospheric diffusion equation. Three-dimensional wind field derived from ground-level measurements. Pollutants emitted from ground-level

sources are injected into the bottom layer of grid cells; emissions from stacks are distributed among the grid cells aloft; numerical solution by method of fractional steps with advection treated by SHASTA algorithm; vertical diffusion and chemistry by Crank-Nicholson method. A 35-step chemical reaction mechanism based on the reactions and reactivities of carbon bond types is used. Development of the model has been completed. Estimated completion of the regional air pollution study (RAPS) model verification is November 1978 (2, 3, 4, 5).

2. Two-dimensional grid model based on the numerical solution of the vertically integrated atmospheric diffusion equation; a modified Gear method is used in the numerical integration of coupled ordinary differential equations. The model utilizes a mass consistent wind field approach for generating detailed wind fields, vertical profiles of velocity, and diffusivity. Pollutants emitted at ground level and aloft are injected uniformly into the appropriate well-mixed cell. A 48-step generalized lumped chemical mechanism based on hydrocarbon reactivity is used. Development of the model has been completed. Estimated completion of RAPS model verification is November 1978 (6).

3. Trajectory model based on a moving column of air in which vertical diffusion and chemical reactions take place. Pollutants are emitted into the appropriate vertical cell. The column of air follows a surface trajectory interpolated from surface wind data. A modified Gear method is used in the numerical integration of coupled ordinary differential equations. A 46-step generalized lumped chemical mechanism based on hydrocarbon structural classes is used. Development of the model has been completed. Estimated completion of RAPS model verification is January 1979 (7, 8).

4. Single well-mixed cell. Coupled ordinary differential equations that include emission, advection, entrainment, dilution, and chemical reactions are solved using the Gear method. Emissions, which are considered horizontally homogeneous, mix instantaneously within the temporally prescribed mixed layer. A 36-step generalized lumped chemical mechanism based on hydrocarbon structural classes is used. Development of the model has been completed. Estimated completion of RAPS model verification is June 1978 (9).

The evaluation of AQSMs has been to assess both the validity of the basic assumptions used in deriving the models' working mathematical equations and potential sources for inaccuracies in the treatment of meteorological, chemical, and emission phenomena by the model (10, 11, 12, 13). A summary of these sources of error and an estimate of their impact on the predicted maximum O_3 concentration of a model is presented in Table 1. Several models have undergone limited verification studies (4, 6, 14, 15), as summarized in Table 2 (13). The reported results from these studies appear promising. Prior to extensive model application studies, further model verification and evaluation is warranted. The verification program under consideration as part of RAPS should provide the extensive model testing that is needed.

Model Verification and RAPS

Model verification studies have been limited in nature due to the lack of adequate air monitoring data bases against which to test models. The unverified status of AQSMs has proved a considerable deterrent in their application, both in terms of the rather extensive data resources required in operating the models and the unknown accuracy of their performance. Uncertainty limits on model prediction inaccuracies caused by all sources of error can be obtained through extensive comparison of model concentration predictions and ambient measurements. Comparisons should be made for a variety of meteorological and, where possible, emission conditions. Exercising models that have a sufficient data base to establish model prediction accuracy and uncertainty limits will provide insight into establishing the degree to which models can be extrapolated to conditions beyond those in the domain of evaluation.

The St. Louis RAPS (16), a 5-year field program sponsored by the U.S. Environmental Protection Agency (EPA) begun in 1972, will provide highly resolved spatial and temporal emissions and ground monitoring data for use in model verification studies. Three major objectives sought by the program are

1. To develop, evaluate, and verify air quality simulation models on an urban scale covering urban and rural stationary and mobile sources;
2. To develop, evaluate, and verify models of local phenomena that complement urban models; and
3. To archive all data collected under the program in the form of a readily retrievable data base to use in evaluating future air quality simulation models.

The principal elements of RAPS are shown in Figure 1. The monitoring network that developed late in 1974

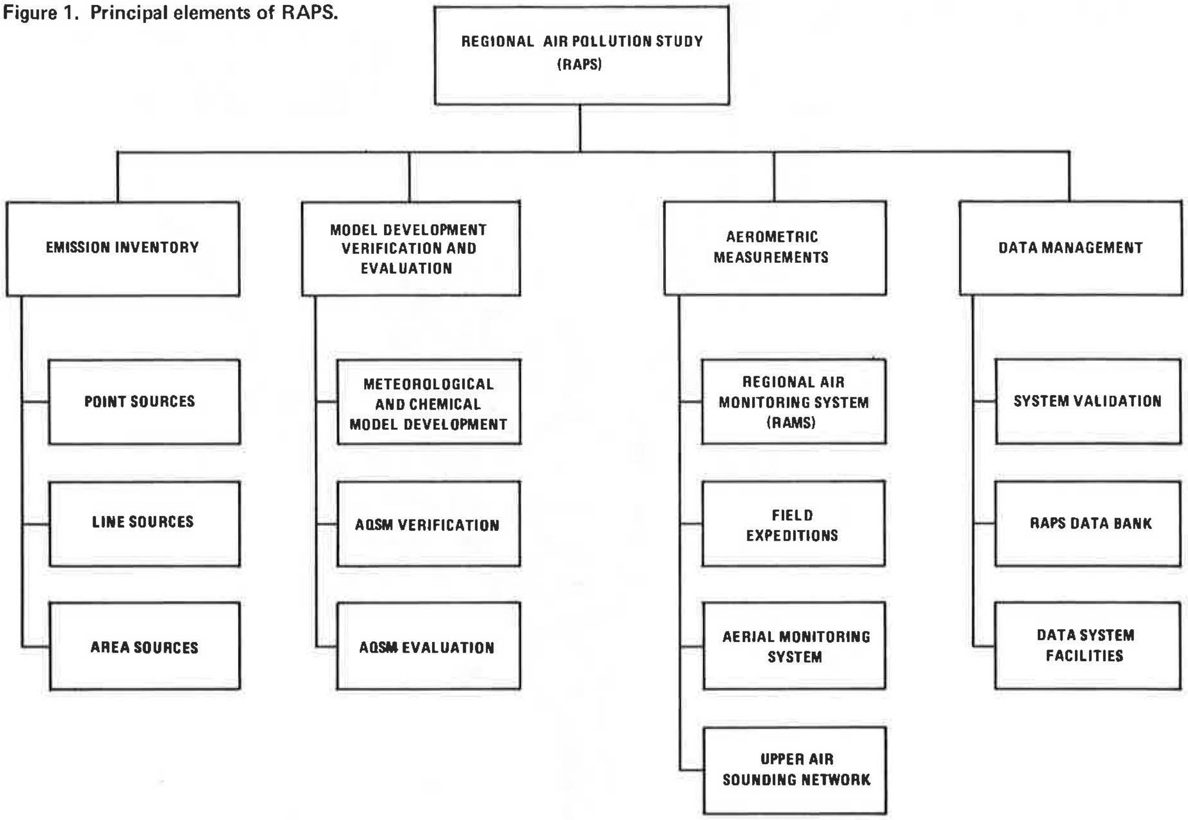
Table 1. Sources of error in PAQSMs and estimated impacts on predicted maximum O_3 concentration.

Source of Error	Uncertainty in Predicted Maximum O_3 Concentration (%)
Chemical mechanism	
Reaction rate constants	±20
Structural or reactive hydrocarbon classification	±30
Unknown reactions	±10
Meteorology	
Wind speed and direction	±20
Mixing depth	±25
Light intensity	±20
Initial and boundary condition	
Horizontal boundary	±20
Vertical entrainment	±50
Initialization	±20
Source emissions	
Spatial resolution	±20
Temporal resolution	±10
Emission factors	±30
Hydrocarbon composition	±20

Table 2. Previous photochemical PAQSM verification studies.

Region	Time Periods	Pollutants Compared
Denver. Portions of south coast air basin. Both 80 × 80-km (50 × 50-mile) and 129 × 161-km (80 × 100-mile) regions.	6 d in 1969; June 26, 1974	Studies performed with both the 15- and 31-step kinetic mechanisms. In both versions, pollutants compared were NO, NO_2, O_3, CO, reactive and unreactive hydrocarbons.
San Francisco Bay area. 170 × 210-km (106 × 130-mile) region. A variety of subregions and grid sizes (1 to 5 km) were employed.	July 26 and 27, 1973; August 20, 1973; September 26 to 28, 1973	Pollutants compared were NO, NO_2, O_3, CO, reactive and unreactive hydrocarbons.
Trajectories in south coast air basin.	6 d in 1969 LARPP data	Pollutants compared were NO, NO_2, O_3, CO, reactive and unreactive hydrocarbons.

Figure 1. Principal elements of RAPS.



consists of 25 monitoring stations, which are spatially distributed in a spiral configuration covering approximately a 6400-km^2 area. Figure 2 shows the geographical locations of regional air monitoring stations (RAMS) in the St. Louis area, and Table 3 gives the parameters measured and the instrumentation used at each station. Operational schedules for the upper air sounding network are as follows:

Sounding	Normal Operation	Intensive Study Periods
Rawinsonde	5 d/week, 4/d (6-h intervals) to 3.0 km; two locations	7 d/week, 4/d (6-h intervals) to 3.0 km; four locations
Pibal	20/d at hourly intervals between radiosondes; two locations	Same as normal operation except at four locations

The majority of parameters measured in the network are sampled at a 0.5-s frequency and archived on a minute and hour averaged basis.

A schematic view of the elements of the RAPS air quality simulation model verification program is shown in Figure 3. Since the verification of every urban AQSM currently in existence is an unrealistic task, a representative sample of modeling techniques was selected from the modeling stockpile. The selected models will then be adapted to the St. Louis region after a 3-d period for model debugging and testing. The EPA will then use the models for the verification study.

Days are selected from the RAPS data base to form a subset of verification days to perform the studies via a series of filtering programs. The filtering criteria include such tests as

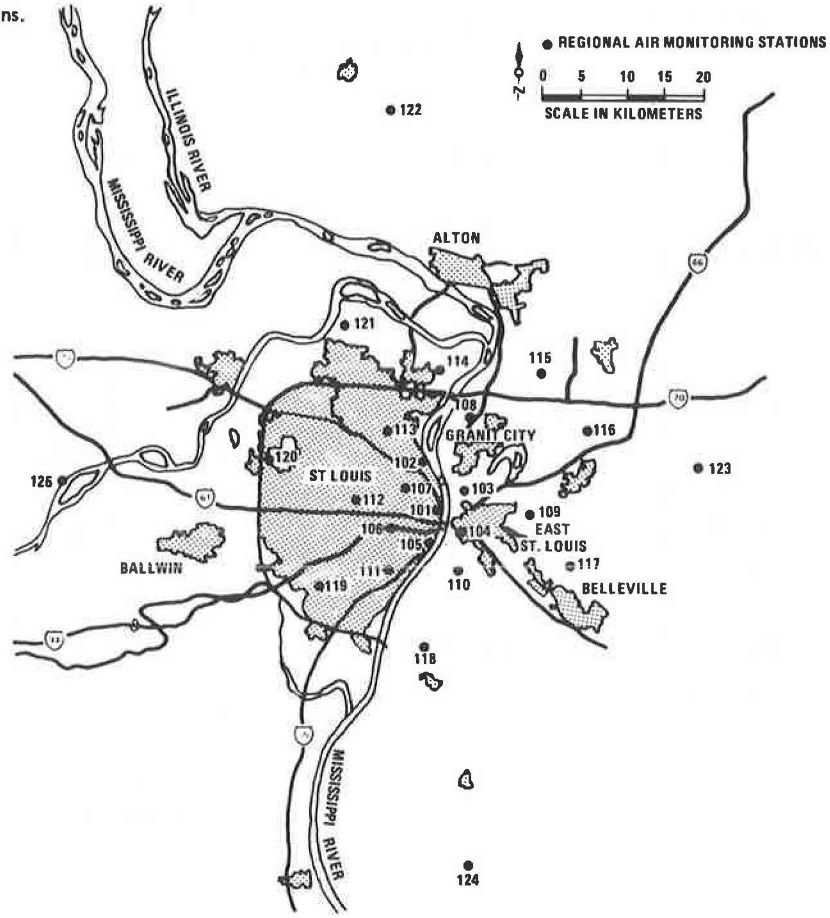
1. Days in which criteria pollutant X had Y percent or greater valid data,
2. Days in which criteria pollutant X exceeded an hourly averaged value of Y $\mu g/m^3$, and
3. Days in which criteria pollutant X exceeded a 24-h average value of Y $\mu g/m^3$.

The specific numbers used by the filters are subject to the primary pollutant to be modeled. The subset of verification days is then stratified by season. Nonreactive models will be tested against randomly selected days within each season. An attempt will be made to distribute the verification test days proportionately among the four seasons. The reactive models will use randomly selected days, but a disproportionate number of days will be selected from the summer months; fewer samples are taken in the other seasons.

After the selection of the model verification test days, a 5-d subset will be chosen and input data to the models for those days prepared. The 5-d subset will be used for preliminary testing and should allow identification of any major model inconsistencies. Obvious minor model refinements will be considered at this stage. All of the models selected will have undergone some form of evaluation and testing, so major unresolvable inconsistencies are not expected. Should such a case arise, the verification studies for the particular model in question would stop and the preliminary test results sent to the model developer for study.

Once the preliminary model testing phase is completed, the statistical verification studies will begin. Approximately 50 d of computer simulation will be considered for each model. Comparisons between computer-predicted and observed hourly averaged concentrations of pollutants will be made on a day-by-day basis. Specific statistical tests for model verification studies have been discussed by Brier (17), Nappo (18), and Liu and others (19). In light of these studies, several ap-

Figure 2. Geographical locations of RAMS stations.



proaches for the comparative studies are under consideration. Model verification will provide the first adequate set of statistical criteria on which to judge model performance and will, in the final analysis, provide the necessary information for assessment and selection of models for various application purposes.

APPLICATION AND FUTURE DEVELOPMENTS

In addition to their obvious role in providing a better understanding of the fundamental chemical and physical processes associated with air pollution, PAQSMs have the potential for addressing many policy, planning, and enforcement questions in air pollution control. These include

1. Evaluation of the effectiveness of current and future emission control regulations in achieving ambient air quality standards,
2. Identification of major sources contributing significantly to air quality deterioration.
3. Determination of air quality impacts based on al-

Table 3. RAMS remote stations instrument distribution.

Parameters	Station Number 101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125
O_3 monitor laboratories 8410	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
NO-NO_x monitor laboratories 8440	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
CO-CH_4-THC Beckman 6800	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
TS-SO_2-H_2S tracor 270HA	X		X	X	X	X		X					X	X	X	X				X	X	X			
TS-Meloy SA 185		X					X		X	X	X	X					X	X	X				X	X	X
Visibility-MRI 1561	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Wind speed-MRI 1022 S	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Wind direction-MRI 1022 D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Temperature-MRI 840-1	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dew point-Cambridge 880	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Temperature gradient-MRI 840-2	X	X		X	X	X	X		X		X	X	X									X	X		
Barometer-Sostman 363	X								X			X										X	X	X	X
Solar pyranometer			X	X				X						X				X				X			
Radiation pyrheliometer			X											X				X				X			
Pyrgeometer (Eppley)			X											X				X				X			
Turbulence-R. M. Young 27002					X		X		X		X		X												
Gas bags-Xonics	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hi-Vol-Sierra 305			X		X	X		X				X			X			X		X		X		X	
Lawrence Berkley Laboratory dichotomous sampler			X		X	X		X				X			X			X		X		X		X	
10-meter tower								X		X				X	X	X	X	X			X				
30-meter tower	X	X	X	X	X	X	X		X		X	X	X						X	X		X	X	X	X

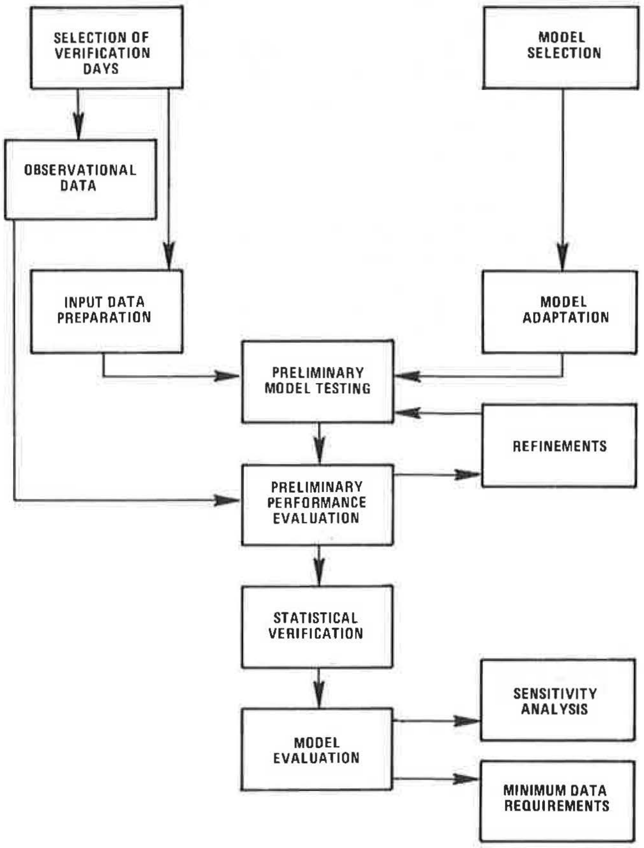


Figure 3. Elements of the RAPS verification program for AQSM.

ternative plans for transportation and land use development, and

4. Evaluation of optimum siting of instrument stations for air quality monitoring networks.

The establishment of statistical performance criteria for AQSMs is essential if effective and creditable applications of these models are to be realized. Such performance criteria are an expected product of the RAPS model verification program. Performance criteria will vary as a function of the modeling approach as well as of the application to be considered. Therefore, the most cost-effective choice of a model for any given study must consider these three factors. Studies that assess minimum data base requirements relative to acceptable model performance must also be considered and guidance given as to the spatial and temporal resolution of model input data required. In addition, model sensitivity analyses that identify key parameters within the model are essential in providing effective use of resources in gathering data for model application. All of these studies are the subject of current and future development over the next several years.

Research and development of a regional PAQSM began early in FY 1977, under EPA sponsorship. Phase 1 of the program, scheduled for completion in early 1978, includes the basic research and formulation of the modeling framework. Phase 2, scheduled to end in early 1979, will test and evaluate the model using data gathered under the Northeast Oxidant Study Field Program of 1975. Further testing using field data gathered in other regions of the country will be considered if the phase 2 results look promising. Ultimately, the model will be used to assess impacts of air pollution control plans on pollutant concentrations many kilometers downwind. As the results from the RAPS model verification program and regional PAQSM development program unfold, further research and development studies may be indicated. The advantage will be that now the areas for refinement will be pinpointed based on extensive comparisons with observed atmospheric data.

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Regional Air Quality Modeling in Los Angeles

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The California Department of Transportation has applied regional air quality models to the Los Angeles area on a limited basis. A Lagrangian, or trajectory, model was used to evaluate the air quality impact of a highway project. An Eulerian, or grid, model is currently being used to evaluate regional transportation plans. The use of these models requires a costly and extensive data base for validation and the cooperation of local and regional agencies. A large aerometric sampling program was undertaken for one of the data bases. Technical problems in model application were related to electronic data processing and reconciliation of data that are tied to different geographic grid systems. In-house computer expertise is essential for application of the model. Model output tends to be voluminous and requires simplification for analysis and presentation.

The Los Angeles region is reputed to have one of the world's most intractable oxidant problems. In June 1974, for example, a 5-d oxidant episode created a peak 1-h value of about 860 $\mu g/m^3$ (44 pphm) in the eastern portion of the Los Angeles basin. The national ambient air quality standard (NAAQS) of 160 $\mu g/m^3$ (8 pphm) was violated for 1400 h that year. In years prior to 1974, even higher values of oxidant have been observed.

The Los Angeles Federal Air Quality Control Region (LAAQCR) encompasses all parts of the six counties shown in Figure 1. This region is roughly 129 km (80 miles) long and 257 km (160 miles) wide and includes approximately 25 205 km^2 (9736 $miles^2$) of land and a population of 10 million people. The principal agency for overall planning in the region is the Southern California Association of Governments (SCAG). This agency is supported by the 127 member cities and five counties within the region and by the California Department of Transportation (Caltrans).

The air quality management planning effort is funded by the U.S. Environmental Protection Agency (EPA). The funds are channeled through the California Air Resources Board (CARB) to the Air Quality Maintenance Planning (AQMP) group, which is also supported by the staffs of the CARB, SCAG, the four-county Southern California Air Quality Management District (SCAQMD), the Ventura County Air Pollution Control District (VCAPCD), the Santa Barbara County Air Pollution Control District (SBAPCD), and Caltrans.

The LAAQCR is a plain, bounded on the north by a high mountain range and on the west by the Pacific Ocean. Some internal geographic features divide it into subregions but do not usually block the west-to-east movement of air through the basin. Typical meteorology during an oxidant episode is a west-to-east air movement at moderate speed, a subsidence inversion producing a mixing depth of 300 to 460 m (1000 to 1500 ft), clear skies, and high ambient temperature. During the night, a wind reversal produces a sloshing effect. These conditions occur several times during the oxidant season (May to October). Other weather patterns (such as weak Santa Ana winds) also produce episodes, but this pattern typically produces the highest levels of oxidants.

The LAAQCR has 44 stations that measure air quality and many that measure wind speed and direction. Much of these data must be used with caution as the wind instruments at the measuring stations are not necessarily sited to produce wind data that are representative of the surrounding area. The sources of pollution are highly variable and geographically dispersed. The CARB emission inventory for the region estimated a background level (geogenic origin) of 1.36 $\times 10^5$ kg/d (150 tons/d) of reactive hydrocarbons (RHC). In 1975, the daily production of RHC from anthropogenic sources was about 1.41 $\times 10^6$ kg/d (1550 tons/d). This was generated 40 percent from light-duty vehicles, 20 percent from all other forms of transportation, and 40 percent from industrial and area sources. Much of the RHC is the result of industrial activities in the western part of

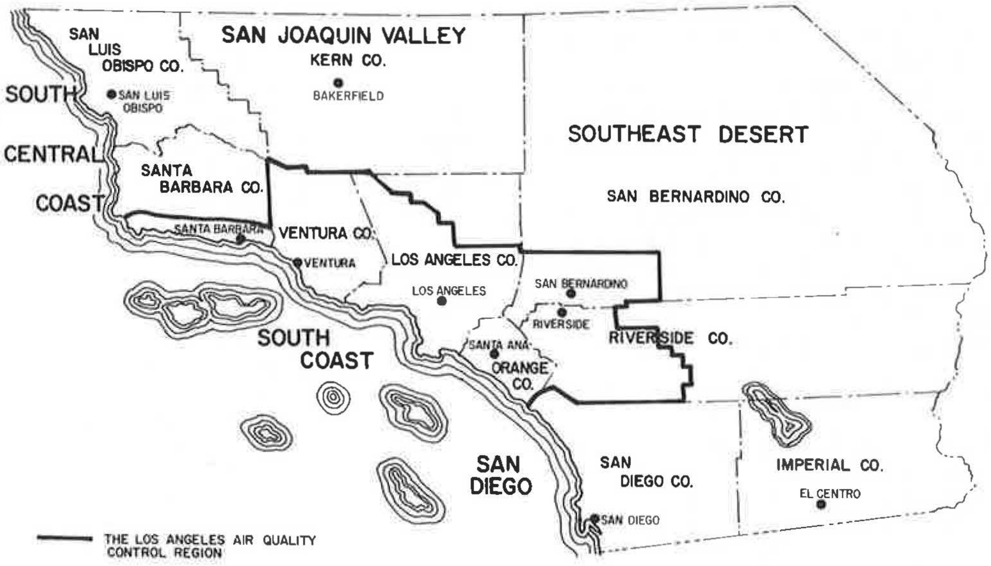


Figure 1. Los Angeles air quality control region.

the basin that are transported to the east. Typically, the highest levels of oxidant are recorded in the middle to east portion of the basin. The shear size of the region, the dispersed emission sources, and complex meteorology make the acquisition of a regional photochemical air pollution model essential.

MODELING ACTIVITIES

To date, Caltrans has used the following models: (a) the proportional model to assess regional impact of project and transportation plans, (b) the Lagrangian grid photochemical trajectory model to assess the impact of the Century Freeway on the region, and (c) a regional Eulerian grid photochemical model to assess regional impacts for SCAG and AQMP.

The proportional model has been used extensively out of necessity, but it yields unsatisfactory results because of its weak basic assumptions and inability to give spatial and temporal variation in concentrations.

The Lagrangian model (DIFKIN) was developed by the General Research Corporation for EPA. The model is used to compute the changes in concentrations that occur within a moving column of air for the various species of pollutants, both photochemical and inert. The air parcel moves across a fixed grid from which pollutants are injected into the air parcel. Caltrans applied the model to the proposed 27-km (17-mile) Century Freeway. The freeway was split into three approximately equal segments. Trajectories for each segment were developed for four beginning hours—7:00 a.m., 9:00 a.m., 11:00 a.m., and 1:00 p.m. This was accomplished by setting the trajectories back in time (from the center of the segment) to some appropriate time (early morning) for each beginning hour. The trajectories were then run ahead in time using the full photochemical diffusion program. Trajectory runs were made for the analysis years of 1980 and 2000, for the with and without project alternatives, and for the segments and hours previously mentioned. This required a total of 48 trajectories.

The results of the runs showed low peak oxidant concentrations, which did not seem realistic. Later analysis indicated that the unrealistic values were the result of inadequate diffusivity parameters. For comparison of the project alternatives, however, the results were judged to be satisfactory. The results indicated no essential differences among alternatives on a regional scale. The diffusivity parameter has since been corrected by CARB; DIFKIN is an adequate model for point source and single freeway analysis.

A trajectory model could not handle the requirements for analyzing the LAAQCR for the areawide transportation systems and other regional plans. Practical considerations such as economics, time, and personpower available require the use of an Eulerian grid model in making the analysis for the entire LAAQCR. The model selected was developed for EPA by Systems Applications, Inc. The model was subsequently modified for Caltrans. It uses the same basic input data required for DIFKIN and operates on the same grid system. A reasonably good validation of this model was made for an episode that occurred in June 1974. No other validations have been attempted.

The model moves the air through the three-dimensional cell matrix in accordance with the wind field data (including wind shear) and the wind field algorithm and incorporates a horizontal and vertical diffusion mechanism. The photochemistry is performed for each cell using hourly variations of solar radiation (UV). The model outputs consist of hourly averaged concentrations for six species of pollutants [ozone (O_3), nitrogen dioxide (NO_2), nitric oxide (NO), carbon monoxide (CO), RHC, and nonreactive hydrocarbons (NRHC)].

The AQMP has used the Systems Applications, Inc., model for four emission scenarios developed by the AQMP planning group. The scenarios varied the total basin emissions of RHC by only 6 percent but made spatial changes in the emission sources. Results of the model runs indicate that only small changes in concentrations occurred in the affected cells, as might be expected from the small emission changes. Additional model runs are not in progress; it is expected that three more days of meteorological episodes will be used and other scenarios will be assessed in the near future. Indications are that the model is useful for estimating the impact of various future scenarios and strategies designed to improve the air quality in the LAAQCR.

Model Data Base

The emission data base grid for both of the models used is a 3.2 × 3.2-km (2 × 2-mile) matrix, 40 cells long by 80 cells wide. Emissions from major stationary sources are placed in the appropriate cells and all other stationary sources are proportioned to the cells by existing or proposed land use. This facilitates the spatial placement of emissions for scenarios in future years. All species involved in the model are given a diurnal variation by hour.

Mobile emissions are obtained from the Los Angeles Regional Transportation Study model. Through computer programs, emission factors are applied to the travel data and the resulting emissions are placed in the appropriate cells (diurnally varied by hour). The meteorological data base is positioned on the same matrix. The necessary meteorological data are hourly values of surface wind speed and direction, values of UV, and inversion height. Air quality data from the regional monitoring stations are required to establish boundary and initial concentrations of the pollutant species.

Problems in Applying Regional Models

The two major technical problems encountered with the Systems Applications, Inc., model were (a) computer connected and (b) model grids. The version of the model available to Caltrans at the time the modeling effort was initiated was based on a 25 × 25-cell matrix. The model was written in a research code, which may be satisfactory for some purposes but does not facilitate improvements or changes. The change from the 25 × 25-cell matrix to the 80 × 100-cell matrix caused many problems in programming.

Another major computer problem stemmed from the state computer system operation. Originally, the model was put on the state system, which uses two IBM 370-168 computers and serves all state agencies. After considerable effort, it became apparent that the core requirements of the Systems Applications, Inc., air pollution simulation program (APSP) of 1.2 megabytes and the way that the state computer system was operated made the two incompatible. The APSP was ultimately set up, therefore, on a CDC 7600 computer at the Lawrence Berkeley Laboratory. The problem could have been avoided if computer expertise had been available in-house during the early planning of the effort.

A rectangular grid system of cells would not seem to be the source of problems, but in this case, it was. The problem is in the correspondence of a grid in the plane on which the model operates with a grid on a curved surface. This is not a problem on a small grid, but became a large problem on a large grid. An emission data base for stationary sources had been established on a 1.6-km (1-mile) grid based on local mapping, which had less than adequate horizontal control. The model grid is based on a reference point designated by a latitude and longitude. All grid cell lines were then placed 3.2 km (2 miles) apart and parallel to the east-west and north-south lines at the reference point. These two grid systems did not correspond throughout the modeling region; in some places the differences were major.

A third coordinate system, the universal transverse mercator (UTM), was also involved. UTM is being used by others to reference present and future emissions and other model input data. This grid system is curved and has a substantial and constantly changing skew with respect to the other grid systems. The problem is to translate the model input data from one of the grid systems into the correct cell in the model grid. Regression equations were computed for correspondence between the grids, but the best solution was to plot the model grid on U.S. Geological Survey (USGS) quad sheets (which include the UTM coordinates) and fit the stationary source data base grid to it. The solution, however, was complicated by the several different agencies involved, each having different interests and ideas as to the best solution.

Generally, relations with the consultant were satisfactory. The consultants were somewhat overly optimistic as to what the models could do, what they could furnish in terms of model modifications, and especially on what amount of time was needed to accomplish the tasks. One notable deficiency experienced by Caltrans was the lack of comprehensive documentation and a user's manual of instructions sufficiently complete to operate the model without considerable consultant assistance.

Problems in Validation

Validation of the model was only attempted for O_3. The principal problem encountered in validation was the expense and time involved to develop an adequate data base to measure model performance. Two sets of data bases were developed. The first was an episode from June 25 to 29, 1974. Meteorological and air quality data were gathered after the fact. This effort involved contacting many agencies such as the National Oceanic and Atmospheric Administration (NOAA), the air pollution control districts in five counties, and CARB. In some cases the data had to be copied by hand. The sheer volume of data required more than 2 person-years of effort to gather, code, punch, and edit. The cost of this data base was about $75 000. As previously mentioned, many of the wind instruments were not placed by using the modeling requirements as criteria, and, therefore, the wind data are suspect; however, these were the only data available at that time.

A subsequent effort was made to obtain a data base of sufficient meteorological data to reflect the three-dimensional wind field and also to contain the pollutant concentrations within the mixing layer that are needed to establish the initial conditions. This was accomplished through a multiagency cooperative effort, initiated and coordinated by Caltrans. The agencies involved were Caltrans, CARB, air pollution control districts (APCD) in five counties, NOAA, EPA-Research Triangle Park, National Environmental Research Center-Las Vegas, U.S. Navy, and the University of California at Los Angeles.

The sampling program consisted of

1. Instrumented aircraft flights,
2. Pilot balloon (Pibal) launches (for winds aloft) through the basin,
3. A network of mechanical weather stations sited to obtain an adequate representation of the surface wind field for the region,
4. Solar radiation measurements both above and below the inversion layer and covering the modeling region, and
5. Air quality data from all the measuring sites in the region.

Except for air quality data, Caltrans accomplished the bulk of the effort. The sampling of a particular day was triggered by the San Bernardino County APCD when their predictions indicated that an oxidant episode the following day would exceed 690 $\mu g/m^3$ (35 pphm). The message to begin the sampling in accordance with a prearranged plan was then relayed to all parties in the sampling program. This system worked very well. One such episode, on July 9 and 10, 1975, was sampled with very satisfactory results. The total cost of obtaining these data, including the costs of coding, editing, and entering it in the computer, is estimated to be about $150 000. Caltrans paid about 80 percent of the cost. Validation runs on this data base will be made in the near future; this base is expected to give better validation than that of 1974.

One area of validation that has not been researched, and should be, is the representativeness of the air quality measuring stations. The air quality stations measure the air from one point, but the model averages the concentrations over an area of 10.4 km^2 (4 $mile^2$). There is no evidence that values from the station are representative of the cells or of the surrounding area. Some of the stations are located on sites where the local vehicular traffic may have a significant influence on the recorded concentrations; therefore, the concentrations may not be representative of the modeling cell.

The costs of running the model on the Lawrence Berkeley Laboratory computer vary considerably, depending on the priority the run is given. For example, a 24-h run at a priority 10 (highest priority range) costs about $3500. On the other hand, the same run at priority 3 (lowest range) would cost $800. Costs also vary considerably, depending on the number of cells in the model.

The most valuable expertise to have in running the models is a knowledge of computers. The Systems Applications, Inc., model has a number of preliminary data preparation programs in addition to APSP and when glitches occur (which is not uncommon), knowledge of computers, computer systems, and computer programming is invaluable.

OUTPUT ANALYSIS

The printed output for the Systems Applications, Inc., model is quite voluminous—24 h of simulation yield about 1200 pages of computer printout. The only practical way to analyze the output, therefore, was to have the output read onto magnetic tape and write computer programs against this file. The output file was, therefore, put into the state computer system and these programs were written. Three principal programs are now available to compare the output of different scenarios. All are printed out by the computer on standard sheets and displayed by gridded cell array over the entire modeling region. These programs produce

1. The maximum concentration of O_3 and the hour it occurred.
2. A grid array that is shaded by using a different symbol for each concentration range. The symbol is progressively darker as the step ranges increase. There is an array for each hour. Thus, the overall impact can be seen qualitatively at a glance.
3. Changes in maximum concentration from the base scenario. This is done by printing the numbers 1 through 9 if the concentrations go up and the letters A through I if the concentrations go down. No change would be a 0. All 9s and I's require examination to see if the change is greater than 9.

The above data displays are useful in assessing a particular strategy's effect on maximum concentrations. They do not give an easily understandable evaluation of the overall impact, either regionally or subregionally. This can be done by developing an index by which the various plans and strategies can be compared. Comparison of hourly concentrations of oxidant for different emissions scenarios for approximately 2500 grid cells is impossible. A powerful approach, then, would be a people-concentration index for the total region and for critical subregions. This index can be obtained by the use of a program that multiplies the population residing in a cell and the sum of all the hourly concentrations in the cell. This product is then divided by the number of hours of simulation to normalize the index. The individual cell indexes can then be aggregated by subregion or the entire region, as desired. This programming is not yet completed. The ability to analyze rapidly the immense amount of output numbers makes computer programming capability a necessity.

AVOIDANCE OF MAJOR PROBLEMS

The following suggestions are for those about to undertake air quality modeling. They may help avoid some of the pitfalls that were experienced by Caltrans.

1. Buy only a modularized model that can be altered easily to keep up with the changes in the state of the art;
2. Have in-house computer expertise available;
3. Insist on a user's manual that gives complete step-by-step procedures on exactly how to operate the model;
4. Know from the beginning what size matrix is needed. If the matrix is too large, it will cost more to run the model and to collect the input data; and if it is too small, the required answers will not be available. Also, carefully examine the correspondence between the model grid and data source grids;
5. Edit all input data carefully; and
6. Be prepared for unforeseen problems.

Oxidant Model Applications: Denver

Denis E. Donnelly, Colorado Department of Highways

In the Denver air quality control region, the abundance of sunlight, the high altitude, and the large per capita automobile population have resulted in a serious oxidant pollutant problem. Local officials have required and the public has supported the use of the latest state of the art to analyze existing air quality and to determine what may be expected in the future. The photochemical oxidant model developed by Systems Applications, Inc., has been used to assess local conditions. The model was calibrated in the winter for a bad carbon monoxide condition and in the summer for a bad ozone condition. The 120 h of carbon monoxide data sets used to compare the measured versus model-predicted values resulted in a correlation coefficient of 0.71. Ozone data for 74 h resulted in a correlation coefficient of 0.80. Linear regression equations were used to adjust the model for minor unaccountable error for each pollutant. To date, the model has been used to analyze regional air quality situations given various transportation and land use scenarios. This use includes the assessment of air quality control strategies, transportation system alternatives, and alternative routing of a major freeway proposal. Recent innovations in the model have improved chemistry reaction rates; the model output now approaches the precision of pollutant monitoring equipment. The improved model has been used to analyze various land use strategies and will be incorporated into the transportation planning process.

The Federal-Aid Highway Act of 1970, section 109j; of Title 23, U.S. Code, requires that each state evaluate its transportation plans and programs annually as to their consistency with the state implementation plan. Also, environmental impact statements for major highway construction projects often require an in-depth air quality analysis.

AIR QUALITY IN DENVER

Denver's serious air quality situation can be related directly to large-scale automobile usage, restrictive meteorology (such as frequent temperature inversions and low wind speed), and high altitude factors. Denver's air pollution problem is dichotomous, depending on the annual season. The two major pollutants are carbon monoxide (CO) and ozone (O_3). CO is produced by automobile exhausts, and O_3 is the indirect product of the combination of automobile exhausts and sunlight. Short-term exposure to both pollutants has been associated with deleterious health effects.

CO has a double-peaked diurnal pattern that reflects the rush-hour traffic. The highest concentrations of CO occur in the winter months, indicating the strong relationship between the meteorological parameters of wind speed and inversion height and CO. CO is not only a local pollutant; it has a regional character that has been particularly noticeable in major suburban activity centers. The continuous air monitoring project (CAMP) station in downtown Denver has proved to be a good indicator of the CO situation in the Denver Air Quality Control Region (DAQCR); because the area traffic counts are higher at the CAMP station than at other locations in the DAQCR, the CO pollutant concentrations might also be higher.

O_3, on the other hand, has a single-peaked diurnal pattern that reflects the intensity of sunlight. O_3 is related more to solar intensity than to other meteorological parameters; therefore, the highest annual concentrations of O_3 occur in the summer months. O_3 is a major regional pollutant that primarily affects areas in the DAQCR in which people reside rather than areas in which people work. The CAMP station has been a very poor indicator of the O_3 situation in the DAQCR, because it underestimates the problem for the suburban areas.

The pollutants are not bound by city or county limits and may reach episode levels over much of the metropolitan region during periods of severe atmospheric stagnation. The DAQCR has a priority 1 classification for CO and O_3 because in Denver these pollutants often exceed the national ambient air quality standards (NAAQS).

MODEL SELECTION

The condition of Denver's air quality prompted public officials to recommend the use of the latest state of the art in assessing present and future conditions. The Federal Highway Administration (FHWA), the U.S. Environmental Protection Agency (EPA), the state air pollution control commission, and the state department of highways worked together to determine the most appropriate model for the Denver metropolitan area.

Nonreactive regional air quality simulation models were used prior to 1975 to assess CO concentrations. The extent of O_3 pollution prompted a search for a photochemical oxidant model that could predict this pollutant in addition to predicting the nonreactive pollutant, CO. Recent work by Systems Applications, Inc., in the Los Angeles basin prompted the state of Colorado to contact them regarding the use of their air quality simulation model in Denver. Representatives of Systems Applications, Inc., were encouraged by the availability of data in the Denver area (including traffic assignment on the metropolitan transportation network, automotive emission factors, an inventory of stationary source emissions, a fairly comprehensive network of surface meteorological data, and a limited amount of upper level meteorological data); however, reaction rates of air pollutant species at Denver's high altitude were not known. The reaction rates used in the Los Angeles basin were later adjusted and found to fit local conditions.

Characteristics and prospective benefits derived from the Systems Applications, Inc., model were presented to local EPA, FHWA, and air pollution control district (APCD) officials for their review. Endorsement was obtained and the recommendation was made to use the model for the section 109j air quality assessment statement (1), air quality maintenance plan statement (2), and an environmental impact statement on a proposed beltway Interstate project (I-470) (3). The model was useful in assessing future air quality, especially when the Denver area's projected rate of growth was considered.

The Systems Applications, Inc., airshed model (4) is based on the numerical solution of the coupled, time-dependent mass conservation equations, expressed as

$$\begin{aligned}(\partial c_i/\partial t) + (\partial uc_i/\partial_x) + (\partial vc_i/\partial_y) + (\partial wc_i/\partial_z)\\ = (\partial/\partial x)[K_H(\partial c_i/\partial x)] + (\partial/\partial_y)[K_H(\partial c_i/\partial_y)]\\ + (\partial/\partial z)[K_V(\partial c_i/\partial z)] + R_i + S_i\end{aligned} \tag{1}$$

where

∂ = standard mathematical symbol for partial derivative;
x, y, z = location of a point in space on a rectangular coordinate system consisting of three mutually perpendicular planes;
c_i = concentration of species i;
u, v, w = wind components in the x, y, and z directions respectively;
K_H, K_V = horizontal and vertical turbulent diffusivities;
R_i = rate of production of species i through chemical reaction;
S_i = rate of production of species i from source emissions; and
t = time.

The equations are three-dimensional in order to handle wind convergence and divergence and elevated inversion behavior. In full photochemical applications, up to six chemical species are considered, including reactive hydrocarbons, nonreactive hydrocarbons, NO, NO_2, O_3, and CO. The chemical reaction rate expressions (R_i) are determined from a 15-step kinetic mechanism, and the source term includes emissions from elevated point sources, such as power plants. Emissions from motor vehicles, fixed sources, and other ground-level sources are input to the model through the boundary conditions.

The major components of the model are as follows:

1. Emissions—An emissions inventory must be prepared for all chemical species of interest. This involves calculations of the total mass of pollutants emitted from automobiles, aircraft, and fixed sources into each ground-level grid cell and the mass of contaminants emitted by elevated point sources into grid cells aloft.
2. Meteorology—Meteorological inputs of wind speed, wind direction, and mixing depth must be specified at the centers of all grid cells.
3. Chemical kinetic mechanism—A chemical kinetic mechanism is required if any of the species of interest react in the atmosphere. The mechanism is used to determine the rate at which pollutant concentrations change as a result of chemical reaction.

The nonlinear, coupled partial differential equations that express the conservation of mass of each pollutant comprise the governing equations of the model. Individual reaction rate expressions (from the kinetic mechanism) are incorporated into the equations, and emissions and meteorological data are inputs to the model. The solution is obtained by numerically integrating the governing equations on a three-dimensional grid; the modeling region is overlaid to obtain the temporal variation of pollutant concentrations in each cell of the grid.

The Systems Applications, Inc., model is embodied in seven computer programs. The most important of these is the atmospheric pollution simulation program (APSP), which is used to predict concentrations of air contaminants in the grid cells that comprise the region to be modeled. The other models are specialized data preparation programs that are used to process the large volume of emissions, meteorological, and air quality data employed by APSP. Ground-level emissions from automobiles, aircraft, and fixed sources are combined by the emission program, SAIEMIS, and the emissions data preparation program (EDPP) to produce an array of total pollutant fluxes into each ground-level grid cell. These fluxes are then placed in the emissions data file (EDF). Hourly wind and mixing depth maps are prepared from available wind measurements and inversion soundings through the use of interpolation procedures in the WIND, DEPTH2, and meteorological data preparation programs (MDPP). The output is stored in the meteorological data file (MDF) for subsequent use by APSP. Initial concentrations required in the solution of the governing equations are computed from available air quality measurements in the program, QUAL, and are stored in the initial conditions data file (ICDF). Figure 1 summarizes the overall structure of the airshed simulation package and indicates the flow of information to and from each program.

After the three input data files are created, operating parameters, elevated point source emissions, and chemical kinetics data for APSP are specified and placed on punched cards. APSP is then used to perform the airshed simulation. Pollutant concentrations are predicted for each grid cell. Based on these values, an estimate can be obtained of the predicted contaminant level at each air quality monitoring station or other point of interest selected by the user. The results of the simulation are presented in three forms:

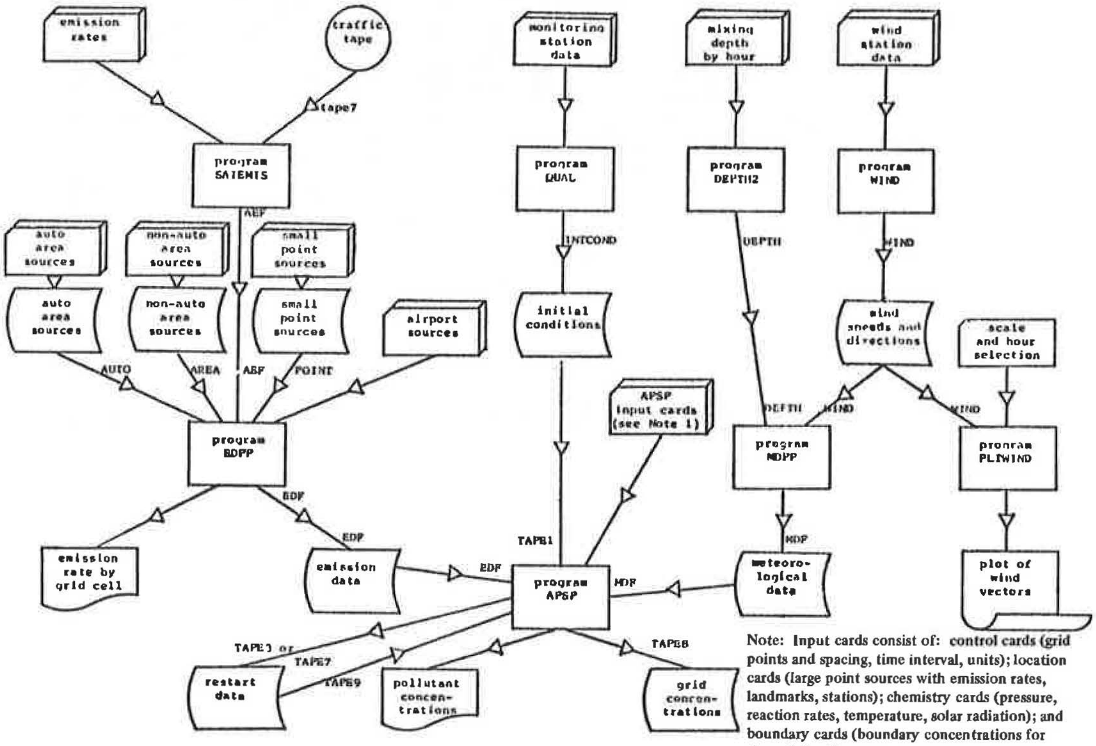
1. Instantaneous ground-level concentration maps for all species, printed at regular time intervals,
2. Printed hourly averaged ground-level concentration maps for all species, and
3. A permanent file containing the instantaneous pollutant concentrations present at the end of the simulation and a permanent file record of all printed output.

Model Calibration

The model must be calibrated for the Denver area to make fine adjustments that cannot be made by using input parameters. This is accomplished by using 2 d to determine the best relation between the measured and predicted values. Extensive monitoring is performed during the 2 d to establish a base. Once the model has been calibrated for current conditions, these factors are used to correct the predicted data for future simulations. These calibrations were based on the emission parameters, which were based on average vehicle route speeds and those emission inputs that incorporated the effect of rush-hour speeds.

The 2 d used to calibrate the model for Denver were November 15, 1974, and July 29, 1975. November 15 was used to observe the ability of the model to predict concentration of CO. July 29 was used to check the

Figure 1. Systems Applications, Inc., model operation flow chart.



Note: Input cards consist of: control cards (grid points and spacing, time interval, units); location cards (large point sources with emission rates, landmarks, stations); chemistry cards (pressure, reaction rates, temperature, solar radiation); and boundary cards (boundary concentrations for six pollutants).

ability of the model to predict concentrations of NO, NO_2, hydrocarbons, and O_3.

Figure 2 shows the sites selected for continuous monitoring (in addition to health department permanent stations) of all pollutants used in the model calibration. During the winter calibration for CO, additional sites were selected to determine the nonreactive pollutant concentration by incorporating mylar bag grab samples. Surface meteorological data were obtained from 17 surface sites and upper air radiosonde measurements were obtained from 3 sites. Traffic counters were placed at strategic sites throughout the metropolitan area to obtain a distribution control on the various roadway classifications and area types. The control statistics were later used to adjust annual average roadway link assignments. The conversion was made to obtain hourly traffic distributions on the study day.

The data collected on November 15, 1974, indicated that Denver was under the influence of a temperature inversion from the previous day's frontal passage and accompanying snowfall. This resulted in high CO readings, which were used to calibrate the model for a typical bad winter day. The highest hourly average CO concentration at the CAMP station was 21 mg/m^3 (18 ppm), the 117th highest hourly average concentration for the year. The 8-h average for that day, 15 mg/m^3 (13 ppm), was the 31st highest 8-h average recorded in 1974. Figures 3 and 4 show the distribution of maximum CO concentrations in Denver. Figures were calibrated in parts per million. Note that 1 mg/m^3 of CO = 0.87 ppm.

On July 29, 1975, a maximum O_3 concentration of 0.204 mg/m^3 (0.104 ppm) ranked it the 22nd highest hourly average concentration for the year. Figure 5 contains a distribution of 1975 O_3 readings exceeding that value. Note that 1 mg/m^3 of $O_3 = 0.051 \times 10^3$ ppm. A tabulation of input data except emissions for the model is listed in Table 1. Hourly correction factors for two photo-dependent reaction rates are listed in the second column. These factors rates are listed in the second column. These factors are directly related to the intensity of the sun. Table 2 gives reaction rates for each equation.

The model correlated very well for both days. Figures 6 through 9 are typical plots of predicted and measured concentrations versus time of day. Predicted and measured concentrations were compared using the BMD02R regression program. For November 15, 1974, 120 CO concentrations were compared and had a corre-

Figure 2. Map of Denver metropolitan area.

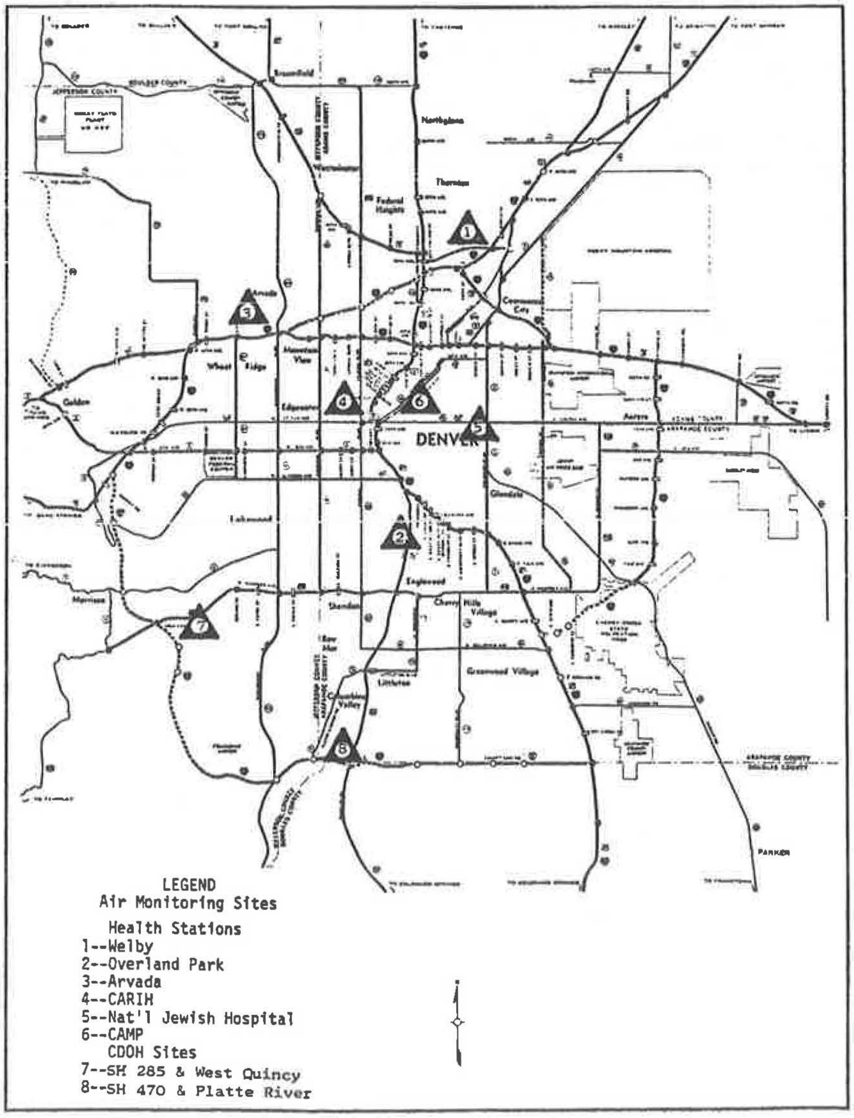
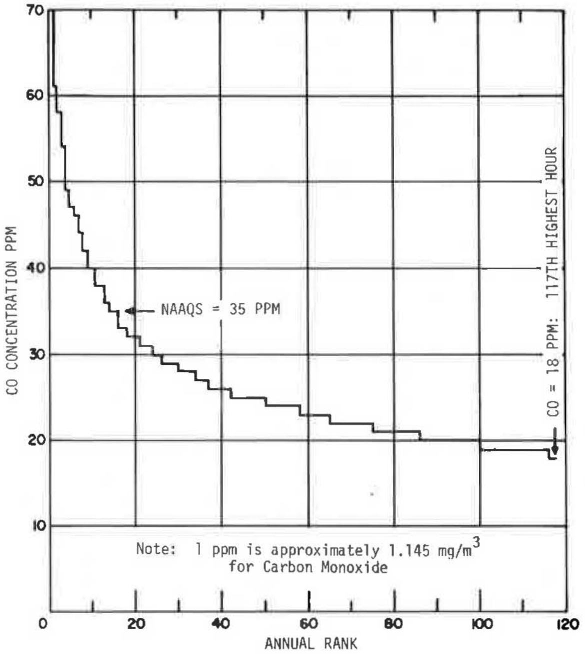
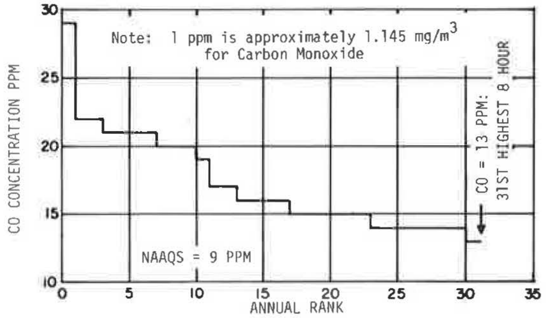


Figure 3. CO concentration exceeding 18 ppm measured on November 15, 1974, at Camp Station.



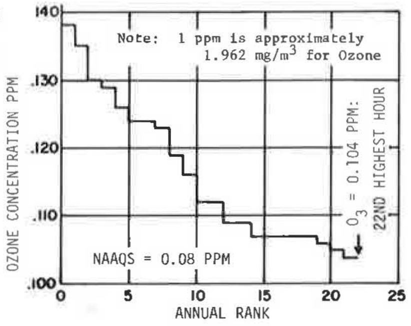
Note: 1 ppm is approximately 1.145 mg/m^3 for Carbon Monoxide

Figure 4. 8-h CO concentration exceeding 13 ppm measured on November 15, 1974, at Camp Station.



Note: 1 ppm is approximately 1.145 mg/m^3 for Carbon Monoxide

Figure 5. O_3 concentration exceeding 0.104 ppm measured on July 29, 1975 at Overland Station.



Note: 1 ppm is approximately 1.962 mg/m^3 for Ozone

Table 1. Environmental inputs to the Systems Applications, Inc., model for Denver.

Date/Time	Hourly Factor for Reaction Rates	Temperature (°C)	Wind Direction (average)	Wind Speed (average) (m/s)	Inversion Height (m)	Stability Class	Factors for Converting Annual Average Daily Traffic to Hourly Traffic
November 15, 1974							
1:00 a.m.	0.001	-3	SW	1	50	4	0.012
2:00 a.m.	0.001	-2	SW	1	50	4	0.006
3:00 a.m.	0.001	-2	SSW	1	50	4	0.005
4:00 a.m.	0.001	-2	SSW	1	50	4	0.004
5:00 a.m.	0.001	-3	SSW	1	30	4	0.005
6:00 a.m.	0.001	-3	SSW	1	30	4	0.013
7:00 a.m.	0.001	-3	SW	2	30	4	0.049
8:00 a.m.	0.015	-2	WSW	2	75	3	0.105
9:00 a.m.	0.263	0	W	2	150	3	0.076
10:00 a.m.	0.538	2	SSE	2	220	3	0.057
11:00 a.m.	0.677	4	SE	3	350	3	0.052
12:00 noon	0.752	6	SE	3	400	2	0.054
1:00 p.m.	0.752	6	SE	3	400	2	0.053
2:00 p.m.	0.752	6	E	3	435	2	0.058
3:00 p.m.	0.549	7	N	2	500	3	0.064
4:00 p.m.	0.282	5	N	2	375	3	0.078
5:00 p.m.	0.041	4	N	3	150	3	0.101
6:00 p.m.	0.001	3	NW	2	100	4	0.090
7:00 p.m.	0.001	2	W	2	75	4	0.058
8:00 p.m.	0.001	1	WSW	2	50	4	0.038
9:00 p.m.	0.001	1	SW	2	50	4	0.030
10:00 p.m.	0.001	-1	SW	1	50	4	0.030
11:00 p.m.	0.001	-1	SW	1	50	4	0.027
12:00 midnight	0.001	-2	SW	1	50	4	0.020
July 29, 1975							
1:00 a.m.	0.001	20	SSW	2	60	5	0.005
2:00 a.m.	0.001	19	S	1	50	5	0.004
3:00 a.m.	0.001	18	S	1	50	5	0.003
4:00 a.m.	0.001	18	S	1	50	5	0.004
5:00 a.m.	0.001	17	S	1	50	5	0.013
6:00 a.m.	0.19	19	SSE	1	50	5	0.047
7:00 a.m.	0.69	21	SSE	1	100	2	0.085
8:00 a.m.	1.06	24	SSE	2	260	2	0.052
9:00 a.m.	1.39	26	SE	2	350	2	0.048
10:00 a.m.	1.60	27	ENE	3	420	3	0.045
11:00 a.m.	1.60	29	NE	3	940	3	0.049
12:00 noon	1.60	31	E	3	2000	2	0.048
1:00 p.m.	1.60	31	N	3	2000	2	0.051
2:00 p.m.	1.42	33	NNW	3	3260	2	0.059
3:00 p.m.	1.12	33	NW	4	2570	3	0.065
4:00 p.m.	0.78	33	WNW	3	2570	3	0.089
5:00 p.m.	0.27	30	WSW	3	250	3	0.068
6:00 p.m.	0.001	29	SW	4	240	4	0.048
7:00 p.m.	0.001	27	SW	4	200	4	0.050
8:00 p.m.	0.001	22	SW	4	160	4	0.039
9:00 p.m.	0.001	23	SW	4	130	5	0.036
10:00 p.m.	0.001	21	SSW	3	50	5	0.039
11:00 p.m.	0.001	21	SSW	3	50	4	0.043
12:00 midnight	0.001	21	SSW	2	50	4	0.010

Notes: t°C = (t°F - 32)/1.8, 1 m = 3.3 ft, and 1 m/s = 3.28 ft/s.
The Systems Applications, Inc., model uses 17 wind recording stations to establish a wind pattern.

lation coefficient of 0.712 and a linear regression equation of

$$\text{Measured value} = 0.6 \times \text{predicted concentration, using average vehicle speeds} \tag{2}$$

Table 2. Reaction rates for Systems Applications, Inc., model.

Equation[a]	Rate November 15, 1974	 July 29, 1975
1	0.266	0.44
2	3 540 000	2 760 000
3	16.2	21.8
4	0.002 6	0.006
5	0.1	0.1
6	0.000 5	0.000 5
7	0.003	0.008 9
8	176	200
9	1 599	1 800
10	3.88	10
11	5 105	7 278.75
12	3 683	9 486.25
13	0.001 66	0.001 87
14	1 800	1 800
15	13.8	13.787 5

[a] Equations can be found in the Systems Applications, Inc., manual (4).

These statistics were later refined by adjusting vehicle speeds to compensate for rush-hour congestion.

On July 29, 1975, 74 O_3 concentrations were compared and had a correlation coefficient of 0.80 and a linear regression equation of ($1\ \text{mg/m}^3 = 0.051 \times 10^3\ \text{ppm}$):

$$\text{Measured value} = 0.95 \times \text{predicted concentration} + 0.053\ \text{mg/m}^3 \tag{3}$$

The regression equations and correlation coefficients for the pollutants predicted may be found in Table 3. These calibrations were then incorporated into the model output to obtain concentrations for the given study day.

Application of Model

Emissions from automobiles, aircraft, and fixed sources are combined to produce an array of total pollutant fluxes into each 2.6-km^2 (1-mile^2) ground-level grid cell contained in the 48.3 × 48.3-km (30 × 30-mile) Denver metropolitan area. Hourly wind and mixing depth maps are then prepared from available wind measurements and inversion soundings for each grid cell through the use of interpolation procedures. Model outputs for surface meteorological conditions are displayed in Figures 10 through 12. The actual airshed simulation uses the

Figure 6. CO concentrations: Overland Station, Nov. 15, 1974.

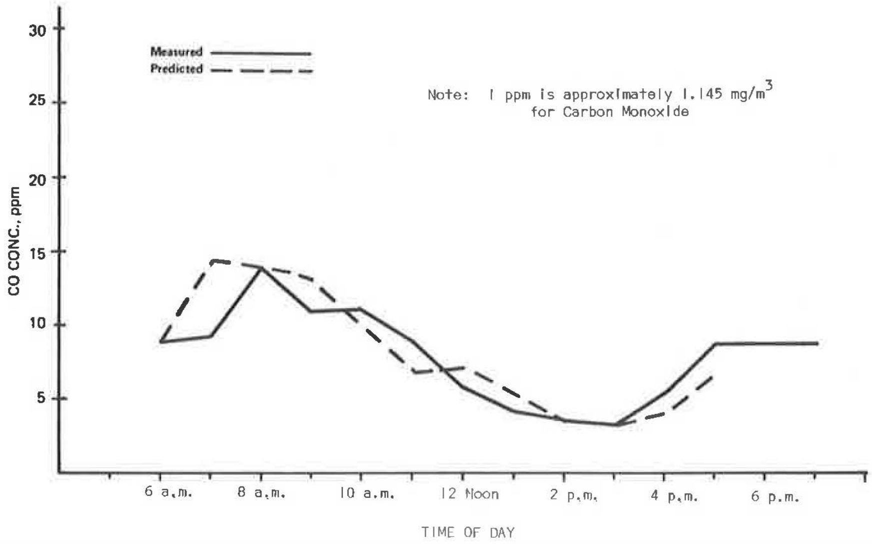
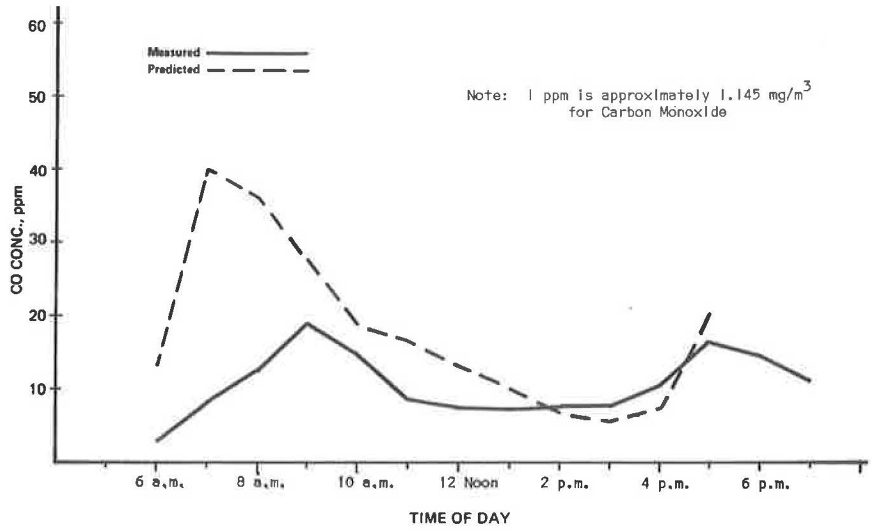


Figure 7. CO concentrations: Camp Station 6, Nov. 15, 1974.



emissions and meteorology to yield the spatial and temporal distribution of contaminants throughout the model region.

The output from the transportation modeling process is used for automotive emissions. This output consists of a highway system that includes a trip table. Each link in the highway system has an assigned traffic volume based on the number of trips desiring to use the link. These link volumes were multiplied by appropriate emission factors and assigned to their respective grid cell for direct input into the airshed model. The traffic assignments that were used depended on the transportation alternative being tested and the study year.

Table 3. Systems Applications, Inc.,model calibration used in Denver.

Condition	Pollutant	Measured Value	Standard Deviation
Average vehicle speed	CO	0.6 × PV	4.8
	O_3	1.26 × PV	0.057
	THC	1.20 × PV	0.33
	RHC	0.43 × PV	0.22
	URHC	0.95 × PV	0.18
	NO	0.34 × PV	0.069
	NO_2	0.97 × PV	0.047
Peak/off-peak vehicle speed	CO	0.75 × PV	3.8
	O_3	(0.95 × PV) + 0.053 mg/m^3	0.033
	THC	(0.44 × PV) + 0.72 mg/m^3	0.34
	RHC	(0.30 × PV) + 0.21 mg/m^3	0.121
	URHC	(0.44 × PV) + 0.64 mg/m^3	0.073
	NO	(0.20 × PV) + 0.05 mg/m^3	0.055
	NO_2	(0.66 × PV) + 0.04 mg/m^3	0.041

Note: For CO, 1 mg/m^3 = 0.87 ppm; for O_3, 1 mg/m^3 = 0.051 × 10^{-3} ppm; for NO, 1 mg/m^3 = 0.081 × 10^{-3} ppm; for NO_2, 1 mg/m^3 = 0.053 × 10^{3}ppm; for HC, 1 mg/m^3 = 0.153 × 10^{-3} ppm; and PV = the predicted value.

Emissions, both mobile and stationary, were the only parameters changed when executing the model simulation. Hence, the output was labeled for a given transportation system and a given year on the study day (November 15 for CO and July 29 for O_3).

In order to determine to what extent the standards would be exceeded during the year being studied, a relation between the second maximum concentration measured during the calibration year and the concentration measured on the calibration study day was determined. This relation factor was then applied to the study day for projected years. Typical output distributions of pollutants are found in Figures 13 through 15 (1). Similar displays appear in the air quality maintenance planning (AQMP) study for air pollution control strategies and the I-470 environmental impact statement (2) for various project alternatives. A quantitative system for ranking alternatives was also included in the I-470 statement. This technique used the probabilities from the normal distribution curve to compute violations of the standard and thereby allow for the inaccuracy of the model.

Figure 8. O_3 concentrations: Overland station, July 29, 1975.

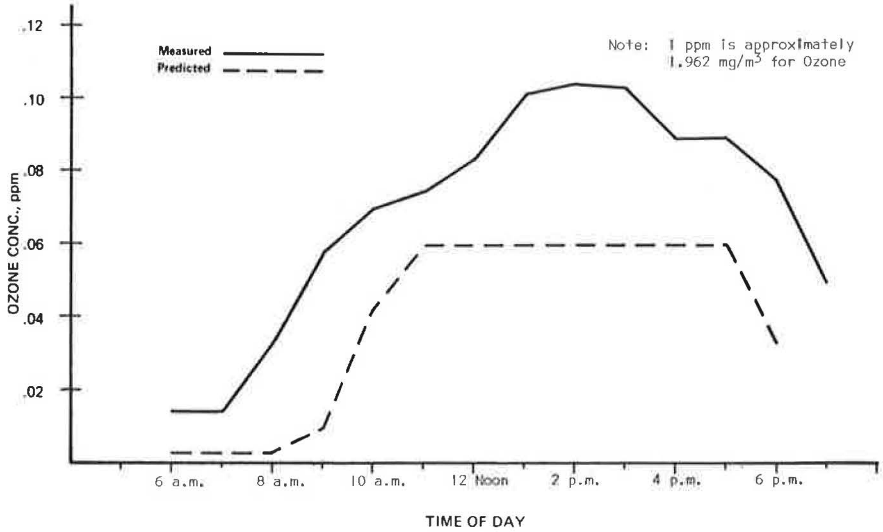


Figure 9. O_3 concentrations: Camp station 6, July 29, 1975.

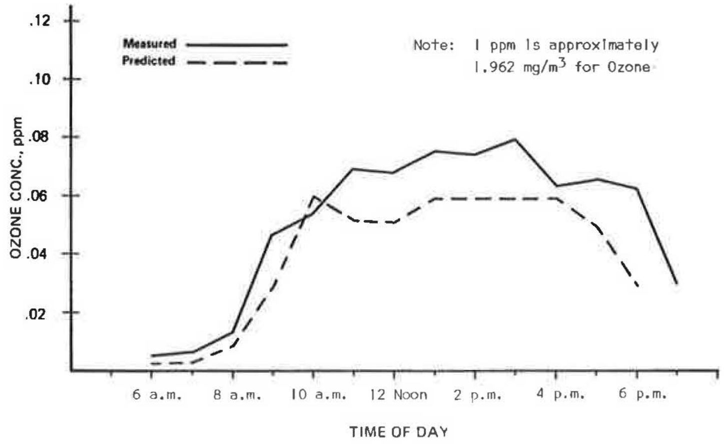


Figure 10. Systems Applications, Inc., model-generated surface winds at 5:00 a.m. MST, July 29, 1975.

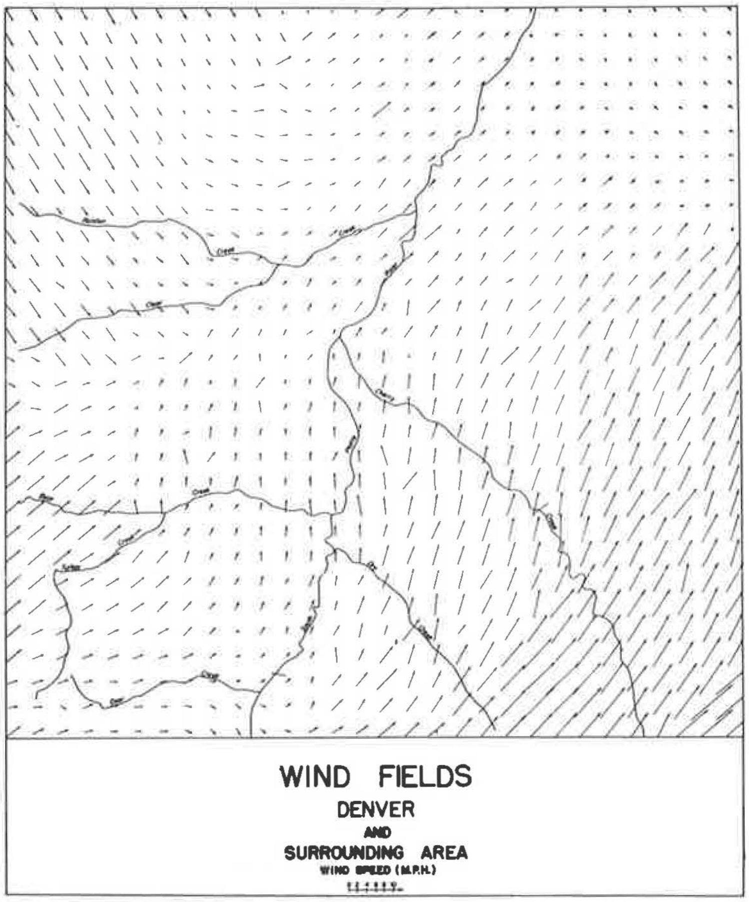


Figure 11. Systems Applications, Inc., model-generated surface winds at 11:00 a.m. MST, July 29, 1975.

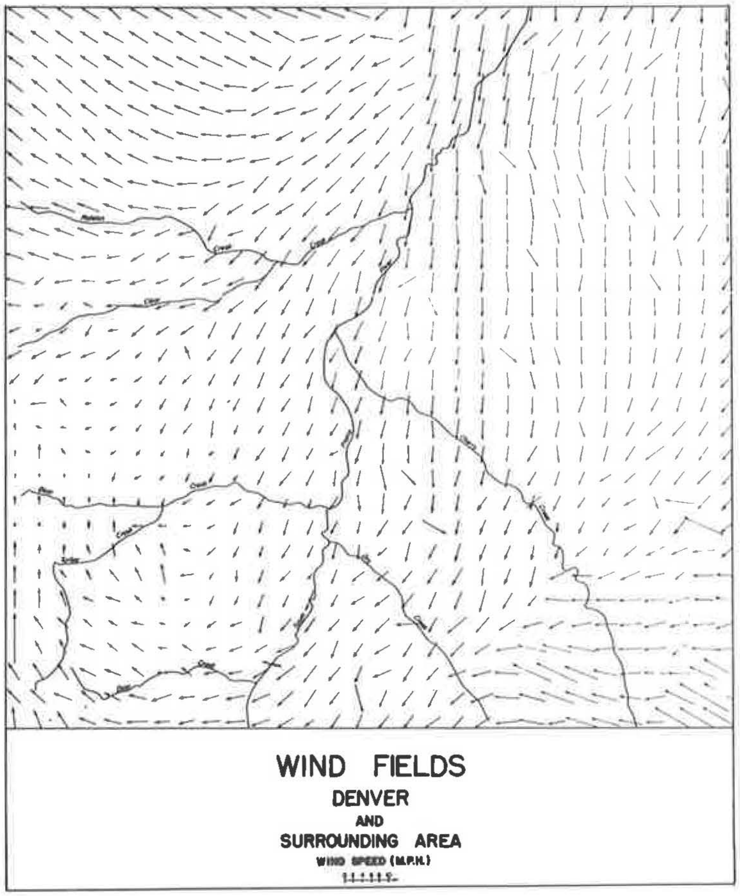


Figure 12. Systems Applications, Inc., model-generated surface winds at 5:00 p.m. MST, July 29, 1975.

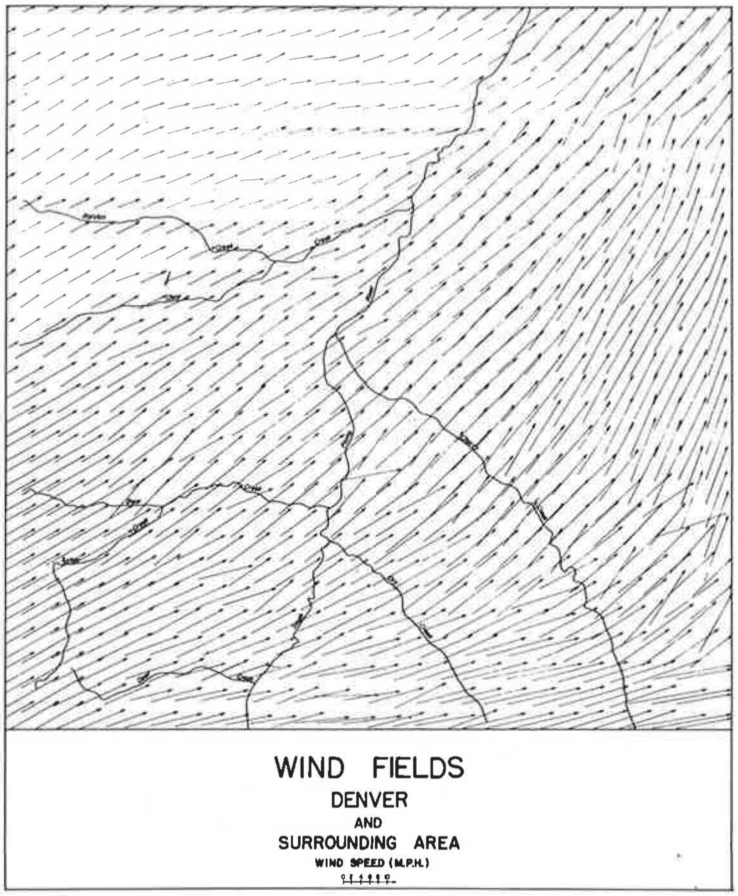
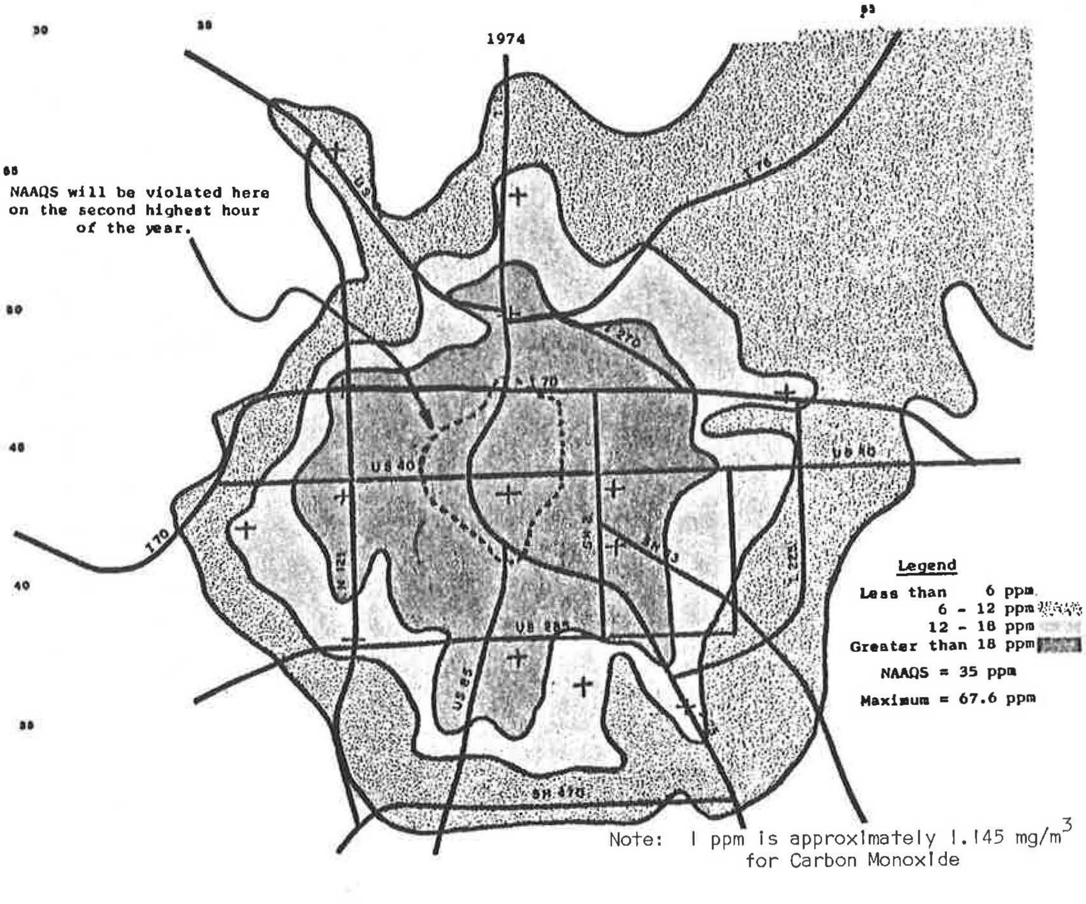
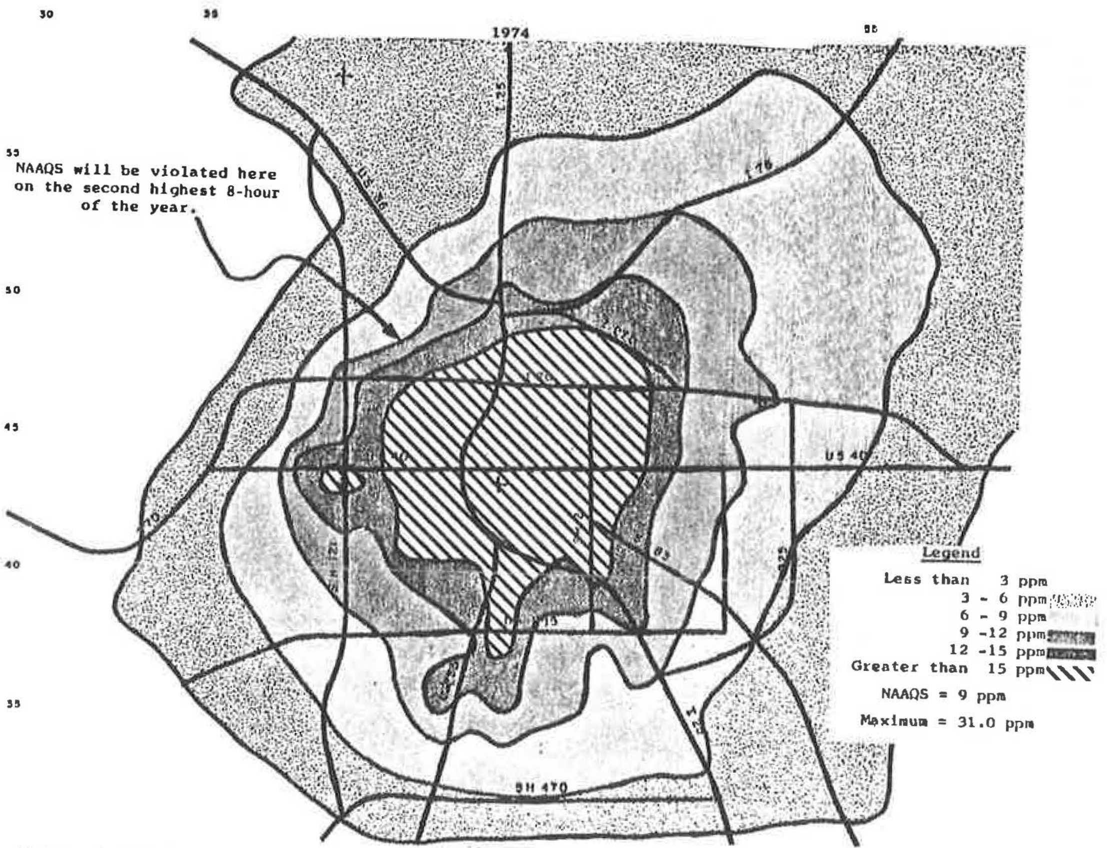


Figure 13. Typical spatial distribution of pollutants as predicted for Denver: second highest 1-h CO concentration.



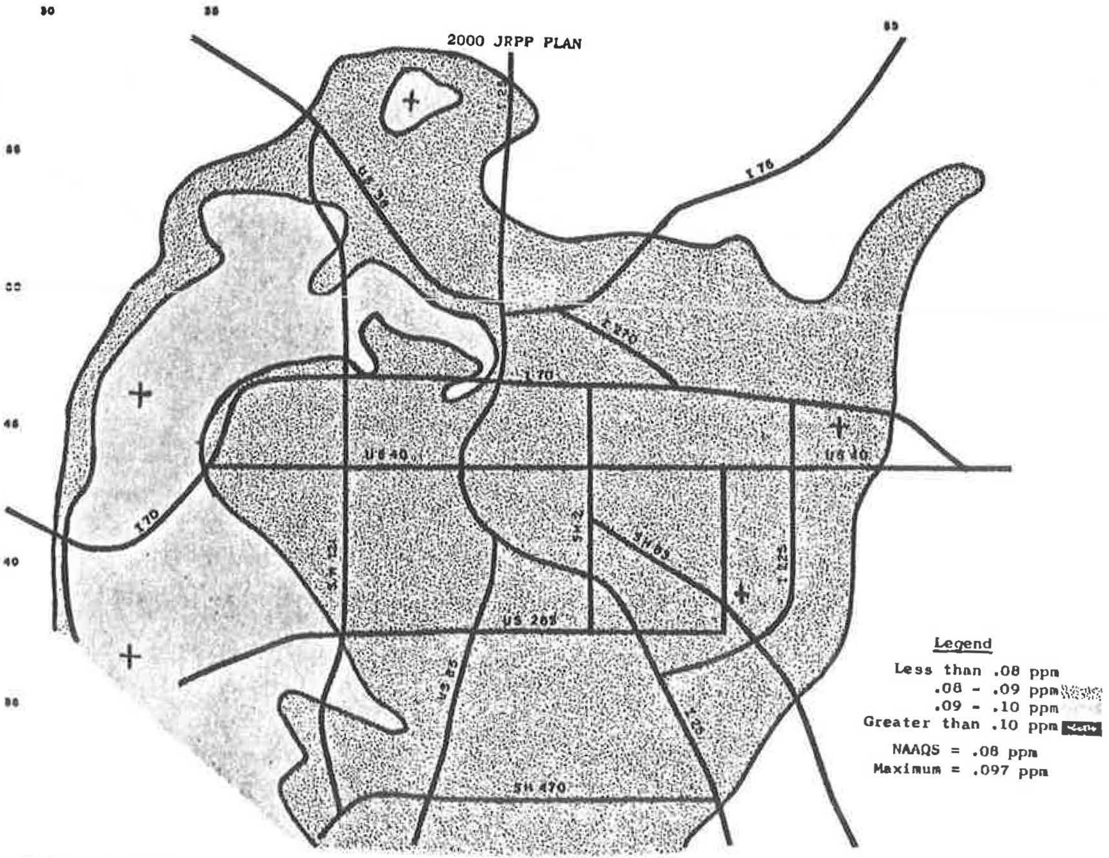
Note: I ppm is approximately 1.145 mg/m^3 for Carbon Monoxide

Figure 14. Typical spatial distribution of pollutants as predicted for Denver: second highest 8-h CO concentration.



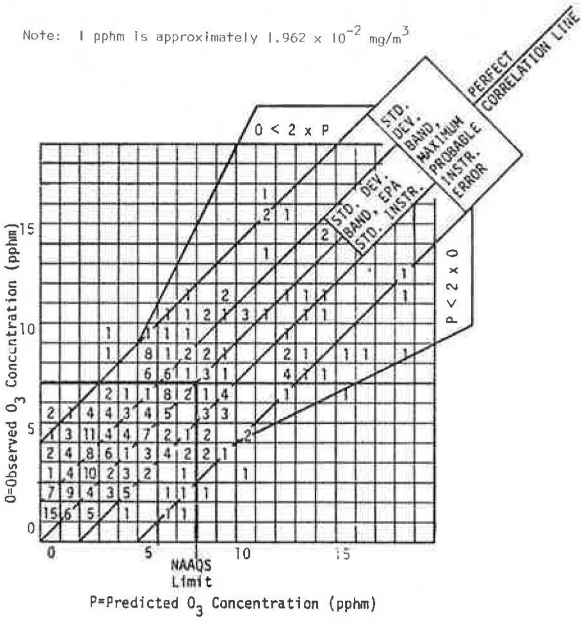
Note: 1 ppm is approximately 1.145 mg/m^3 for Carbon Monoxide

Figure 15. Typical spatial distribution of pollutants as predicted for Denver: maximum 1-h O_3 concentration.



Note: 1 ppm is approximately 1.962 mg/m^3 for Ozone

Figure 16. Denver model predicted O_3 correlated with observations.



MODEL PREDICTIONS CORRELATED WITH INSTRUMENT OBSERVATIONS OF OZONE (DATA FOR 3 DAYS, 9 STATIONS, DAYLIGHT HOURS)

Planned Revisions

During the past 2 years, considerable experience has been gained in the application of photochemical models to the Denver area. During 1975, the original version of the System Applications, Inc., model was adopted. Subsequently, during 1976 to 1977, System Applications, Inc., conducted a study sponsored by EPA (5) to examine the influence on air quality of urban growth associated with the availability of new wastewater treatment facilities. An updated version of the model was applied for this effort. System Applications, Inc., is currently engaged in further model-evaluation studies under a contract from the FHWA. Similarly, engineers and environmentalists from the Colorado departments of health and highways have gained expertise in the operation and application of photochemical models. This expertise has led to minor model adjustments that better simulate conditions in Denver, expansion in the monitoring network in the Denver area, and continuation of the search for a day to calibrate the model under conditions of worst case air quality.

The Colorado departments of health and highways plan to adapt the model as used in the EPA study for use in evaluating transportation alternatives. This later version of the model (including a 39-step chemistry) will be executed on the CDC 7600 computer system at the Lawrence Berkeley Laboratory in California. (The conversion from the 15-step chemistry exceeds the capacity of the CDC 6400 computing system currently being used at the University of Colorado.)

The use of the new, second-generation model for the EPA contract revealed some flaws in the model that was originally used in Denver. The revised model, commonly referred to as the Denver model, considers a 12-species chemistry, including aldehydes. Now that the comparison has been made, the new chemistry must be used if we are to attempt to model the realities of urban atmospheres.

The use of the revised model has been demonstrated to be more reliable when predicting photochemical oxidants (O_3). Although background concentrations of O_3 are not well determined (low background concentrations are difficult to measure accurately), the higher concentrations are more predictably distributed. The Denver model appears to be capable of reproducing a representative distribution of the higher, and thus more important, O_3 concentrations. The correlation between observed and predicted O_3 concentrations is shown in Figure 16. The numerical correlogram in this figure shows the number of occasions for which any particular combination of observed and predicted concentrations was obtained. Observations and predictions would be perfectly correlated if all points were on the diagonal through the origin. The points, in fact, lie generally along the diagonal but spread substantially about that line. This spread of points from the diagonal indicates that, except for a small underprediction at the lowest concentrations, the mean fractional deviations are modest and, apparently, random. These data do not confirm any finding of systematic error in the simulations.

The comparison between observed and predicted values of O_3 improves when individual sites are averaged. Data similar to that displayed in Figures 8 and 9 were averaged over all days correlated with the Denver model. When the data were averaged over time of day, all days, and stations, the average prediction was found to be just 0.8 mg/m^3 (0.4 ppm) less than the average observations. Of course, this averaging process hides individual differences. However, no basic shortcomings in the model are identified by this measure.

Cost

The cost to run this program varies, depending on the computing facilities and the area being studied. The air quality simulation performed in the Denver metropolitan area was run on a Control Data Corporation 6400 computing facility that had input from a 30 × 30 grid of approximately 15 000 traffic links. The data preparation programs consisting of allocation of emissions into grid cells, meteorological distribution, and others are executed and used as input to the air quality simulation program. These preparation programs constitute 10 percent of the total cost for photochemical oxidant simulations and 25 percent of the total cost for CO-only simulations. All preparation programs need not be run for each simulation, however.

The version of the Systems Applications, Inc., program run on the CDC 6400 requires approximately 41 000 words in central memory and takes approximately 25 central processor unit (CPU) min/h of photochemical simulation. If only CO concentrations are desired, the photochemistry can be bypassed and concentrations can be computed using approximately 1.5 CPU min/h of simulation. Using the Colorado Department of Highway's CDC system, this translates into $300/h for oxidant runs and $25/h for CO runs during prime computing time.

CONCLUSION

The Systems Applications, Inc., photochemical model is easily adapted to urban areas. This is especially true when transportation assignments are available for the roadway network, a stationary source emission inventory exists, and a reasonable meteorological data base is available. The model is a very good predictor of the 1-h and 8-h average CO concentrations by grid cells in the Denver area. The model, as used in the past, adequately predicts O_3 concentration in order to address the NAAQS. The revised Denver model improves this capability to where it approaches the accuracy of on-line monitoring equipment.

Model outputs are comprehensive and adequately address a system analysis throughout an airshed region. The model can be useful for determining impacts from alternative major transportation facilities, transportation system concept variations, and proposed air pollution control strategies. Revisions in model capabilities and accuracy are being made continuously; however, care should be exercised to avoid a model that is beyond the state of the art for pollution monitoring and requirements for data base inputs.

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2. I-470 Detailed Assessment Report. Colorado Division of Highways, Sept. 1976.
3. Analysis of Air Quality in the Denver Air Quality Maintenance Area. Air Pollution Control Division, Colorado Department of Health, March 1977.
4. J. Ames, S. D. Reynolds, and D. C. Whitney. Instruction Manual for the SAI Urban Air Pollution Simulation Model. Systems Applications, Inc., San Rafael, CA, DOH 75-109, Jan. 1976.
5. G. E. Anderson and others. Air Quality in the Denver Metropolitan Region 1974-2000. System Applications, Inc.; Region 8, U.S. Environmental Protection Agency, Rept. 68-01-4341, May 1977.

Photochemical Oxidants in Phoenix

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The standard for photochemical oxidants is often exceeded during the summer in the Salt River Valley in the vicinity of Phoenix. Assessment of the photochemical oxidant problem in Phoenix is complicated by relatively low concentrations of nitrogen oxides in the morning, winds that switch direction in the middle of the day, and large changes in mixing height. In this paper, current measurements, modeling efforts, and control strategies are discussed as they apply to Phoenix. Although linear rollback or semiempirical correlations based on smog-chamber or actual measurements are now used to evaluate transportation strategies, better results could be obtained from mathematical air pollution simulation models. The linear rollback analysis currently used by local transportation planners shows that continued inspection and maintenance programs for automobiles and some vapor recovery programs will be required to reduce the maximum photochemical oxidant concentrations in Phoenix to levels below standard. The purpose of this paper is to review the current status of the photochemical oxidant problem in Phoenix and to make projections for the future.

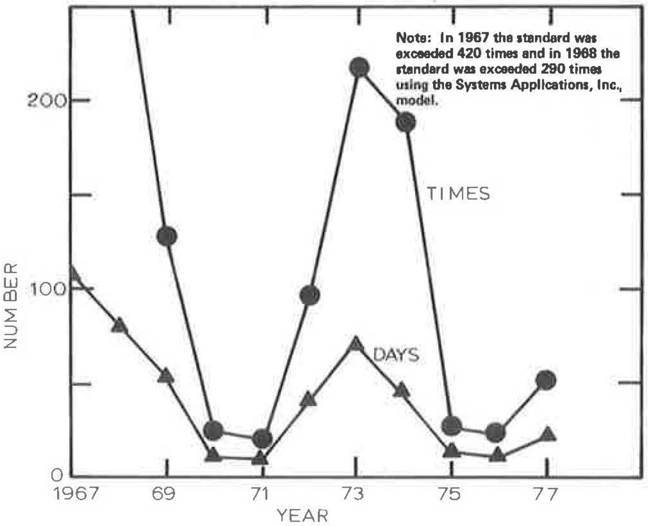
Although the 1-h photochemical oxidant standard is often violated during the summer months in Phoenix, the frequency of violations varies considerably from year to year. Some form of control of nonmethane hydrocarbon (NMHC) and nitrogen oxide (NO) emissions is necessary to reduce the photochemical oxidant concentrations in the future. A limited amount of measurement data indicates that approximately a 50 percent reduction in NMHCs will be necessary by 1982.

In 1974, the Phoenix standard metropolitan statistical area was designated an air quality maintenance area for carbon monoxide (CO) and photochemical oxidants. Since then, considerable effort has been expended by the state departments of transportation and health services and the U.S. Environmental Protection Agency (EPA) to prepare an implementation plan for Phoenix. Yearly revisions will require continuous evaluation of the progress toward attainment of the standard.

PHOTOCHEMICAL OXIDANT MEASUREMENTS

A long-term record is available at only one location in Phoenix; however, in 1974 the method of analysis was changed from continous colorimetric to continuous ultraviolet absorption. Thus, comparisons between pre- and post-1974 data may not be meaningful. At the central Phoenix location maintained by Maricopa County, the number of violations of the 1-h oxidant standard of 160 $\mu g/m^3$ and the number of days on which the violations occurred are shown in Figure 1 for 1967 through August 1977. Clearly, more information is needed to evaluate the trends. The maximum measured hourly average concentration showed a drop from approximately 370 $\mu g/m^3$ to 250 $\mu g/m^3$ from 1973 through 1976 at the same central Phoenix location. However, in 1976 Aerovironment, Inc., performed a study at two locations, one about 19 km southwest of this site and the other 19 km east; a maximum con-

Figure 1. Number of times and number of days the oxidant standard was exceeded for the years 1967 through August 1977 at the Phoenix central station.



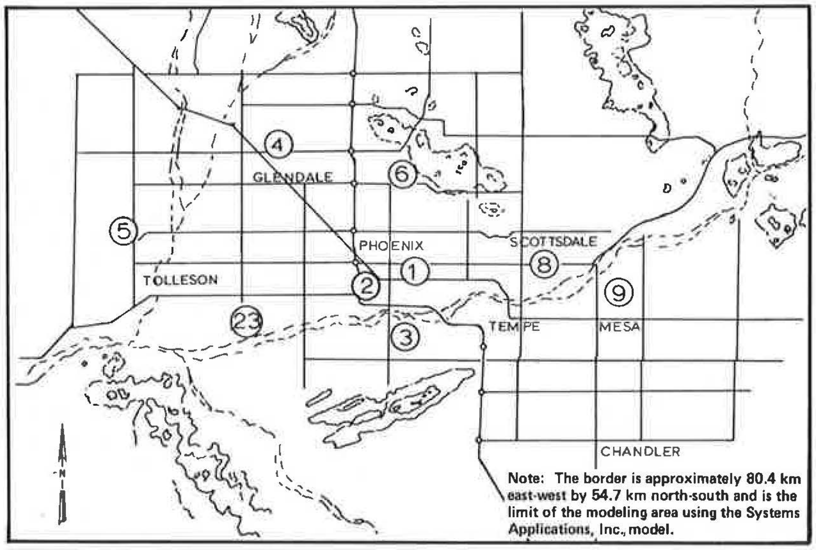
Note: In 1967 the standard was exceeded 420 times and in 1968 the standard was exceeded 290 times using the Systems Applications, Inc., model.

centration of over 400 $\mu g/m^3$ was measured. The central Phoenix station is site 1 in Figure 2 and the Aerovironment, Inc., sites are 23 and 8. Also, the number of days exceeding the standard at the western Aerovironment, Inc., site was about 30 compared to 10 for the entire year at the central Phoenix site.

An examination of the meteorology of the area and the distribution of concentrations will show how such a large difference can occur. Most high oxidant measurements occur in the summer months (June, July, and August), when the solar insolation is highest for the year. A complex wind pattern over the whole metropolitan area joins with the influences of solar heating, topography, and pressure gradient winds. Figure 2 shows the major topographical features and the location of monitoring sites in the Phoenix area. The average wind speed during the summer months along the Salt River near the lettering "Phoenix" on the map is approximately 2.5 m/s from the east between 2:00 a.m. and 12:00 p.m. After noon, the wind shifts direction (so that it is from the west) but the speed remains 2.5 m/s until 2:00 p.m. The afternoon winds increase in magnitude to reach over 4 m/s at 4:00 p.m. and remain at this velocity until midnight. Throughout the day, the winds correspond to downslope in the morning and upslope in the afternoon. Near the locations labeled Tolleson and Scottsdale on the map, upslope is toward the north, and the wind patterns are correspondingly different from those in Phoenix. Late afternoon winds throughout the area are dominated by the circulation about the thermal low pressure in the Pacific Ocean, southwest of Phoenix. On some days each month the thermal low is weak and winds decay after 2:00 p.m. until almost calm conditions exist after sundown. Such days usually give the highest measurements of photochemical oxidant.

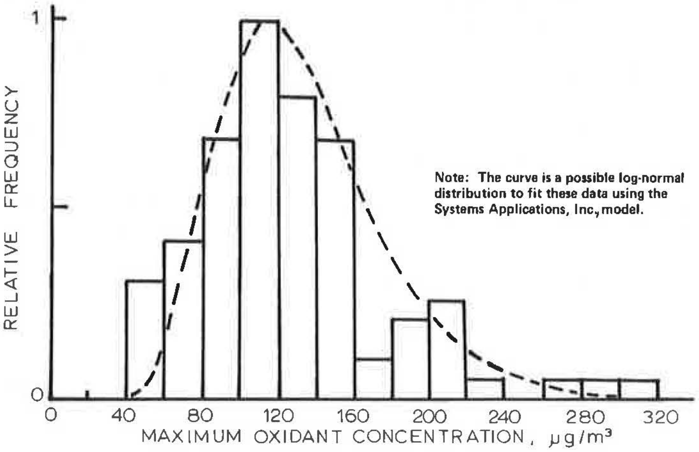
Figure 1 indicates that much longer records are required to assess adequately the magnitude of an oxidant problem in Phoenix. Perhaps a better indication of the maximum concentrations can be found from a frequency distribution plot. Figure 3 shows a graph for the combined months of June 1975 and June and July 1977 at the central Phoenix location. A log-normal curve that approximates these data has a maximum at 114 $\mu g/m^3$. Twenty-five percent of the days would have maximum concentrations over 160 $\mu g/m^3$ according to the log-normal approximation. The data at the Aerovironment, Inc., sites for a 6-week period beginning in late May 1976 are shown in Figure 4. The maximum is at 160 $\mu g/m^3$; 60 percent of the measurements are over 160 $\mu g/m^3$. The two sets of data cannot be compared in 1976 because the record is incomplete for the central Phoenix site. When similar days are com-

Figure 2. Map of the Phoenix area showing major monitoring sites as circled numbers.



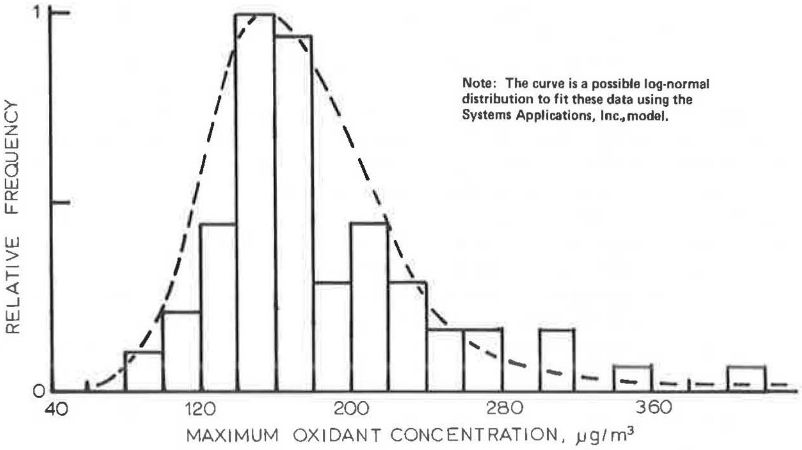
Note: The border is approximately 80.4 km east-west by 54.7 km north-south and is the limit of the modeling area using the Systems Applications, Inc., model.

Figure 3. Frequency of occurrence of maximum daily oxidant concentration for June and July in 1975 and 1977 at the Phoenix central station.



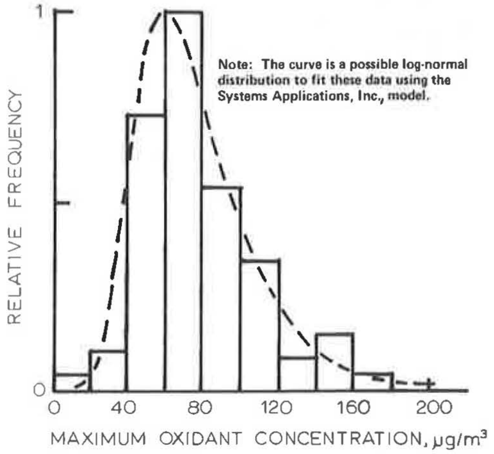
Note: The curve is a possible log-normal distribution to fit these data using the Systems Applications, Inc., model.

Figure 4. Frequency of occurrence of maximum daily oxidant concentrations in the early summer 1976 at Aerovironment sites.



Note: The curve is a possible log-normal distribution to fit these data using the Systems Applications, Inc., model.

Figure 5. Frequency of occurrence of maximum daily oxidant concentrations for the winter 1974-1975 at site 5.



Note: The curve is a possible log-normal distribution to fit these data using the Systems Applications, Inc., model.

pared, the Aerovironment, Inc., locations have higher oxidant concentrations and the concentrations in the western location are higher than those in the eastern.

The typical wind pattern moves the most concentrated cloud of urban pollutants in the morning to the southwest from the center of Phoenix. After noon the oxidant concentration is highest and the cloud is near the western Aerovironment, Inc., site. Figures 3 and 4 are reasonable representations of daily maximum oxidant levels in the summer at any location in Phoenix. The differences are due to the short record and particular meteorology of the time period for the measurements. For the remainder of the year the curves are similar in shape but displaced toward lower concentrations. For example, at location 5 in Figure 1, the maximum daily oxidant distribution over a 12-week period during the winter of 1974-1975 is shown in Figure 5. The log-normal curve has a maximum at 60 $\mu g/m^3$. Only 2 percent of the total would be over 160 $\mu g/m^3$ for this log-normal distribution.

Log-normal distribution patterns appear to be typical in the Phoenix area; concentrations in the summer are about twice those in the winter. This also corresponds to the difference in radiation intensity for these seasons. If the data shown in Figures 3 and 4 are characteristic of long-term averages, there is considerable variation spatially within the metropolitan area. Over a 1-year period, the meteorological pattern could shift the distribution measured at one location so that 10 to 60 percent of the days in June, July, and August would have maximum concentrations that exceed 160 $\mu g/m^3$.

Oxidant concentration changes during a day of high maximum concentrations are shown in Figure 6. The average daily traffic and the solar insolation curves are also given for comparison. The peak concentration at the central Phoenix location generally occurs about noon. However, at the Aerovironment, Inc., sites, the peak on high oxidant days occurred at approximately 4:00 p.m., as shown in Figure 7. The NMHC, NO, and NO_2 concentrations are also shown in Figure 7. The smog-chamber-like pattern in the afternoon may indicate some air stagnation. The lag in the peak at the Aerovironment, Inc., site could be a result of winds blowing the air mass from Phoenix to the southwest and then back again followed by stagnation in the afternoon. Normally, vigorous upward mixing is present in the desert during the day even if horizontal wind speeds are low. Any limitations on this mixing should also increase the pollutant concentrations.

NMHC EMISSION SOURCES

Currently, controls on emissions of NMHCs are the only proposed strategy for the reduction of photochemical oxidants in Phoenix. The emissions for the 1975 base year and for future years as estimated by the Technical Operations Committee of the Phoenix Air Quality Maintenance Area (AQMA) Task Force are given in Table 1. Transportation-related activities accounted for 80 percent of the total NMHC emissions in 1975. When the reactivity of the hydrocarbon species and the temporal distribution of emissions are taken into account, the influence of automobiles and trucks is even greater. Future estimations were based on projected population increases prepared by the state of Arizona Department of Economic Security. These estimates predict an increase in Maricopa County from 1.3 million people in 1975 to 2.3 million people in 2000. The projected traffic emissions were estimated by EPA (1). Details of the calculations are given in reports by the Maricopa Association of Governments (2) and the Arizona Department of Health Services (3, 4). Revised estimates based on the Clean Air Act Amendments of 1977 are currently in progress.

Table 1 shows that the replacement of older automobiles by newer models, which have more emission controls, results in lower total NMHC emissions until 1995. Then, the effects of increased population will reverse the trend. The problem faced by transporta-

Figure 6. Variations in O_3, traffic volume, and solar isolation at the Phoenix central location (June 14, 1977).

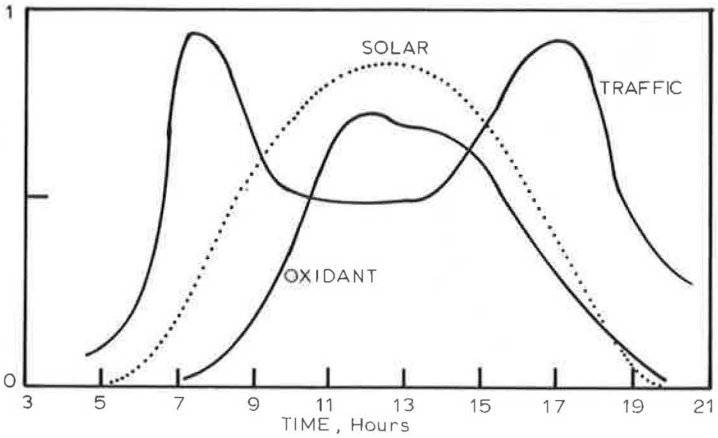


Figure 7. Measured concentrations of NMHC, nitrogen oxides (NO and NO_2), and O_3, at Aerovironment site 23 (June 27, 1976).

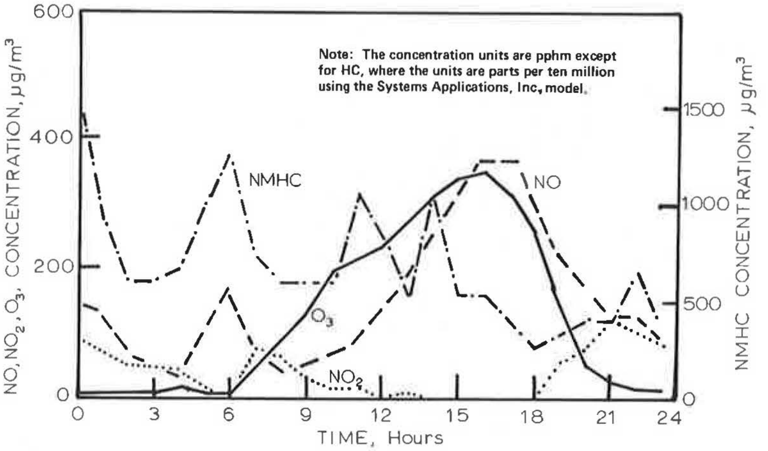

Note: The concentration units are pphm except for HC, where the units are parts per ten million using the Systems Applications, Inc. model.

Table 1. Phoenix NMHC emissions.

	Emissions (Mg/d)					
Emission Source	1975	1980	1985	1990	1995	2000
Traffic[a]	131.6	95.9	61.2	43.6	46.5	52.3
Commercial	0.3	0.3	0.4	0.4	0.4	0.5
Industrial	1.3	1.5	1.5	2.1	2.6	3.5
Miscellaneous[b]	45.2	43.6	40.9	38.1	33.5	37.5
Airports	2.6	2.7	2.7	2.8	3.0	3.1
Railroads	2.0	1.8	2.1	2.3	2.5	2.7
Point sources	12.3	12.3	12.3	12.3	12.3	12.2
Total	195.3	158.1	121.1	101.6	100.8	111.8

Note: 1 Mg = 1.1 tons.

[a] Includes some improvements for future projections.

[b] About 50 percent relates to gasoline handling operations.

tion planners is to find out how much more reduction is necessary to comply with air quality standard regulations so that the standards are reached in 1982 and air quality is maintained at that level.

EVALUATION OF NECESSARY REDUCTIONS IN NMHC

The Technical Operations Committee of the AQMA task force selected 1975 as the base year for analysis. The second highest oxidant measurement in 1975 was 250 µg/m^3 at the central Phoenix station. The use of the Appendix J method (5) to determine the necessary reduction in NMHC to reach 160 µg/m^3 results in a 38 percent reduction. Table 1 shows that such a reduction is achieved in 1985. Additional controls or transportation strategies are necessary to meet a 1982 deadline.

An alternative to Appendix J is the linear rollback method (6). The necessary reduction for the 1975 base year is 100 µg/m^3 or 38 percent of the second highest measurement. Roth and others (7) show that linear rollback for concentrations higher than 250 µg/m^3 results in a smaller reduction in hydrocarbons to meet the standard. In Phoenix, Appendix J or linear rollback gives the same results.

Criticism of the Appendix J and linear rollback methods has been considerable, and other methods of analysis are under study. Most of the current technology is summarized by Roth and others (7). In Phoenix, the question of what to use as a basis for the evaluation is of at least equal importance. Indications are that the EPA western region will require 1977 to be the base year for air quality analysis in Phoenix. No methods use the frequency distribution, although the log-normal curves show that a mean concentration of about 60 µg/m^3 would be necessary in the summer to reduce the possibility of exceeding the standard to less than 2 percent of the days. Assuming a linear relationship between hydrocarbon emissions and oxidant, a 48 percent reduction from the 1977 average would be required. All of the other methods work on the high concentration days and try to predict the necessary reduction for the second highest day to meet the standard. We have looked at all of the days that exceed the standard over the past 10 years to see if any of the empirical methods correlate with the Phoenix data.

One empirical method is to construct graphs using smog-chamber results. The effect of both nitrogen oxides (NO_x) and NMHC can be evaluated when a mixture is irradiated over a fixed period. When the 6:00 to

9:00 a.m. average NO$_x$ and NMHC are used to predict maximum O$_3$ concentrations, the predictions are high for Phoenix. For example, in Figure 7 the average NO$_x$ is 300 $\mu g/m^3$ and the average hydrocarbons are 730 $\mu g/m^3$ as carbon over the 6:00 to 9:00 a.m. period. The correlation with smog-chamber results given by Dimitriades (8) gives a maximum oxidant concentration of 600 $\mu g/m^3$ compared to the measured 370 $\mu g/m^3$. For this particular day the reductions in hydrocarbons necessary to meet the standards would be about 65 percent from Appendix J and 70 percent from the smog-chamber results. We assume no change in NO$_x$, use the smog-chamber studies of Dimitriades, and base the reduction on the hydrocarbon concentration to give 160 $\mu g/m^3$.

Another method used to assess the oxidant control problem is to use actual atmospheric data. That is, curves are constructed of the isopleths of maximum oxidant as a function of 6:00 to 9:00 a.m. NO$_x$ and NMHC. EPA (9) has prepared one such curve using data from Philadelphia, Washington, and Denver. The Phoenix measurements fit well on this correlation, except for cases of high hydrocarbon and low NO$_x$. Unfortunately, that condition often represents the yearly maximum in Phoenix. There are not enough data at the present time to construct a correlation of this type for Phoenix that will work for the low NO$_x$ state often found. In addition, the air parcel that gives the 6:00 to 9:00 a.m. NO$_x$ and NMHC is not the same as the one that gives the maximum oxidant reading when measurements are taken at a fixed location.

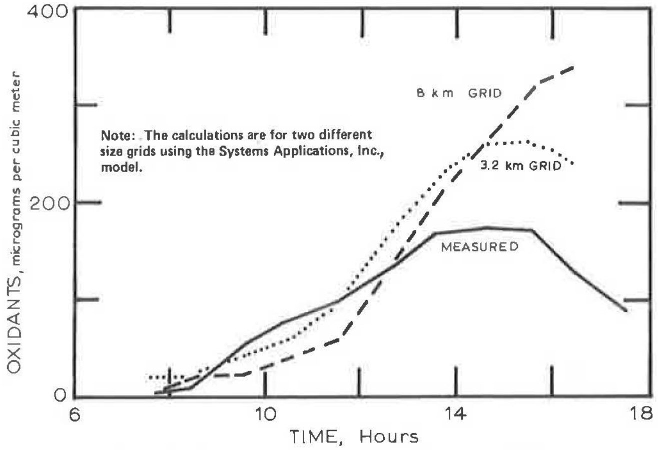
Some of the problems associated with the oxidant control methodologies previously discussed can be removed when a physicochemical model is used. Two studies have been made in Phoenix, one by Aerovironment, Inc., using a trajectory model and one at Arizona State University using a grid point model. The results of the Aerovironment, Inc., study (10) that used a REM-2 to evaluate the environmental impact of a new freeway development will be available in the near future.

The Arizona State University study, supported by the Office of University Research of the U.S. Department of Transportation, uses the Systems Applications, Inc., 1973 model (11, 12) to calculate the photochemical oxidant concentration in Phoenix. Inputs to this model are hourly average wind speed, wind direction, mixing height, traffic emissions, and fixed-source emissions. Only one class of reactive hydrocarbons is considered in this model, so only 15 reactions are used to simulate the atmospheric changes. The emissions were obtained from the AWMA study by Aerovironment, Inc., and the Arizona State Department of Transportation. Several changes were necessary to use the Systems Applications, Inc., model for Phoenix. The original model was set up for Los Angeles, where a constant mixing height is permissible. Major changes were to allow variation of the mixing height and a different treatment of the boundary conditions. Details can be found in the final report (13).

Calculations were made for a typical day in the summer of 1975. The wind speed was set low enough so that the grid map covering the outlined area in Figure 2 could be used: Then the plume created in the morning rush hour stays within the modeling area.

Only a single combination of vertical eddy diffusivity and mixing height has been tested. Results for the central station and for the 3.2- and 8-km^2 grids are given in Figure 8. From 7:00 a.m. through 5:00 p.m., the correlation coefficients were 0.86 for the 3.2-km grid and 0.97 for the 8-km grid compared to measured results for one of the higher oxidant days in August 1975. The preliminary results show a hot spot to the west of the central station near the Aerovironment site and another hot spot to the east late in the afternoon.

Figure 8. Measured and calculated oxidant concentrations at the Phoenix central station (August 5, 1975).



Note: The calculations are for two different size grids using the Systems Applications, Inc., model.

The Systems Applications, Inc., model calculations show that the western hot spot is 60 percent higher than the central station at 11:00 a.m., 36 percent higher at 12:00 p.m., 22 percent higher at 1:00 p.m., 18 percent higher at 2:00 p.m., and only small amounts higher afterward, when the wind shifts. If the wind dies down before noon and limited upward mixing is present, the hot spot would remain in the same position and have higher readings than the central station. Studies are continuing using a Systems Applications, Inc., model that has improved wind fields and chemical kinetics. Although Figure 8 shows much higher calculated oxidant concentrations than those measured, the magnitude is influenced by the eddy diffusivity. Somewhat higher eddy diffusivities are present in Phoenix than the values used in the study presented in Figure 8. Future upper air measurements in Phoenix should result in data that will improve computer simulations.

STRATEGIES TO ACHIEVE REDUCTIONS

More than a 50 percent reduction in photochemical oxidant concentration is necessary to ensure that the number of days exceeding the standard in any year approaches 1. Evaluation of the necessary reactive hydrocarbon and NO$_x$ reductions would require a computer simulation and extensive measurements of mixing parameters. If the linear rollback method is used, hydrocarbon reductions must be 50 percent and strategies to achieve the 50 percent reduction must be found.

The AQMA task force evaluated several strategies for the reduction of NMHC. Some of the reductions will be the result of normal traffic improvements and land planning in the future and are included in the base in Table 1; others will be the result of an inspection and maintenance program, carpooling, and vapor recovery. The base case gives a 30 percent reduction in NMHC from 1975 to 1982. Inspection and maintenance can be evaluated from current EPA projections and gives an additional 10 percent reduction. Carpooling is expected to have only a 2 percent net reduction in NMHC and phase 1 vapor recovery is expected to have a 3 percent reduction. Phase 1 is the recovery of vapors from filling a service station's main supply tanks. Recovery of vapors from each automobile at the pump is called phase 2. Implementation of phase 2 cannot be completed by 1982. The net reduction by 1982 is 45 percent, although the real effect on oxidant reduction could be larger. All of the strategies are transportation related and would reduce the 6:00 to 9:00 a.m. peak in a greater proportion than 45 percent. Computer modeling is needed to see if the effects of the high early morning hydrocarbon concentration do, indeed, contribute significantly to the oxidant level when relatively high dilution rates are present after that time.

Maricopa County already has an inspection and maintenance program, and other controls will be recommended for implementation in 1978. Given the limited historical record and the high population growth rate of the area, it is difficult to say if these controls will be enough.

ACKNOWLEDGMENTS

I acknowledge the support of the Office of University Research, U.S. Department of Transportation. Data were supplied by the Arizona Transportation and Health Services Departments, the Maricopa County Health Department, and Aerovironment, Inc. David Chen and Daniel Bradford helped with the analyses.

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Monitoring and Modeling of Resuspended Roadway Dust Near Urban Arterials

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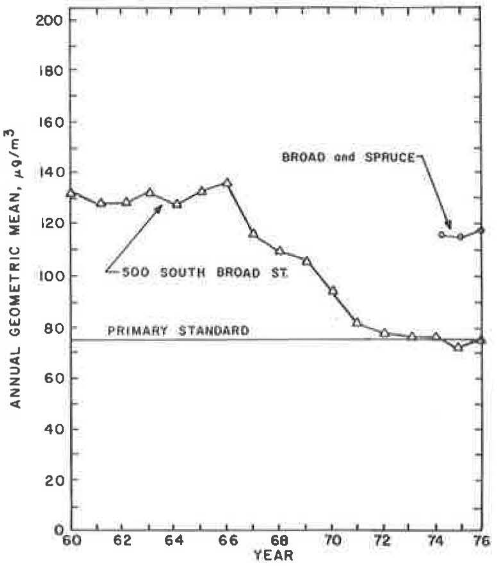
The probability that resuspended roadway dust plays a predominant role in many violations of the ambient particulate standards is now widely accepted. Quantification of this effect is needed before control strategies are developed. In addition, there is increasing concern that strategies should, for reasons of health, also address the respirable fraction of total particulates. This paper describes a twofold approach to the problem of identifying the sources of particulates within the city of Philadelphia and presents selected results from the study. One approach used a sampling program designed to investigate the contribution of traffic-related emissions. Measurements were made using conventional high-volume air samplers at four heights near an intersection and at rooftop level on either side of the main street. The U.S. Environmental Protection Agency dichotomous sampler and the GCA ambient particulate monitor were used to discriminate between respirable and nonrespirable particulates. The second approach used diffusion modeling techniques to calculate the contribution of source categories. Also, a test was conducted to

measure the effectiveness of street washing in reducing ambient particulate levels. The results suggest that about one-fourth of the particulates measured at the roof of the Health building were vehicle related, but approximately one-half of the particulates measured at the top of a trailer at a busy intersection were from these sources. Based on a comparison of data from the dichotomous sampler and the high-volume sampler, only about one-fourth of the particulates measured by the high-volume sampler at the trailer were respirable. Ambient particulate levels increased dramatically immediately after street washing.

This paper describes the design and operation of a sampling program to investigate the contribution of traffic-related emissions to total suspended particulate concentrations. The program was part of a general project designed to increase understanding of the principal sources of particulates within a major urban area, their dispersion, and the feasibility of their control. To help define the spatial impact of traffic-related emissions, measurements were made with conventional high-volume air samples at three heights on a 12.2-m tower adjacent to an intersection and at roof-top level (about 11 m) on either side of the main street at distances of 15 to 60 m.

Two highly specialized instruments were used to discriminate between respirable and nonrespirable particles. One, the U.S. Environmental Protection Agency (EPA) dichotomous sampler, also allows for detailed chemical analysis of the collected particles without the serious interferences normally encountered with glass fiber filters. The other, the GCA ambient particulate monitor (APM), determines the short-term (e.g., hourly) changes in both the respirable and total particulate loadings. A fractionating head high-volume sample was used to provide additional data on particle size distributions. Concentration measurements as a function of wind direction were made by a National Aeronautics and Space Administration (NASA) Air Scout at one of the rooftop locations. Automatic traffic counters provided continuous data throughout the two sampling periods. Selected filters were analyzed by sophisticated techniques to determine particle characteristics under various sampling conditions. The experiment was run for two 2-week periods, in February 1977 and in June 1977. The latter sampling period included a 3-d period when the city of Philadelphia conducted intensive street washing to test its effectiveness in reducing ambient particulate levels.

Figure 1. Annual mean TSP concentrations at two sites.



In a second part of the project, numerical diffusion modeling techniques and an upgraded emissions inventory for particulates were used to calculate the contribution of each major source category to the total suspended particles (TSP) loadings at the various city monitoring sites. The results of the field measurement program provided a basis for selecting an appropriate emission factor for reentrained dust for use in the model calculations.

The underlying problem is illustrated in Figure 1. Over a period of years the control of major industrial and fuel combustion sources has caused a striking decrease in particulate levels, but the national standards are still not uniformly met. In the case illustrated, the decrease in annual mean TSP levels at 500 South Broad Street is evident, especially after 1966. This site is located on a flat roof at an elevation 11 m above ground and 30 m back from the street. The data from the site at the corner of Broad and Spruce streets demonstrate that significant differences in TSP observations can occur within a distance of only two blocks. The high-volume air sampler at the Broad and Spruce street location is on top of the air monitoring trailer, 4 m above ground and only 9 m back from South Broad Street.

Observations such as this as well as other high TSP measurements near such areas as unpaved parking lots, dirt roads, and storage piles have led many observers to question the presumption that sufficient reduction of major point source emissions will result in the uniform attainment of the standards. This situation is obviously not limited to Philadelphia; it calls for a careful assessment of precisely where the measured particulate matter is coming from.

NETWORK DESIGN

As noted earlier, recent observations identified the area in the vicinity of the 500 South Broad Street site and the intersection of South Broad and Spruce streets as a promising one for a detailed study of the spatial impact of traffic-related particulates. Here, within a distance of approximately 275 m, the rooftop location at 500 South Broad Street has an annual mean concentration of pollutants nearly equal to the primary standard, and the trailer-top location near the intersection of Broad and Spruce streets experiences an annual mean concentration 50 percent higher. The only obvious differences between the sites is the proximity to vehicular traffic. In spite of the complicating effects of the surrounding building structures, we decided to perform the field study at this location, where the problem was known to exist. Figures 2 and 3 show the building heights and streets in the vicinity of the two sites.

A 12.2-m self-supporting tower was erected on the corner of Broad and Spruce streets next to the Air Management Services air monitoring trailer, as shown in Figure 2. The tower was outfitted at three heights with six high-volume air samplers. This allowed operation of the high-volume sampler on a 24-h basis without requiring the presence of the operator at midnight to change filters. The effective heights of the high-volume samplers were 11.2, 9.1, and 6.1 m. The vertical profile was completed by a pair of high-volume samplers at an elevation of 4.0 m on the trailer rooftop. In addition, the EPA dichotomous sampler, the GCA APM, and the fractionating head high-volume sampler were operated on the roof of the trailer to provide particle size information and short-term concentration data. Traffic counts were automatically recorded every 15 min at four locations on Broad and Spruce streets.

Figure 2. Local neighborhood at Broad and Spruce streets.

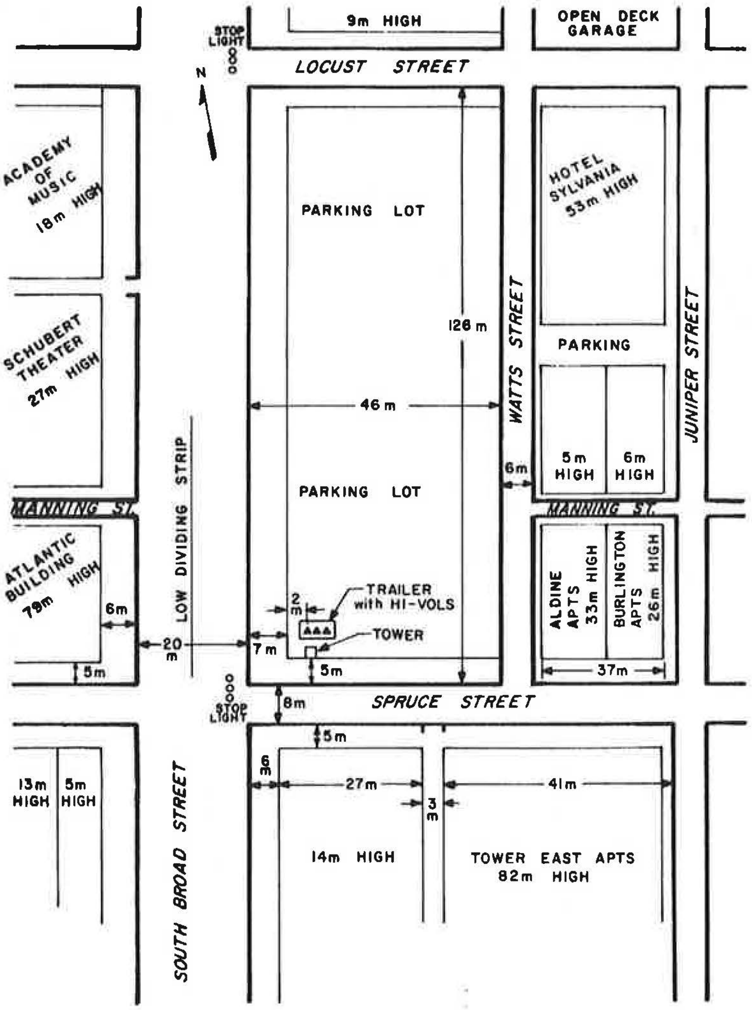
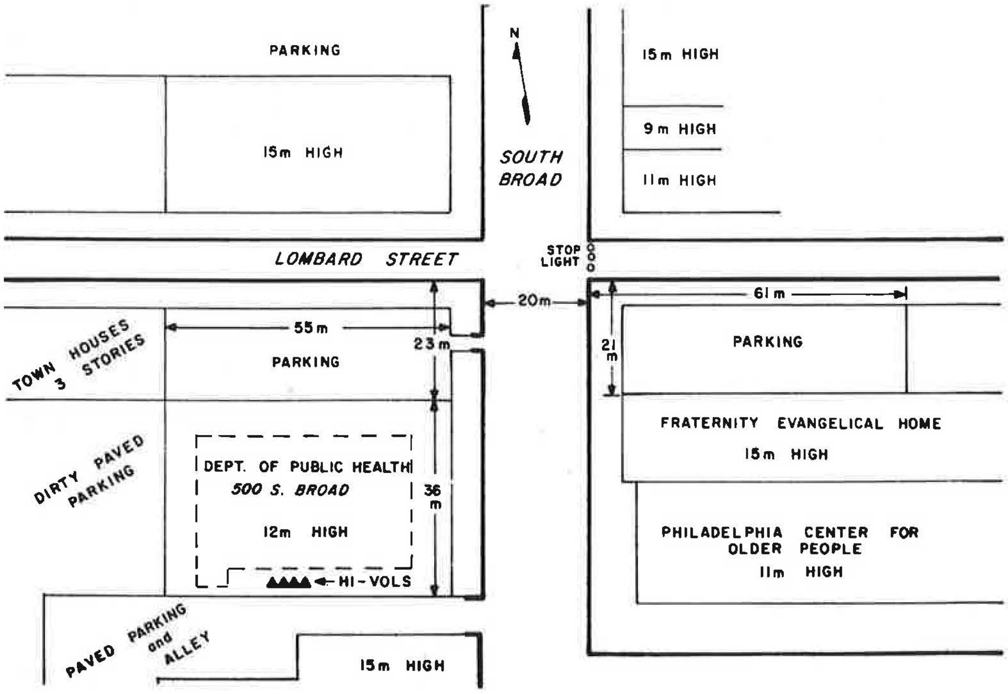


Figure 3. Local neighborhood at 500 South Broad Street.

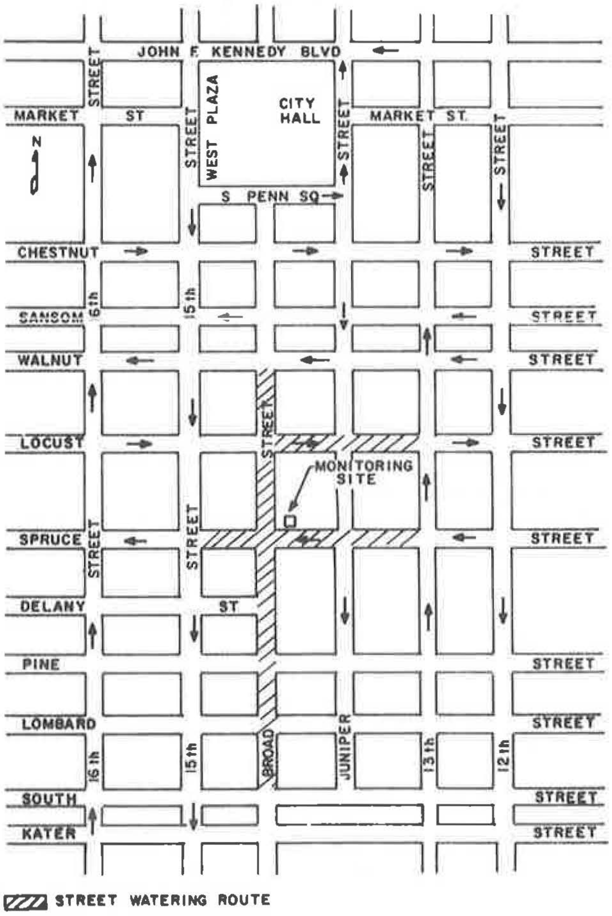


At 500 South Broad Street, the existing Air Management Services high-volume samplers were supplemented by a high-volume sampler on the front edge of the roof near Broad Street and a high-volume sampler on the back edge of the roof away from Broad Street. Meteorological instrumentation to record wind speed and direction was positioned on an elevated portion of the roof near the back of the building. Directly across the street from 500 South Broad Street, on the roof of the Philadelphia Center for Older People, two additional sites for high-volume samplers were established. One was on the front edge near Broad Street and the other on the back edge away from Broad Street. This resulted in a horizontal array of five high-volume sampler sites at nearly the same elevation above Broad Street. The three on the 500 South Broad Street roof were on the west side of Broad Street, at distances of approximately 9, 30, and 58 m from the street. The high-volume samplers on the east side of Broad Street on the Philadelphia Center for Older People were approximately 9 and 34 m from the street. In addition, during the February sampling period a NASA Air Scout directional sampler with its meteorological sensors was operated on the Broad Street edge of the 500 South Broad Street roof.

Sampling Schedule

The basic high-volume sampler network (the vertical array at the tower site and the horizontal array at rooftop level approximately 275 m to the south) was operated from February 4 to 20, 1977, and from June 7 to 20, 1977. These observations were supplemented by APM and dichotomous sampler data from the roof of the trailer during the 2-week sampling period in February; at the end of this period, the dichotomous sampler was moved to the rooftop at 500 South Broad Street and operated for an additional 2-week period. Intensive street washing took place on June 15, 16, and 17, 1977. The streets washed during this period are shown in Figure 4. At the end of the third day of street washing, the high-volume samplers at Broad and Spruce streets were operated on a 4-h schedule, which continued until 8:00 p.m. on June 19.

Figure 4. Area of street-flushing experiment.



EPA Dichotomous Sampler

The dichotomous sampler utilizes virtual impaction to separate the respirable and nonrespirable fractions. Air is drawn into the inlet at a relatively high flow rate to ensure collection of particles up to 20-μm aerodynamic diameter. The inlet has a deflector rim on the bottom of a rain shield to direct particles into the sampler during high wind conditions. At the bottom of the inlet a portion of the total sample flow is isokinetically sampled at a rate of 14 L/min and transported to the two-stage virtual impactor. A servo system and pump maintain a flow rate of 13.6 L/min to the fine-particle collector and 0.4 L/min to the large-particle collector. This results in particles in the range of 3.5 to 20 μm aerodynamic diameter being collected on one membrane filter and particles less than 3.5 μm aerodynamic diameter being collected on another membrane filter. At the conclusion of the sampling period, which is typically 24 h, the filters are removed and the concentrations of the respirable and nonrespirable fractions are determined gravimetrically. The membrane filters are then available for chemical analysis free from the interferences inherent with glass fiber filters.

GCA APM

The APM also utilizes a high flow rate at the inlet of the instrument and a configuration such that the conditions are similar to that of a high-volume sampler. The APM uses beta attenuation sensing for mass determination and, since the sensitivity depends on small-area collection, a flow rate of 9 L/min is isokinetically withdrawn via two probes. One probe has a cyclone that removes the nonrespirable fraction (i.e., greater than 3.5 μm) and the other probe collects the total particulate. The flow rates into the two probes are kept constant either by means of a specially designed sonic venturi nozzle or by an active feedback mass flow control system.

The aerosol to be measured is collected on a reinforced glass fiber filter tape and analyzed by beta radiation. In practice, an area of the tape is tared by a beta source-detector pair, the tape is indexed by a stepping motor to the collection port where the sample is collected, and, after the selected sampling period, is indexed to a second beta source-detector pair where the transmitted beta radiation is again measured. The appropriate calculations are performed by a microprocessor and the TSP concentration for each fraction is printed on a tape. The sensitivity of the system allows collection times much shorter than the conventional high-volume sampler without seriously affecting the measurement error. During this study, sampling periods of about 1 h were used.

NASA Air Scout

The Air Scout was developed by scientists at the NASA Lewis Research Center to permit collection of airborne particulate samples as a function of wind direction. It includes a system for recording wind speed and direction, and the wind direction is also fed to the circuitry of the sampling device.

Eight individual electrically actuated poppet valves, positioned in a circular pattern in a housing above a high-volume sampler, control air flow through the ports. Each port represents one of the eight directions of the compass. A solenoid actuates each valve and is connected electrically to a set of contacts in the wind vane corresponding to the direction assigned to the valve. Thus each valve, when open, permits collecting a particulate sample in a discrete location on a filter slide when it is in sampling position over the housing. The sample thus collected represents particulates in the air coming from a 45° arc of the compass. The central hole in the housing does not have a control valve. It is open continuously so that the sample collected on the filter slide can provide a measure of the TSP. The solenoids opening the valves have sufficient force to overcome the suction of the high-volume sampler that runs continuously during the sampling period.

SELECTED RESULTS

Data collected by the dichotomous sampler and by high-volume samplers during the February and early March sampling period are compared in Table 1. The observations were not taken concurrently, but have been assembled to present a composite picture of the spatial distribution of particulates during the period. Specifically, only one dichotomous sampler was used to provide the breakout of fine and coarse particulates at the two heights. It was operated approximately every other day for about 2 weeks on the roof of the trailer at Broad and Spruce streets and then moved to the roof of the Health building at 500 South Broad Street for a similar period. Also, although the data from the trailer top and rooftop high-volume samplers contain observations spread over the entire period during which the dichotomous sampler was operated, the concentration entered for the top of the tower was established on the basis of the average decrease in concentration as a function of height that was observed during the shorter 2-week tower experiment. With these limitations, the following three-dimensional picture emerges:

1. Turbulent mixing created by the passage of motor vehicles, the release of hot exhaust gases, and buildings of varying heights and sizes results in a nearly uniform mix of particulates over the height of the tower.
2. Rooftop concentrations average about 27 percent lower than concentrations at a corresponding height at the exposed intersection location.
3. Assuming a cutoff of 20 μm by the dichotomous sampler, approximately 62 percent of the particulate mass collected by the high-volume sampler at the trailer top location was composed of particles of aerodynamic diameter greater than 20 μm. At the rooftop location, this percentage dropped to approximately 55 percent.
4. About 70 percent of the particulates captured by the dichotomous sampler were respirable at the rooftop location, but only 60 percent were respirable at the trailer top location.
5. Using the dichotomous sampler to define the respirable fraction, 32 percent of the particulates captured by the high-volume sampler were respirable at the rooftop location, but only 23 percent were respirable at the trailer top location.

Table 1. Comparison of dichotomous and high-volume sampler results.

		Concentration by Sampler (μg/m³)			
		Dichotomous Sampler			
Location	Height (m)	Fine	Coarse	Total	High-Volume Sampler
Top of tower	11	-	-	-	130
Rooftop	11	30	13	43	95
Trailertop	4	34	23	57	149

Elemental Concentrations

Table 2 lists the six elements found to have the highest concentrations in the dichotomous samples and the most probable major source of each. Tabulated concentrations are based on the totals found in the two size fractions. The bottom line was obtained from the total mass of particulates collected by the dichotomous sampler.

Of these six elements, S has the highest concentration; and when expressed as sulfate (SO_4), it makes up approximately 19 and 25 percent respectively of the particulate mass measured by the dichotomous sampler at the Broad and Spruce streets and 500 South Broad Street locations. There is little decrease in average concentration with height, which indicates the thorough mixing and transport from nonlocal sources.

Si, Ca, Fe, and Al are presumed to be primarily of mineral origin, are most abundant in the coarser particles, and with the exception of Ca, decrease substantially in concentration between the trailer top location at Broad and Spruce streets and the rooftop location at 500 South Broad Street, which indicates strong contributions from local fugitive dust sources. Pb is the third most common element at Broad and Spruce streets and the fourth most common at 500 South Broad Street. Pb, like S, is found predominantly in the fine particulates, but unlike S, it shows a rapid decrease in concentration with height, in agreement with the hypothesis that motor vehicles are its principal source.

Comparison of Observed and Calculated Street-Level Contributions

Although the Broad and Spruce streets site appears to be typical of urban intersections, it is not at all obvious that conventional modeling procedures can be of great use in evaluating source contributions and control strategies at such locations. As can be seen from Figure 2, the physical configuration of buildings in the vicinity of this site bears no resemblance to that of the ideal sites used in the development and validation of line source models. Further complications in modeling street-level particulate emissions in downtown areas arise from the difficulty of either measuring or estimating reliably background concentrations, and in assigning appropriate emission factors. For these reasons, a number of ex-

Table 2. Six highest elemental concentrations and probable sources.

		Concentration by Location (μg/m³)			
Element	Major Source	Broad and Spruce	500 South Broad	Average Fine (%)	Reduction With Height (%)
Sulfur	Fuel combustion	3.65	3.58	87	2
Silicon	Crustal material	2.71	1.50	12	45
Calcium	Crustal material	1.15	1.08	14	6
Lead	Motor vehicles	1.36	0.86	85	37
Iron	Crustal material	1.22	0.63	24	48
Aluminum	Crustal material	0.87	0.56	8	36
TSP		56.4	42.8	64	24

ploratory calculations were carried out prior to making the final model calculations used in assessing the Philadelphia particulate problem.

The approach taken was to assume that the street contribution to concentrations measured at the tower is simply the difference between the tower concentrations and the rooftop concentration measured at 500 South Broad Street. The street contribution was further assumed to come from both Broad and Spruce streets and that emissions were directly proportional to traffic volume. Current information was judged to be insufficient to warrant making adjustments in the emission rates of either reentrained street dust or tailpipe particulate emissions according to vehicle speed or operating mode. The exploratory calculations at the Broad and Spruce street intersection included the application of a Gaussian line source model and a box model for a 24-h period, and the use of the STAR model meteorological summary with the Gaussian model for a 1-year period. The cut-section submodel of HIWAY (highway air pollution model) was used to calculate the average annual impact of reentrained dust at rooftop level at 500 South Broad Street and at the Philadelphia Center for Older People.

February 8, 1977, a day with westerly winds and the requisite hourly traffic and meteorological data, was chosen for the initial exploratory calculations. An emission rate of 0.42 g/km for each vehicle [developed from data in a draft report by Midwest Research Institute (1)] was used for reentrained dust. EPA emission factors of 0.21 and 0.12 g/km for each vehicle were used respectively for tailpipe exhaust and tire wear (2). It was assumed that the source height of these emissions was 1.0 m above street level and that the standard deviation of the vertical concentration of the model (σ_z) was equal to 1.5 m at the source. An adaptation of the HIWAY model (Intersection-Midblock model) was run for each hour of the day for four receptor heights on the tower and the results were averaged over the 24-h period. The solid curve in Figure 5 is the result. The rapid decrease in concentration with height is to be expected in view of the assumed vertical dimension at the source and the fact that no adjustment in stability class was made to account for additional turbulence induced by the building structures.

Using Figure 5, a comparison can be made between the calculated amount of traffic-related particulates and the observed amount as indicated by the difference in concentration between the tower and the rooftop at 500 South Broad Street. This concentration difference, estimated to be 18 μg/m^3 over the height of the tower, is indicated in the figure by the dashed vertical line. The approximate agreement between calculated and observed flux of particulates by the tower is shown by the close equivalence of the two shaded areas.

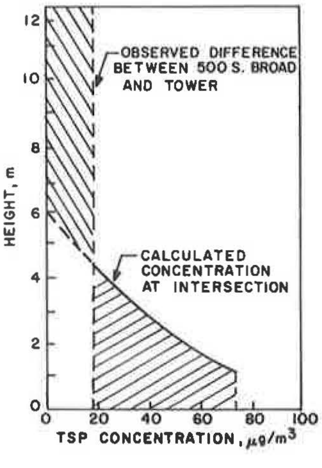


Figure 5. Comparison of calculated and observed vertical TSP profiles on February 8, 1977.

The thorough vertical mixing that takes place within a layer at least as deep as the tower suggests that conditions near the intersection might be more realistically represented by a box model instead of a Gaussian model. To apply a box model on February 8th, the following assumptions were made:

1. The height of the box is equal to the height of the tower (12 m).
2. The box is flushed by the average rooftop wind speed (2.3 m/s).
3. Traffic-related emissions are contributed at a rate per vehicle of 0.75 g/km by all vehicles entering the intersection of Broad and Spruce streets during the day (39 000 vehicles).

Using these assumptions, the following calculation provides an estimate of the average concentration of traffic-related particulates within the box on this day:

$$\begin{aligned}\text{Concentration} &= \text{mass added/volume}\\ &= [39\,000 \times (750/24) \times 3600]/(12 \times 2.3 \times 1)\\ &= 12\ \mu\text{g/m}^3 \qquad (1)\end{aligned}$$

which is in agreement with the estimate of 18 μg/m^3 obtained from the observations.

To obtain some further idea of the suitability of the 0.42 g/km emission rate per vehicle for reentrained dust in combination with the Intersection-Midblock model, the model was applied to the tower site over a 1-year period, arbitrarily using a 2-m receptor height. For this calculation, the STAR meteorological summary for 1974 was used. The STAR summary does not distinguish hour of the day; therefore, the average daily traffic volume was assumed to be distributed evenly over a 24-h period. Also, traffic counts from the February 1977 field program were assumed to represent average travel during the year. The result of these calculations was an annual average concentration of 37 μg/m^3. This is in agreement with the annual differences of 43 and 44 μg/m^3, respectively, experienced between the 500 South Broad Street site and the Broad and Spruce street site in 1975 and 1976. However, judging by the concentration profile shown in Figure 5, the calculated 2-m concentration should have exceeded the annual difference by a factor of 2 for good agreement. If tailpipe and tire wear emissions are unchanged, this could be accomplished by increasing the emission factor for resuspended dust by a factor of 3.

This emission rate was also used with the cut-section submodel of HIWAY to calculate the average annual impact of reentrained dust at rooftop level at 500 South Broad Street and the Philadelphia Center for Older People. The resulting concentrations were 2.6 μg/m^3 at 500 South Broad Street and 9.4 μg/m^3 at the Philadelphia Center for Older People. The difference in average concentration between the two sides of Broad Street reflects the prevailing westerly winds. Although there are no annual values with which these model estimates can be compared, the estimates are in approximate agreement with the average downwind values experienced during the February field program.

Source Contributions to Annual Geometric Means

Under a previous EPA contract, GCA updated the TSP point source inventory for the metropolitan Philadelphia Interstate air quality control region (AQCR) and developed a regional TSP area source emission inventory. The use of this emission inventory and the emission factor per vehicle of 0.42 g/km for fugitive dust emissions from paved roads (which was tested at the Broad Street sites) gives the breakdown by source category of annual geometric means for the two sites shown in Figure 6. The 43 μg/m³ attributed to local reentrained dust and vehicular emissions at Broad and Spruce streets is simply the difference in measured concentrations at the two sites. Figure 6 illustrates the use of modeling to provide the basic understanding of the particulate problem needed prior to the development of control strategies.

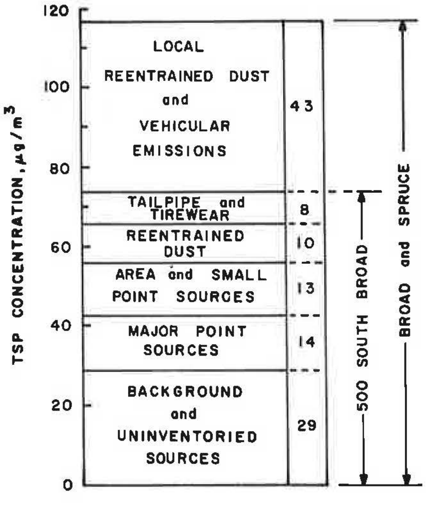
CONTROL STRATEGY MONITORING

The major role played by reentrained street dust in violations of the particulate standards in urban areas has now been generally accepted, but the formulation of feasible control strategies is proving to be a formidable task. The use of street washing as a possible control strategy was tested at the Broad and Spruce street site during the June field program. The city of Philadelphia performed washing on three consecutive days between 7:00 a.m. and 6:30 p.m. along the street segments shown in Figure 4. On the third day, washing was delayed for 2 h by a parade. The amount of water used was as follows: June 15 th, 4.3×10^5 L; June 16 th, 4.2×10^5 L; and June 17 th, 3.1×10^5 L. At the end of the third day of street washing, the high-volume samplers at Broad and Spruce streets were operated on a 4-h schedule in an attempt to measure the rate of increase in TSP levels resulting from accumulating street dust. This 4-h schedule continued until 8:00 p.m. on the 19 th. Traffic volume data were taken by automatic counters located on South Broad and Spruce streets.

TSP concentrations preceding, during, and following the washing experiment are plotted in Figure 7. The Broad and Spruce street curve shows the average concentration for the trailer and tower high-volume samplers; the x's indicate average 4-h concentrations at this location. The 500 South Broad Street curve shows the average concentration measured at this rooftop location. The third curve shows the average concentration measured at the two other sites in the city with approximate daily sampling. The periods of intensive street washing are also indicated in the figure.

Several features of Figure 7 deserve comment. First, citywide concentrations, as indicated by the LAB-, S/E-, and rooftop-site monitors, were generally low through the 13 th, increased during the 14 th and 15 th, gradually decreased somewhat during the 16 th and 17 th, and were down to approximately 75 μg/m³ on the 18 th and 19 th. Also, the average concentration at the LAB and S/E sites and the rooftop concentrations followed each other quite closely. Second, the average 24-h concentration at the Broad and Spruce street site did not appear to be affected significantly by the intensive daytime street washing, which took place on the 15 th and 16 th, remaining roughly 40 μg/m³ higher than the average citywide index. On the 17 th, this difference increased somewhat. Third, the concentrations at Broad and Spruce streets increased dramatically to the highest levels observed during the field program immediately following the washing, while the citywide concentrations remained low.

Figure 6. Source contributions to annual geometric means in 1976.



The failure of street washing to reduce TSP concentrations at the intersection and the unusually high concentrations measured there following the washing were both unexpected and at first puzzling results. The most plausible suggestion made to date is that the vigorous, forced washing plus splashing by motor vehicles redistributed particulates that had previously become concentrated adjacent to the curbs. Many of these redistributed particulates probably became airborne as soon as the streets were dry. Also, recall that the washing operation was less extensive on June 17 due to a parade, giving additional time for reentrainment. This hypothesis of reentrainment of the redistributed dried particulates by vehicular traffic is supported by Figure 8, which compares the volume of traffic entering the intersection at Broad and Spruce streets in a 4-h period with the average TSP concentration measured at that site. The correspondence between the two curves is surprisingly close. Calculation of the linear correlation coefficient for the 11 pairs yielded a value of +0.79, which is significant at the 1 percent level.

SUMMARY

Based on experience gained in performing this work, we offer the following general comments for consideration in the design of similar programs. A number of devices are currently available for monitoring ambient particulates, as illustrated by the wide range of instruments that were deployed in this field program. In contrast to

Figure 7. TSP trends during street-flushing experiment.

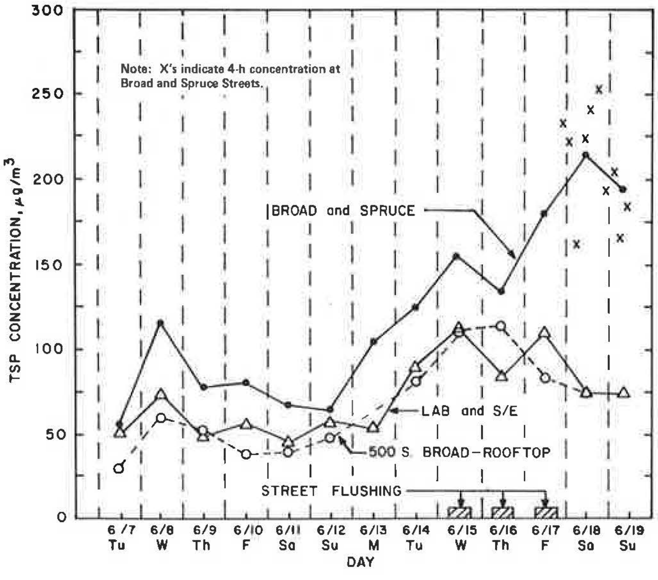
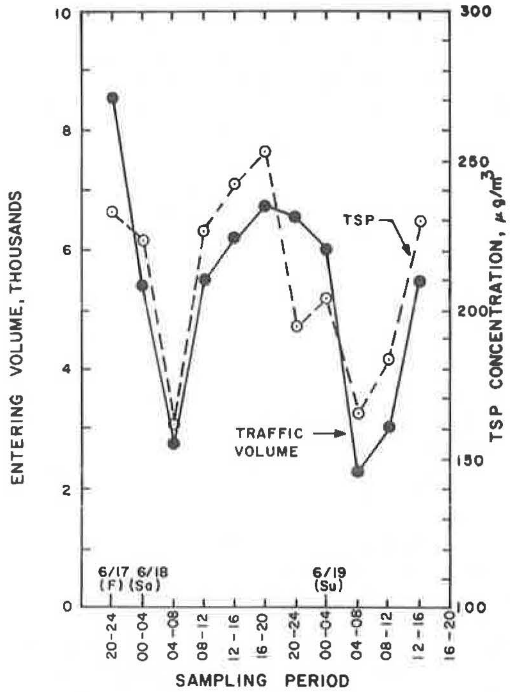

Note: X's indicate 4-h concentration at Broad and Spruce Streets.

Figure 8. Comparison of TSP concentration and traffic volume following street flushing.



the selection of monitors for gaseous pollutants, the selection of instrumentation for particulate monitoring requires that careful consideration be given to the purposes of the monitoring program and to any special characteristics of the candidate instruments. Although in principle the choice of instruments can be made on the basis of sampling time, particulate size cut, and type of chemical or physical analysis desired, if any, the actual results may be influenced by the particular instrument selected and perhaps by the atmosphere being measured. For example, in a limited comparison of total suspended particulate concentrations made during this program, the APM and the dichotomous sampler yielded concentrations that were roughly 70 and 40 percent, respectively, of the high-volume sampler concentrations. Much of the difference can be explained by differences in inlet configurations, but some of the discrepancy may result from a mass accretion on the high-volume sampler filters as a result of passive particle deposition and chemical reactions between collected particulates and various gaseous species present in the ambient air. The larger discrepancy that occurred with the dichotomous sampler presumably resulted in part from its upper particle size cutoff of 20 μm.

The selection of appropriate emission factors for fugitive and reentrained dust continues to be one of the most perplexing problems associated with particulate modeling. Enough measurements have been made to confirm that roadway emission rates and the size distribution of the emitted particles within an urban area vary widely both spatially and temporally. Generalizing from these measurements frequently leads to unreasonable results. For example, the introduction of emission factors for roadway dust developed for residential areas (1) (using a nonstandard collection inlet configuration) leads, through the use of the air quality display model, to excessively high estimates for the contribution of reentrained dust within the metropolitan Philadelphia AQCR. If these emission factors are, in fact, generally applicable, it would appear that large losses of particulates occur as they move from the roadway to monitoring locations, possibly due to the screening and cleansing effects of vegetation. An approach that holds some promise, and one that was adopted in this project, is to accept an emission factor for general use that yields consistently reasonable results throughout the area for rooftop monitors or for monitors removed from any obvious local particulate source. An attempt is then made to explain deviations from these rooftop model estimates by local sources either by modeling or by the use of empirically derived expressions.

ACKNOWLEDGMENTS

This paper is based on work that was supported by the U.S. Environmental Protection Agency. The opinions, findings, and conclusions expressed are ours and not necessarily those of the EPA or of cooperating agencies. Mention of company or product names is not to be considered as an endorsement by EPA.

We wish to express our appreciation to Robert K. Stevens of the Environmental Services Research Laboratory, EPA, who arranged for the use of the dichotomous samplers in the field program and for the analysis of the exposed filters, and to the National Aeronautics and Space Administration Lewis Research Center for the loan of the NASA Air Scout. We would also like to thank members of the Philadelphia Air Management Services Laboratory and of the city sanitation department for their cooperation during the program. Finally, we express our gratitude to Victor Corbin, who carried out the model calculations, and to other members of the GCA/Technology staff, who worked on the field and laboratory phases of the program.

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Review of U.S. Environmental Protection Agency Guidelines for Evaluating Indirect Sources and Carbon Monoxide Hot Spots

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Two guides have been developed to aid in identifying locations where significant carbon monoxide concentrations can be attributed to mobile source emissions. Both guides use state-of-the-art traffic engineering practices, emission factors, and dispersion techniques to provide a comprehensive yet manageable analysis of carbon monoxide concentration impacts. One guideline is oriented to indirect sources (e.g., shopping malls or sports stadiums) and provides a comprehensive manual methodology for assessing both 1- and 8-h average carbon monoxide concentration impacts corresponding to the national ambient air quality standards time averages. The second, or hot-spot guidelines, is designed to assess urban problems and employs a more general approach for estimating carbon monoxide concentrations at individual roadways and intersections. The term hot spot is used to indicate locations where carbon monoxide concentrations are estimated to be above the national ambient air quality standards. Both guidelines use a series of annotated worksheets, graphs, and tables, which are supplemented by background information on technique development and applications. Results of limited validation studies are included in each guide. These guidelines are particularly useful in evaluating indirect sources, planning transportation controls, assessing new roadway projects, and evaluating and selecting air quality monitoring sites.

Mobile source emissions produce virtually all carbon monoxide (CO) emissions at street level (1) and thus are primarily responsible for the magnitude of CO concentration levels in the immediate vicinity. People live and work near indirect sources of CO, roadways, and intersections, so such locations are priority locations where acceptable air quality should be maintained. Planners of air quality maintenance programs, however, have limited resources for ambient air quality monitoring and limited resources for detailed computer analysis and interpretation.

A simple yet comprehensive screening technique is needed for assessing the air quality impact of CO attributable to mobile sources. Past studies indicate that simple hourly traffic counts do not adequately represent variations in source strength or subsequent roadside CO concentrations (2, 3). CO concentrations are highly variable from one location to another (4); therefore, the few existing sites for which detailed modeling or monitoring have been conducted are believed to reflect CO levels only in the immediate vicinity. They provide a poor indication of CO levels at other sites, especially when traffic and location configurations are different.

The two guides discussed in this paper are referred to as the indirect source guidelines (ISG) (5) and the hot spot guidelines (HSG) (6). These guides provide comprehensive, easy to use manual techniques for preliminary screening of mobile source CO impacts. This concept depends on current traffic engineering practices, current and projected emission factors, and state-of-the-art dispersion modeling techniques.

ISGs evaluate indirect sources. An indirect source is any facility that attracts mobile sources but is not itself a source, such as a new major intersection, a recreational area, or a sports stadium. The guideline allows for detailed consideration of variable meteorology, traffic, and emission factors. The procedures are best applied to an evaluation of a well-defined scenario (present or future) for a specific facility, including the nearby roadway network, in order to estimate quantitatively the CO impact near these sources.

In contrast, the HSG document is useful for quick screening of individual roadways and intersections on an urban basis. Instead of the detail and flexibility that ISGs employ to refine the concentration estimates, HSG use realistic worst-case assumptions to identify potential CO hot spot locations.

HSG and ISG provide powerful screening tools for a preliminary analysis of existing or potential CO impacts on air quality near mobile source locations.

TECHNIQUES

Both HSG and ISG employ current techniques to calculate emissions and estimate pollutant concentrations. The difference between the techniques is in the level of detail of input information, calculation procedures, and subsequent concentration estimates. The procedures are based on

1. Mobile source emission factors—techniques for estimating CO emissions for current and future years (7);
2. Modal model—a model used to estimate automobile emissions under a set of base conditions for any driving cycle (1);
3. HIWAY—a line source dispersion model (8);
4. Traffic engineering theory and practice for estimating the interplay of various roadway and traffic parameters (9, 10, 11, 12);
5. Local observations of traffic parameters, meteorological conditions, and air quality; and
6. Available information from local planning and transportation agencies on specific roadway designs, vehicle usage, and current and future alternative network plans.

ISG are primarily facility oriented; therefore, more detail about the facility design and the nearby roadway network is required in order to estimate CO impacts. The project developer can generally supply these data, which are then combined with information on model year, calendar year, vehicle mix, ambient temperature, and automobile starting characteristics to derive emissions estimates for the desired scenario from emission factor tables. Receptor location, atmospheric stability, wind speed and direction, and type of source are then entered into nomographs (such as Figure 1) derived from HIWAY model simulations to estimate the CO impact of the source.

The document gives guidance for examining total CO impacts at intersections (all approaches) as well as whole parking lots, including entering and exiting ve-

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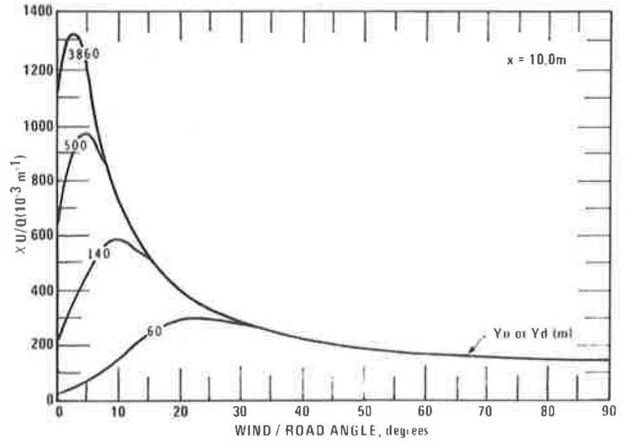
*Mr. Schewe was on assignment from the National Oceanic and Atmospheric Administration when this paper was written.

hicles. Intersection and roadway validations in the ISG agree within the limits of the modeling procedures, but the techniques for analyzing parking lots need further evaluation. Worksheets, such as the one in Figure 2 (5), are provided for performing calculations. The user, however, is expected to become familiar with the bases for the techniques, their applications, and limits before proceeding to an analysis. ISG are designed for persons who have some prior experience in traffic and air quality analysis.

The level of detail required for ISG methods hinders their usefulness in an iterative fashion when many sources or locations are being evaluated. To facilitate such a procedure another set of guidelines, HSG, were developed. HSG are similar to ISG in emissions, traffic, and dispersion modeling methods but differ in detail of input data, ease of use, and intended use of the results. Instead of the one-level detailed analysis, HSG employ two levels of screening that are based on worst-case receptor locations (i.e., traffic and meteorology interact to yield a maximum estimate of CO concentration). This allows many roadways and intersections to be evaluated in a reliable manner consistent with worst-case assumptions. HSG provide adequate identification of potential hot spots in less time and with less effort than do more complex techniques. HSG are designed to be useful to persons who have limited background in either traffic or dispersion modeling.

The two screening levels in HSG include a simple yes-no determination as to whether the estimated ambient CO concentration is likely to be above the national ambient air quality standards (NAAQS) and a method to rank such locations (Figure 3 is an example of the type of nomograph used in the yes-no determination). HSG techniques were derived from ISG through iterative applications of ISG procedures to find maximum concentration estimates for worst-case conditions. Limited validation of HSG shows that estimates are conservative and that they adequately identify potential CO hot spots.

Figure 1. Variation of the normalized CO concentration with roadway length, road/receptor separation (x), and wind/road angle, for stability = D and σ_{z_o} = 5.0 m.



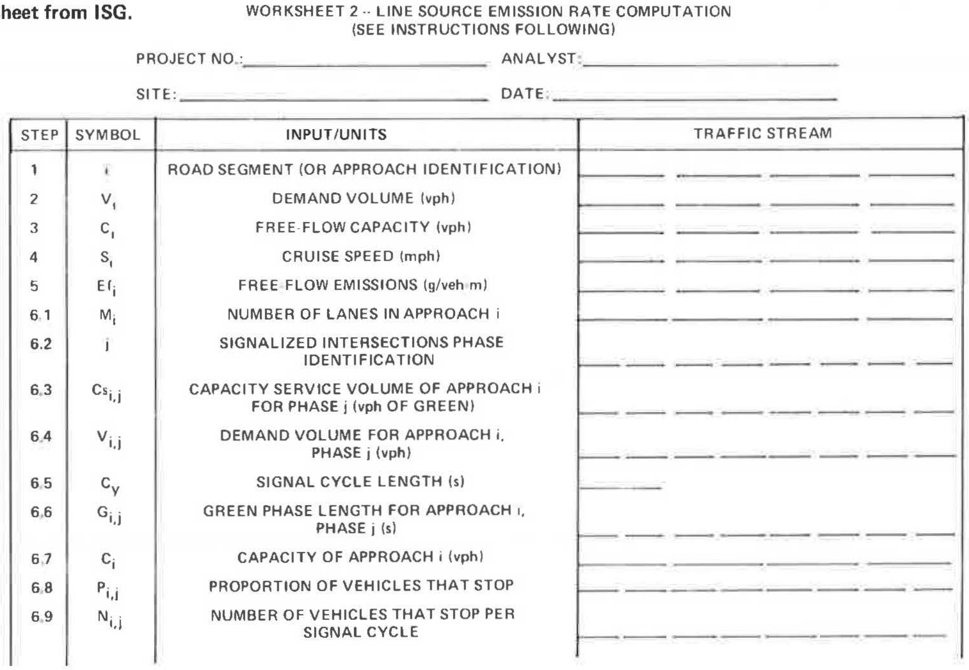
Applications and Uses

HSG allow an initial assessment of a whole network of streets and intersections and the possible interplay between them in terms of increasing or decreasing CO hot spot potential. This type of analysis will assist in evaluating whether existing CO monitoring locations are representative and in planning new ones. HSGs also provide procedures for assessing the impact of inspection and maintenance and other transportation control plan measures on emissions and, therefore, on CO impacts. Alternative traffic routing and signaling effects on worst-case network CO impacts may also be assessed through the HSG screening techniques.

ISG are designed for a preliminary assessment of CO concentrations near an indirect source. Instead of worst-case estimates at each source-receptor location, however, the user may use on-site conditions or projections to estimate the combined impact at a receptor of nearby parking, exit lanes, intersections, or streets.

Both guidelines allow adjustments to automotive emissions for future years, cold starts, hot starts, temperature, and speed. This, along with nomographs for various road and lane configurations, allows alternative scenarios to be modeled and compared. Alternatives

Figure 2. Example worksheet from ISG.



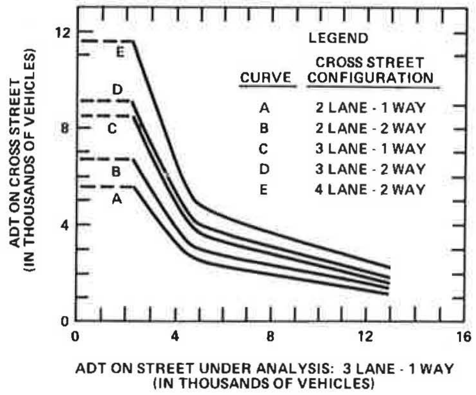
WORKSHEET 2 -- LINE SOURCE EMISSION RATE COMPUTATION
(SEE INSTRUCTIONS FOLLOWING)

PROJECT NO.:__________ ANALYST:__________

SITE:__________ DATE:__________

STEP	SYMBOL	INPUT/UNITS	TRAFFIC STREAM
1	i	ROAD SEGMENT (OR APPROACH IDENTIFICATION)	
2	V_i	DEMAND VOLUME (vph)	
3	C_i	FREE-FLOW CAPACITY (vph)	
4	S_i	CRUISE SPEED (mph)	
5	Ef_i	FREE-FLOW EMISSIONS (g/veh-m)	
6.1	M_i	NUMBER OF LANES IN APPROACH i	
6.2	j	SIGNALIZED INTERSECTIONS PHASE IDENTIFICATION	
6.3	$Cs_{i,j}$	CAPACITY SERVICE VOLUME OF APPROACH i FOR PHASE j (vph OF GREEN)	
6.4	$V_{i,j}$	DEMAND VOLUME FOR APPROACH i, PHASE j (vph)	
6.5	C_Y	SIGNAL CYCLE LENGTH (s)	
6.6	$G_{i,j}$	GREEN PHASE LENGTH FOR APPROACH i, PHASE j (s)	
6.7	c_i	CAPACITY OF APPROACH i (vph)	
6.8	$P_{i,j}$	PROPORTION OF VEHICLES THAT STOP	
6.9	$N_{i,j}$	NUMBER OF VEHICLES THAT STOP PER SIGNAL CYCLE	

Figure 3. Critical volumes at signalized intersections.



may include changes in network design and ambient conditions and subsequent impacts on emissions.

These guidelines allow the user to screen through receptor sites at three levels of detail:

1. Initial screening to identify potential CO hot spot locations (HSG).
2. Secondary screening to estimate worst-case CO concentrations at potential hot spots (HSG).
3. Manual detailed techniques to consider other than worst-case conditions (ISG).

Supplementary computer techniques are also available (13) to enable a user to perform levels 2 and 3 above for roadways and intersections.

Advantages and Disadvantages

These guidelines attempt to fill a gap in modeling mobile sources by providing simplified preliminary estimates. Advantages over detailed modeling or over simple traffic characterizations include

1. The guidelines are easy and quick to use for the level of detail discussed above;
2. They do not require computer resources;
3. They provide the best methods for treating intersections in a manageable and logical way;
4. They are comprehensive because even the simplest HSG technique uses a variety of assumed inputs to relate emissions to CO concentrations;
5. Alternatives or future years may be analyzed;
6. The guidelines can be used to screen many sources (HSG) and many receptor sites (ISG); and
7. They are based on state-of-the-art modeling techniques.

Disadvantages include

1. Neither guideline can handle complex situations (e.g., intersections that have more than four approaches or tunnels);
2. Neither guideline can treat congested conditions; and
3. Validation is limited to several cases. The HSG are validated only to the extent that they identify locations of potentially high CO concentrations.

SUMMARY

Two documents designed for screening locations of potentially high CO concentrations due to mobile sources have been developed. ISG are facility oriented, require detailed data inputs, and are designed for an experienced engineer. They provide the capability to estimate CO concentrations at any location under variable traffic, emissions, and meteorological conditions. HSG are oriented to areawide analyses, require limited data inputs, and are designed for use by a general technical audience to estimate maximum potential CO concentrations under assumed worst-case traffic and meteorological conditions.

Both guidelines are based on current emissions information and modeling practices but are subject to changes as new emissions data become available or as federal motor vehicle control schedules are revised.

An application of HSG has been completed for Washington, D.C. (14). Midurski and Mills describe the experiences of applying HSG to Washington and the role that CO concentration estimates played in analyzing transportation and air pollution control strategies. A similar, more detailed study is under way in Providence, Rhode Island.

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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.

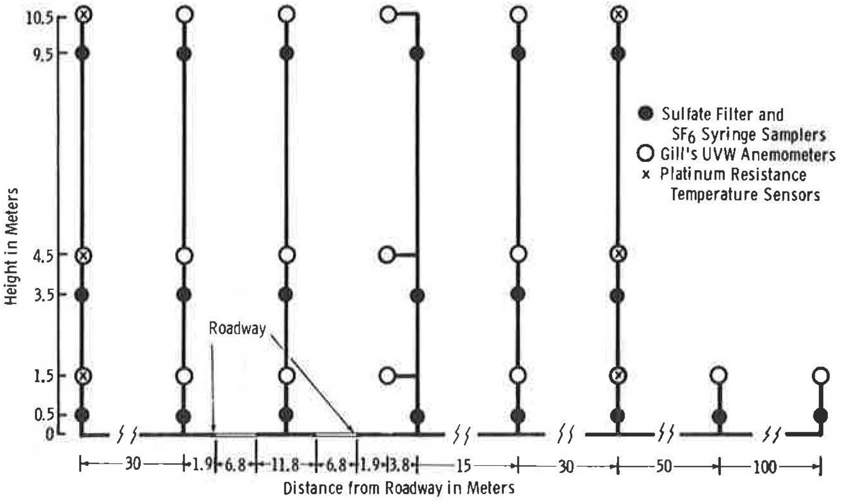


Figure 3. A view of the instrument layout.

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.

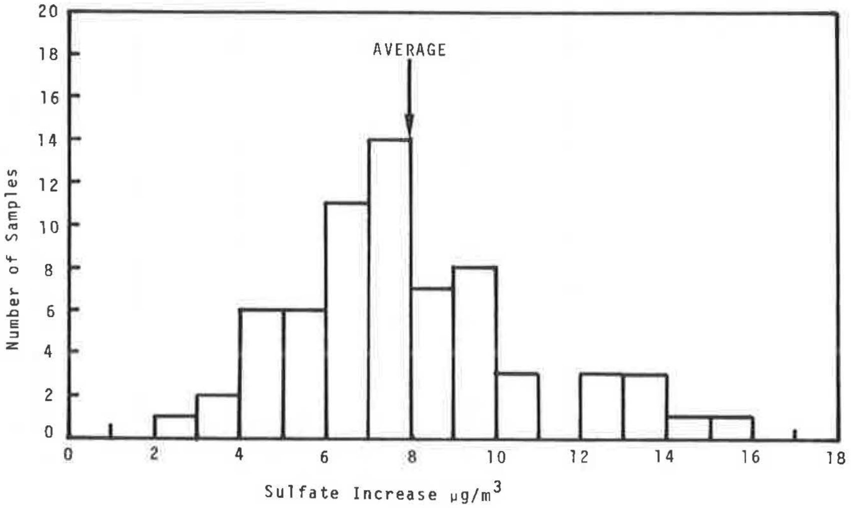
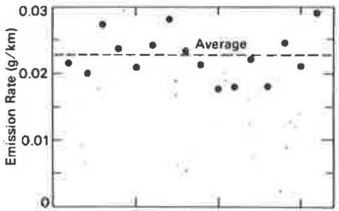


Figure 5. Day-to-day variation in sulfate emission rate.



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.

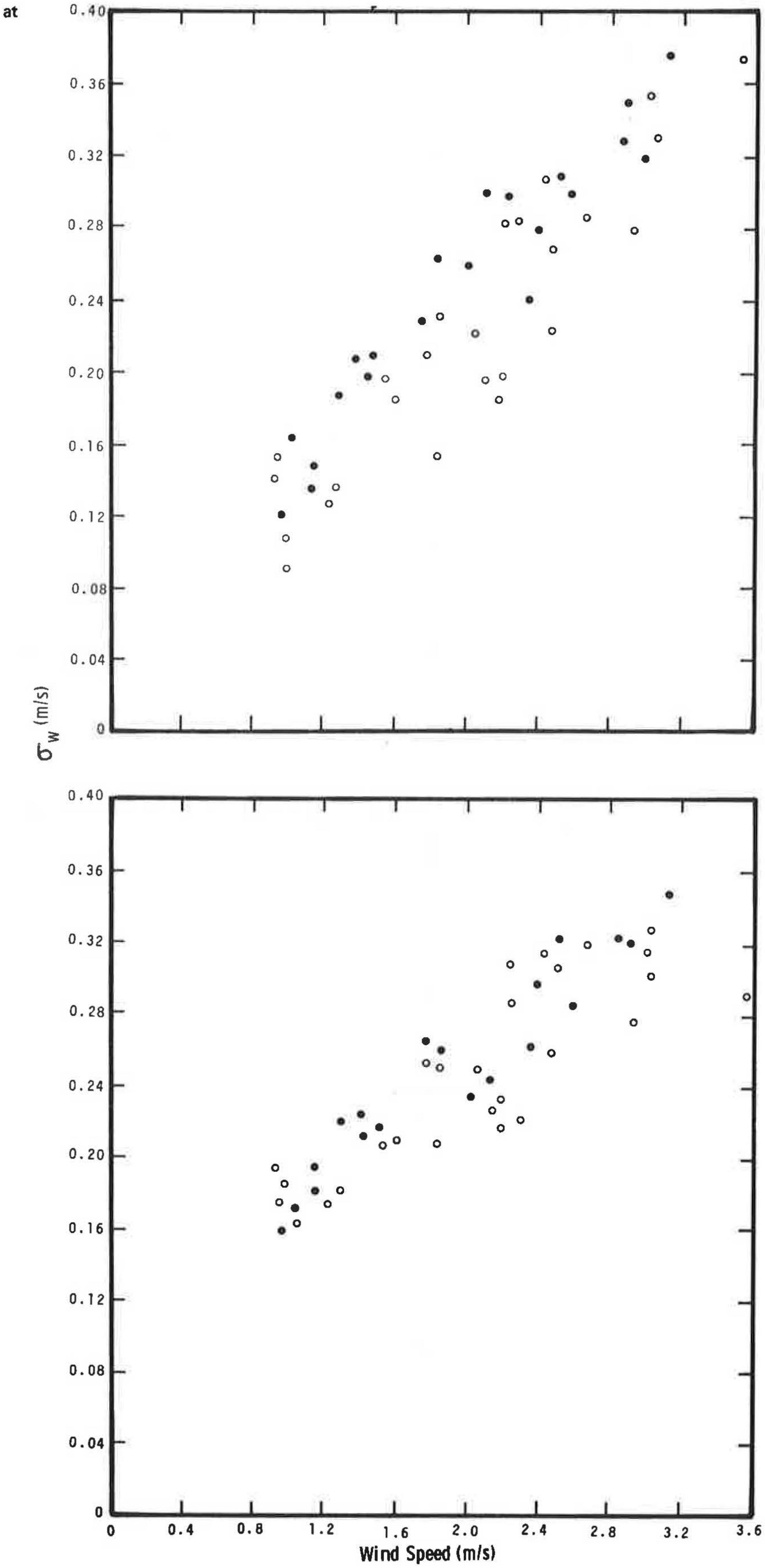


Figure 7. The upwind-to-downwind SF_6 concentration ratios for the 0.5-m level of the roadside towers, as a function of the ambient wind.

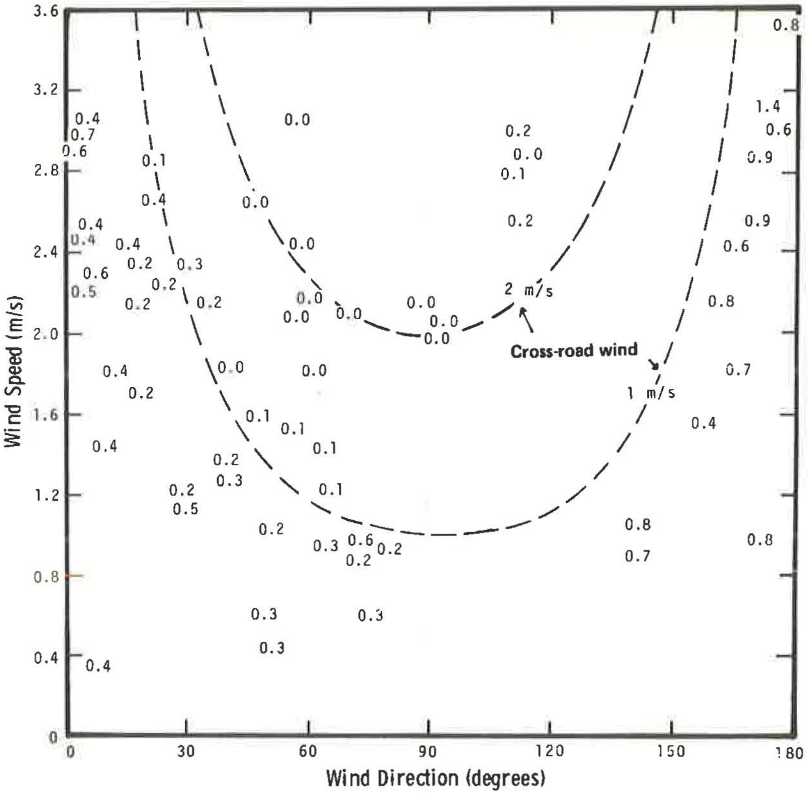
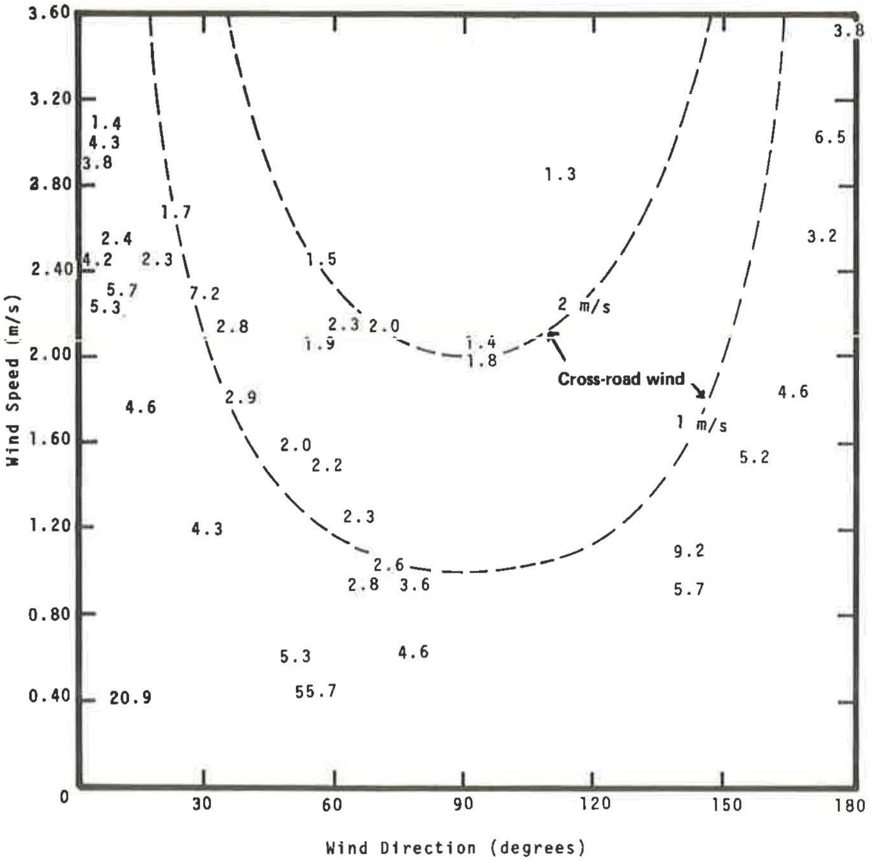


Figure 8. The predicted-to-observed SF_6 concentration ratios for the 0.5-m level, 30 m downwind of the road.



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 ($|r_1-1| - |r_o-1|$) where r_o 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

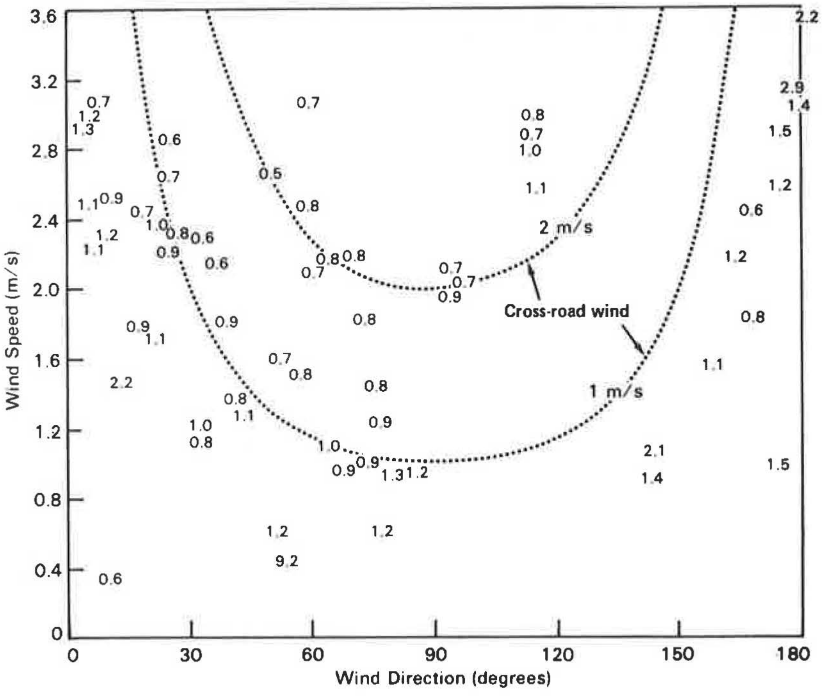
The simple line-source model is useful in estimating dispersion near roadways, but we also hoped to develop a physically more realistic model that satisfies conservation of mass and allows for the presence of wind shear, for the effects of traffic-induced turbulence, and for different boundary conditions.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

$$\sum_{j}(\partial/\partial x_j)(U_jC) = \sum_{ij}(\partial/\partial x_i)[K_{ij}(\partial C/\partial x_j)] + S \qquad (1)$$

where

C = the mean concentration,
U_j = the j th 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

Non-General Motors participants in the experiment included Ford, Chrysler, and American Motors, who contributed a portion of the automobile fleet; researchers from EPA and its contractors: University of Minnesota, University of Washington, Florida State University, Research Triangle Institute, and Environmental Quality Research, Inc.; the U.S. Department of Transportation; and Brookhaven National Laboratory.

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

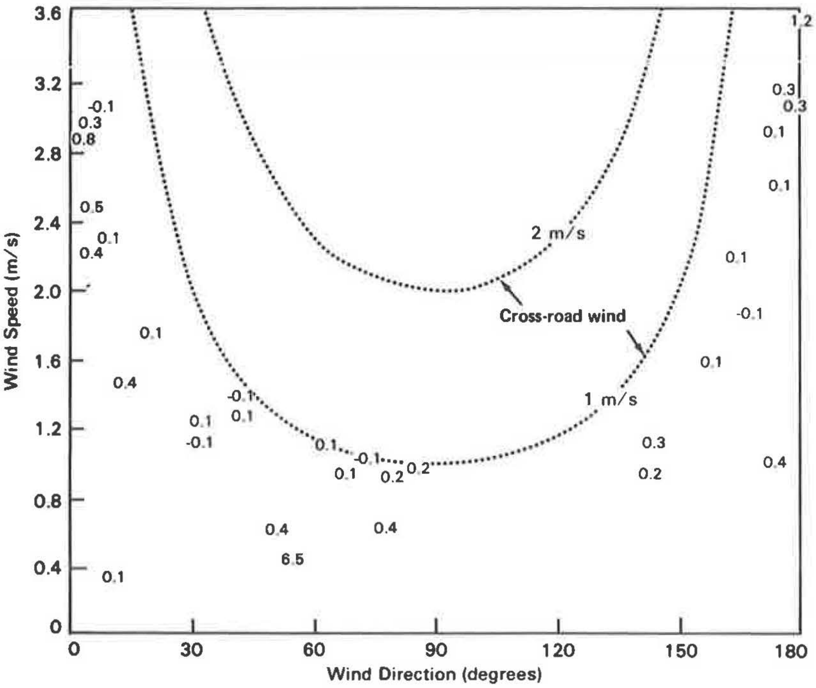
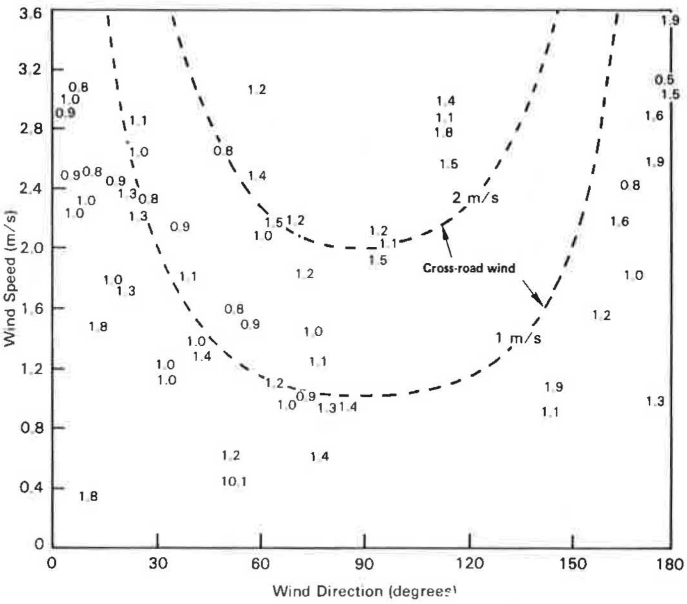


Figure 11. The predicted-to-observed SF_6 concentration ratio values from the advection-diffusion model.



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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 location for a given time, the local terrain and road site, and the roadway vehicles. The nature and magnitude of the the dispersion are affected by the general speed and direction of the wind passing over the roadway as well as by the induced air motions and turbulence generated by the highway and traffic. A part of the fluctuations and turbulence comes from vehicle presence and operations that produce heat as well as aerodynamic disturbances, such as wakes. The turbulence from highway traffic is a complexity of wall, free, and convective types.

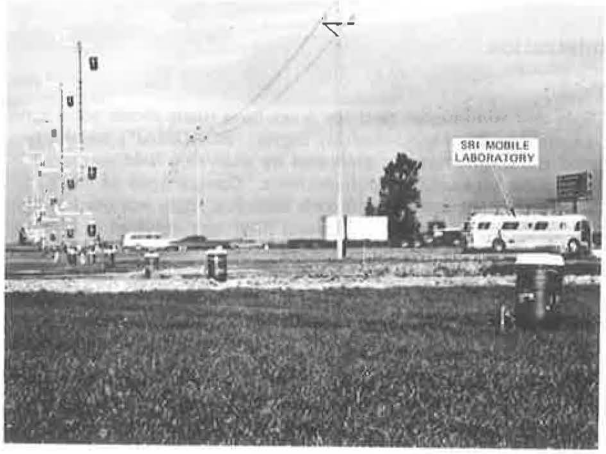
Estimates of air pollutant dispersion near roadways have usually not given adequate consideration to the fluid mechanics involved. Accurate estimates are necessary to gauge receptor impacts and plan remedial measures. A thorough three-dimensional analytical model, however, is still unverifiable and could be unwieldy or impractical at this time. Nonetheless, to increase the conceptual understanding of the air flows and quality on and near roadways, the Federal Highway Administration (FHWA) has had an extensive study conducted by Stanford Research Institute International.

A new model, the roadway atmospheric dispersion model for air pollution (ROADMAP), utilizes the experimental work of this study and considers highway geometry, vehicle waste heat, and turbulence. The focus is on relatively simple, definable, and common highway traffic situations. Included in ROADMAP are coordinated tasks in fluid dynamic evaluations, explorations of other pertinent measurements, analytical modeling, scale model wind tunnel tests, extensively measured highway field location, descriptive modeling, and trial applications.

EXPERIMENTAL PROGRAM

Aerometric measurements were made near a wide range of roadway configurations to investigate the dispersion process as it relates to site geometry, traffic conditions, and meteorology. Atmospheric field tests were conducted under various atmospheric and traffic conditions at grade-level, vertical-wall cut, and viaduct sections. A broader range of site geometries was considered during the more than 300 wind tunnel tests: 17 configurations were studied under varying traffic and wind conditions (stability, however, was always neutral). Included were at-grade level sections of varied smooth and rough terrain, vertical- and slant-wall cut, airtight structure, fill, viaduct, and hillside sections.

Figure 1. Photograph of grade-level highway test site.



Field Sites

Traffic and meteorological effects were investigated at a flat, grade-level location for wind-tunnel test comparisons and to avoid the aerodynamic complexities of the other, more intricate site configurations. Results of the tests at the highway-cut section and viaduct section provided useful concepts but, because of limited use in model development, discussion here focuses on the at-grade site. Measurements for that site were made in 1975 on US-101 (Bayshore Freeway) in Santa Clara, California, 80 km southeast of San Francisco. The road is a major intrastate freeway of three lanes of traffic in each direction; the roadway is oriented nearly east-west at the test site. The traffic flow is heavy [around 110 000 average daily traffic (ADT)] and varies markedly throughout the day, both in speed and in volume by direction.

The median strip is sufficiently wide to permit installation of towers (five were used) for meteorological and air sampling purposes. A comprehensive microsampling network monitored wind, temperature, air quality, and traffic. Figures 1 and 2 illustrate the location and orientation of the aerometric instrumentation. Ambient meteorological data were measured at four heights (2.0, 3.8, 7.5, and 14.2 m) on the five towers. Wind and turbulence measurements were made on all five towers, but precision temperature profiles were only measured on the two towers adjacent to the roadway edges. All 50 meteorological data inputs were sampled, digitized, and recorded on magnetic tape every 2.5 s. Hourly and 15-min summaries of primary and derived parameters were prepared. Comprehensive traffic information about speed and axle number for each vehicle, segregated on a lane-by-lane basis, was recorded throughout the study period. Summaries were also tabulated every 15 min for each of the 45 h encompassed by the study.

Sequential multiple-bag samplers were programmed to obtain hourly air samples of 4 L at each of 35 locations (see Figure 1); 20 samplers were located at the ground surface out to 100 m from the roadway edges and 15 were placed on the towers. The air samples were analyzed to determine ambient concentrations of carbon monoxide (CO), total hydrocarbons (THC), and methane (CH_4), in addition to concentrations of two tracer gases [sulfur hexafluoride (SF_6) and fluorotribromomethane ($CFlBr_3$)] released on the highway. Two vans were equipped to release each of the two tracer gases. They were driven continuously in the traffic stream, always in the middle lane at general speed, but not exceeding 90 km/h (55 mph). The drivers released SF_6 in the west direction and $CFlBr_3$ in the east direction.

Wind Tunnel Studies

The principal component of the highway model used in the Calspan wind tunnel was a moving roadway. Its function is to distribute the exhausts from model vehicles in analogy to the full-scale situations. The model vehicles were attached to two moving belts; for most tests two lanes of traffic were attached to each belt. The belts could be driven in the same or in opposite directions. Beneath the belts a plenum chamber supplied a He-N gas mixture, which was vented to the atmosphere through exhaust ports on each vehicle. In turn, the entire roadway model was constructed to fit into the 2.2-m diameter turntable in the floor of the wind tunnel; by rotating the turntable, the angle between the wind vector and roadway axis was easily varied. The thin roadway-plenum chamber construction enabled the model to be elevated to simulate a viaduct, fill, or hillside section; by lowering the model roadway, cut sections were also simulated. The model cars and trucks were mounted on belts of two different spacing configurations: high density of an average spacing of two car lengths, and a low-density spacing of four car lengths.

Capillary tubes were used at 20 locations to sample the air near the roadway for pollutant concentrations. The He concentration in each sample was then determined with a He-leak detector, modified to provide a direct reading of the concentration.

TURBULENCE DATA

Values of the total (i.e., three-component) intensity of turbulence (TTI) from the US-101, grade-level roadway experiment were compared at each of several heights among near-upwind, median, and near-downwind sensor locations. As used here, TTI is defined as

$$\mathrm{TTI} \equiv \left[\overline{(u')^2 + (v')^2 + (w')^2}\right]^{1/2} \qquad (1)$$

where

u = the longitudinal wind component,
v = the lateral wind component, and
w = the vertical wind component.

The prime notation denotes the departure from the period average; the overbar denotes the period average of the function. The south-to-north turbulence gradient [ΔTTI ≡ TTI (north) - TTI (south)] between sensors 10.5 m from either edge of the roadway ranged from +0.50 to -0.50 m/s at the 2.0-, 3.8-, and 7.5-m levels with southerly and northerly winds, respectively; at 14.2 m, the range was ±0.35 m/s. When ΔTTI is normalized by dividing by the upwind turbulence intensity at corresponding heights, the range of maximum normalized gradients has a similar height dependence: ±1.5 at 2 m; +2.0 to -1.0 at 7.5 m; and ±0.75 at 14.2 m. Similar comparisons made among the upwind (near-roadway) values and the turbulence data measured in the roadway median show this median-upwind gradient to range up to -1.10 m/s at 2 m, to -1.20 m/s at 3.8 m, and to -0.60 m/s at 7.5 m (see Figure 3).

The turbulence data were also grouped into six wind-direction categories and correlated with various independent traffic and meteorological variables; 13 independent variables were defined using the following basic parameters:

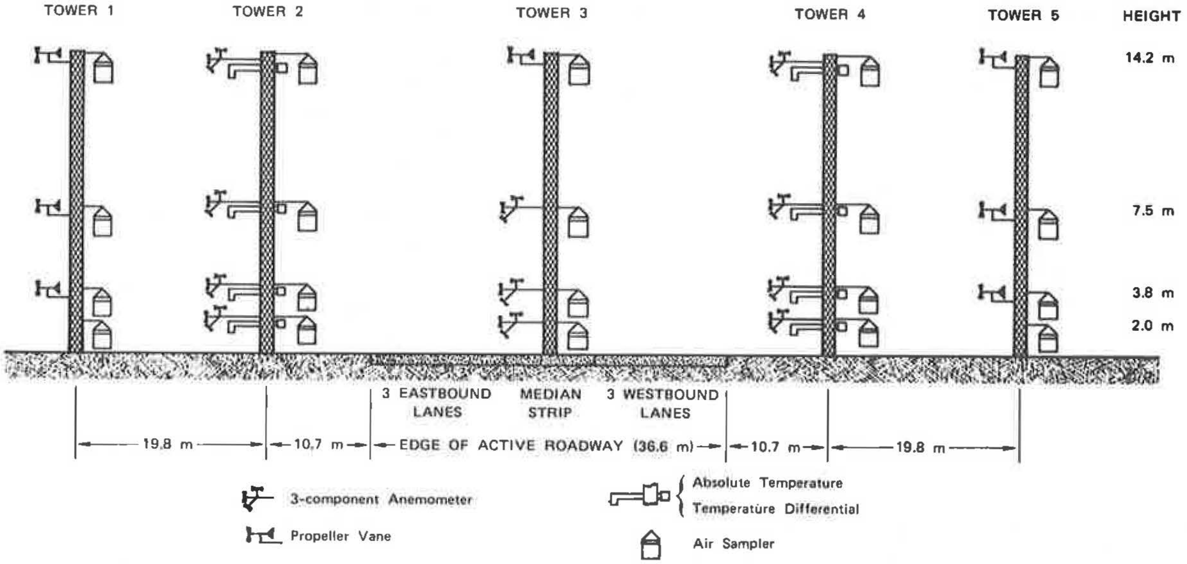
1. Upwind turbulence intensity,
2. Upwind wind speed,
3. Cross-roadway wind speed component,
4. Cross-roadway temperature gradient,
5. Vehicle volume,
6. Vehicle speed, and
7. The computed vehicle drag-induced ambient flow.

The south-to-north turbulence gradient correlated consistently over the six wind-direction categories with only one parameter, the south-to-north temperature gradient. Even so, the average correlation coefficient of 0.55 (and 0.40 for normalized ΔTTI) is not particularly significant. The average correlation for winds ≥ 45° to the road increased to 0.68 for the normalized turbulence gradient and remained at 0.55 for the nonnormalized gradient. The upwind-median gradient of turbulence correlated consistently with only the upwind wind speed (u_{ref}). The average correlation coefficient for TTI and u_{ref} was 0.47 for all categories and only 0.32 for winds ≥ 45° to the road. The normalized TTI correlated with u_{ref} at 0.56 for all directions and at 0.51 for the more oblique directions.

TEMPERATURE DATA

Temperatures measured 10.5 m from either edge of the roadway at the grade-level site showed significant cross-roadway gradients [ΔT ≡ T(north) - T(south)]. At the 2-m level, south-to-north gradients ranged up to 2.5°C for southerly winds and up to -1.5°C for northerly winds. At 3.8 m, ΔT ranged from +1.5° to -0.75°C for northerly and southerly winds (Figure 4), respectively, and at 7.5 m the range was +0.75° to

Figure 2. Aerometric instrumentation layout at grade-level test site.



NOTE: Additional air samplers located at ground level on both sides of road beyond towers at 15.2 m intervals to 91.5 m from roadway edges.

Figure 3. Wind directional variation of the normal upwind-minus-median turbulence intensity.

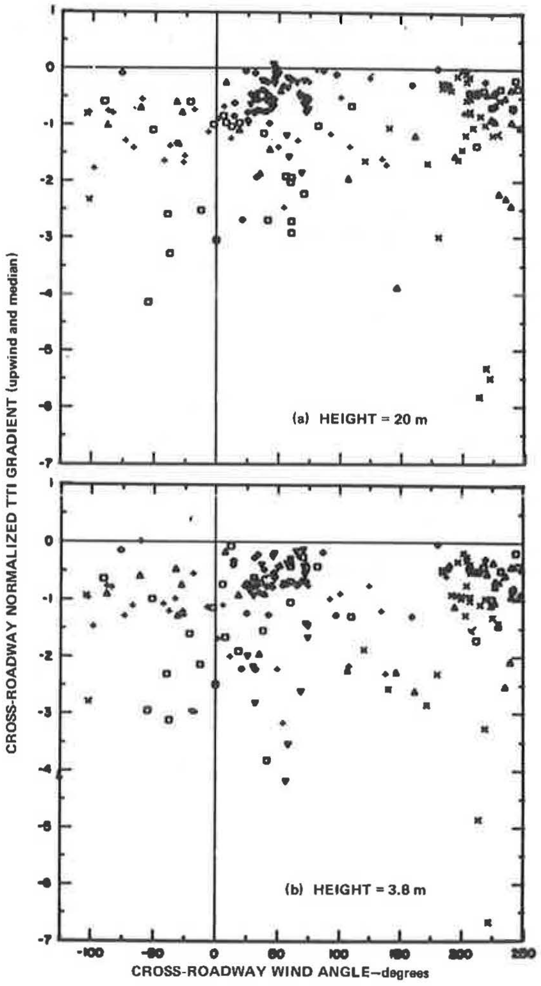
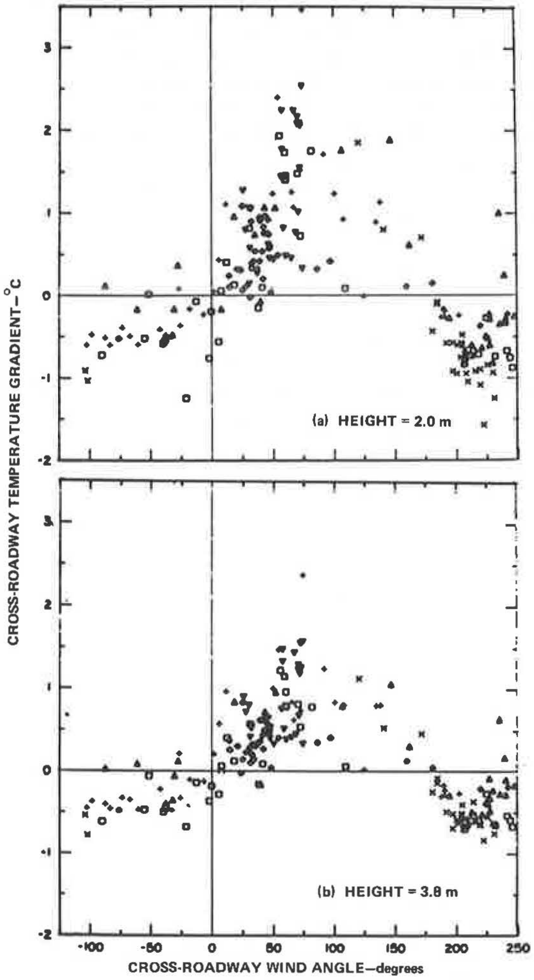


Figure 4. Variation of cross-roadway temperature gradient with wind direction.



-0.4°C. The temperature gradient data were stratified into six 15° (arc) categories according to the absolute value of the angle between the wind vector and the roadway bearing. The ΔT data were then correlated within each of the six categories with each of six independent variables:

1. Upwind turbulence intensity,
2. Cross-roadway wind speed,
3. The product of 1 and 2,
4. Vehicle volume,
5. The product of vehicle volume and speed, and
6. The quotient of 5 and 3.

The only consistently significant linear correlation coefficient ($\bar{r} = 0.71$) was with the cross-roadway wind speed (u_{road}). A scatter plot of ΔT versus u_{road} shows that at low wind speeds, T increases with increasing u_{road} values.

The near-roadway vertical temperature data are important for two reasons: (a) they provide an indication of the thermal stability of the air near the roadway and thus serve to describe the diffusion characteristics of the air into which vehicular pollutants are emitted; and (b) they serve as a tracer of vehicle pollutant emissions. Before the full utility of the temperature data can be assessed, it is necessary to understand the causes of the observed cross-roadway temperature gradients. Three processes are potential contributors: (a) vehicle waste heat emissions; (b) differences in the atmospheric sensible heat flux among the clay soil of upwind fetches and the concrete and asphalt surfaces of the eastbound and westbound lanes, respectively; and (c) vertical mixing induced by air flow over the traffic stream and the subsequent transport of heat to (inversion conditions) or away from (lapse conditions) the ground.

To aid this analysis and understanding, the vertical temperature profile data have been examined in more detail. First, the 15-min vertical wind profiles for the near-roadway upwind tower were analyzed to obtain eddy diffusivity values (K, cm^2/s). Because of the relatively few anemometers and the possible influence of traffic and other local surface discontinuities, the eddy diffusivity for momentum (K_m) was estimated from the value of the friction velocity (u^*, cm/s) obtained from the logarithmic wind profile equations,

$$u^* = k \cdot z(\Delta u/\Delta z) \tag{2}$$

and

$$K_m = ku^*z \tag{3}$$

where

k = the Karman constant (0.43),

u = wind speed, and
z = height.

Next, the atmospheric sensible heat flux density [H, $(J/cm^2)/s$] upwind of the roadway was computed:

$$H = -\rho c_p K_h [(\Delta T/\Delta z) + \Gamma] \quad (4)$$

where

ρ = density (g/cm^3),
c_p = the specific heat at constant pressure [(1.00 J/g)/°C], and
Γ = the dry adiabatic lapse rate (9.8°C/km).

The eddy diffusivity for heat (K_h) has been assumed to equal that for momentum.

The significance of the effect of vertical mixing over and downwind of the roadway on the cross-road temperature gradient is clarified by examination of the ambient heat flux data. ΔT values were consistently greater with southerly winds; 72 percent of the south-wind cases occur under stable atmospheric conditions. Thus, on the downwind side, the effect of enhanced vertical mixing over the roadway is to increase temperatures near the surface and, as a result, increase the cross-road temperature gradient. With northerly winds, lapse conditions dominate (84 percent), and the mixing decreases temperatures near the surface downwind of the road and also decreases the ΔT values.

To summarize, the effect of vehicle-induced vertical mixing is to increase the magnitude of the cross-road temperature difference under stable conditions and to decrease the difference under lapse conditions. But this effect only moderates the magnitude of ΔT. The source of heat, however, must be either the vehicles or the roadway pavement. If the latter effect dominates, then warmer temperatures should occur downwind part of the day and cooler temperatures should occur at other times (provided the daily average surface temperature is the same for pavement and soil—a reasonable assumption). This type of diurnal pattern is not observed. To understand the significance of vehicle waste heat emissions, the waste heat flux density averaged over the roadway-median area was computed and evaluated against ambient fluxes.

Waste heat emissions from automobiles have been estimated on the basis of the fuel consumption rate for steady driving. Motor gasoline has an energy equivalent of about 3.46×10^7 J/L; it is assumed that 85 percent of the energy is released as sensible heat. Thus, for cruise speeds below 64 km/h, the waste heat emission rate per vehicle is 3.46×10^6 J/km; above that speed, the heat emission increases at a rate of 2.279×10^4 $(J/km^2)/h$. The resultant heat flux density is then given as the product of the speed-dependent emission rate and vehicle volume divided by the roadway width (36.6 m, including median). The vehicle heat emission rate is generally in the range of 1.4 to 2.1×10^2 W/m^2, with a peak value of 2.5×10^2 W/m^2; for comparison, the peak solar flux density is 5.5×10^2 W/m^2, while the ambient sensible fluxes are generally a factor of five less than the vehicle fluxes.

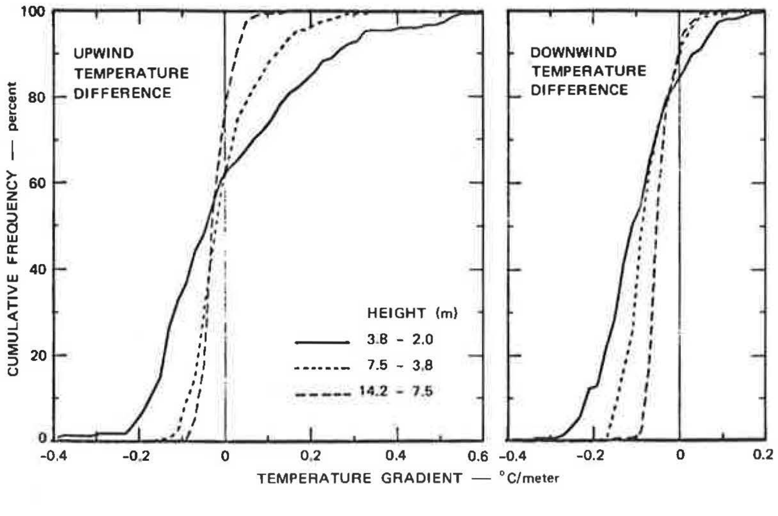
To further understand the implications of these data, the magnitude of the temperature lapse rates that result from the vehicle heat emissions alone was estimated using Equation 4. The eddy diffusivity above and close to the roadway surface was assumed to be caused primarily by the effect of vehicle motions. Considering K as the product of a turbulent velocity (V_*) and a characteristic length scale (ℓ), we let V_* equal the vehicle speed and ℓ equal the square root of the vehicle frontal area ($\ell \approx 2$ m). Temperature lapse rates estimated this way are generally in excess of the autoconvective lapse rate. It is unrealistic to exclude the advection of sensible heat from the regions upwind of the roadway. To estimate the combined effects of ambient and vehicular heat fluxes and diffusivities, the arithmetic sum of each was computed to obtain a net vertical temperature gradient from Equation 4. The combined effect is to further enhance instability by day; even for most periods of stable ambient conditions (except when traffic volumes are very low), the vehicle heat emission is sufficient to create an unstable state over the roadway.

These findings are confirmed by the observational data given in Figure 5, where cumulative frequency distributions of the vertical temperature differences (2 to 3.8 m, 3.8 to 7.5 m, and 7.5 to 14.2 m) are given for both the upwind and downwind sides of the road. The decrease in stability downwind of the roadway is apparent at all levels, though most pronounced near the surface.

DISCUSSION

The wind and turbulence data are harder to interpret than either the temperature or tracer gas data. The wind and turbulence data are more influenced by local effects and thus may not provide a true picture of the general flow regime. The apparent dichotomy of the

Figure 5. Cumulative frequency distributions of vertical temperature gradients.



turbulence observations is that, although turbulence levels are enhanced significantly by the roadway, they are not correlated with traffic parameters. This suggests that either the turbulence generation mechanism is insensitive to traffic volume and speed variations over the ranges observed or other effects need to be considered; in fact, both concepts may be true.

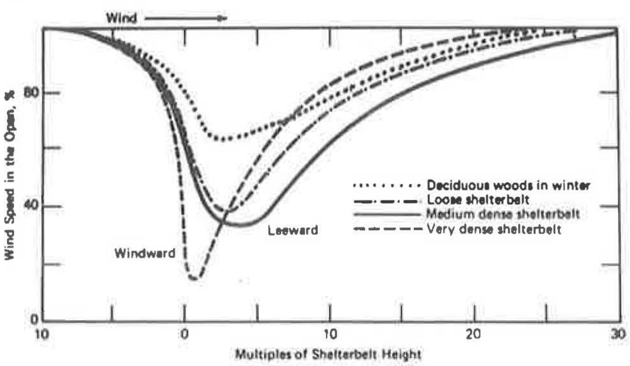
Further examination of the tracer dispersion data supports the traffic-insensitivity concept. Differences in the dispersion from the upwind and downwind lanes do not correlate significantly with any of the traffic or meteorological parameters tested. Yet the individual dispersion coefficients from both traffic streams correlate well with meteorological parameters alone, as shown in Table 1. But the individual dispersion coefficients do not correlate well with traffic parameters alone and the correlation with the meteorological parameters is not enhanced by the inclusion of traffic volume or vehicle occupancy. Furthermore, the dispersion values correlate negatively with vehicle volume and occupancy alone.

Considering the dispersion of the exhaust gases of a single isolated vehicle, the tailpipe emissions are entrained and rigorously mixed within the wake behind the vehicle. At the same time, the aerodynamic drag of the vehicle imparts a mean flow in the direction of the vehicle movement. Thus, we can hypothesize that the effect of the vehicle motion is primarily to disperse the emissions in a plane oriented vertically and parallel to the roadway. (Some lateral mixing occurs because of the streamline divergence of the flow about the vehicle. The extent of this region is on the order of one obstacle width for fully turbulent atmospheric flow about a stationary bluff body. The net effect for a multilane roadway, however, would appear to be minimal.) The vehicle-induced vertical mixing does affect the concentration. The remaining question is whether the presence of multiple vehicles in longitudinal proximity increases the vertical extent or intensity of the vertical dispersion. Based on the turbulence and tracer-dispersion observations, the implication is that there is not such amplification that is dependent on either vehicle spacing (i.e., volume) or speed. Measurements at this field site failed to indicate any influence of vehicle speed on turbulence and downwind dispersion. The role of such turbulence appears to be largely to mix the air in the vertical space above the pavement. Wind tunnel experiments, however, showed about a 10 percent increase in air pollutant dispersion as vehicle speed increased from 2 to 20 km/h, and about a 7 percent increase as the speed increased from 20 to 80 km/h.

Table 1. Matrix of correlation coefficients.

	Dependent Variables	
Independent Variables	σ Upwind	σ Downwind
σ_θ/u_{road}	0.84	0.87
σ_ϕ/u_{road}	0.84	0.90
Traffic volume (Vol)	-0.43	-0.42
Vehicle occupancy	-0.43	-0.40
Vol × σ_ϕ/u_{road}	0.84	0.90
σ_θ/vol × u_{road}	0.52	0.48

Figure 6. Sheltering at different porosities.



This suggests that while the turbulence generated by a second automobile may further mix the pollutants emitted by a first automobile, the wake of the first automobile may already be thoroughly mixed such that the further mixing has no effect on the concentration; and the turbulence in the wake of the first automobile is normally sufficiently damped so that there is no dynamic interaction with the wake of the following automobile that could lead to an increase in the depth of the mixed zone. However, the mean depth of the mixed zone is a function of vehicle density and speed insofar as these factors affect the thermal instability over the roadway. As vehicles are in disturbed zones of one another, the drag and turbulence intensity per vehicle decrease.

The lateral (i.e., cross-roadway) dispersion is apparently not enhanced by increasing vehicle density or speed. However, consideration of the static effect that a wall of vehicles imparts on the cross-roadway wind and turbulence structure and subsequently on the cross-roadway pollutant dispersion may be necessary. Heretofore this shelterbelt effect has not been considered in understanding near-roadway dispersion. Several studies (1) have been made of the effects of shelterbelt porosity on both the magnitude and extent of the wind speed reduction; Figure 6 illustrates the sheltering at different porosities. The maximum velocity reduction at a single point occurs with a near-solid obstruction, and the maximum sheltering (i.e., spatial integral of velocity deficit) has been observed with porosities of 30 to 50 percent.

The accompanying shear in the mean vertical gradients of velocity enhances the turbulent wind fluctuations and the net transfer of momentum and mass. Plate (2) reports that the intensity of turbulence in the blending region (i.e., the leeward zone where the ambient and disturbed flows merge) increases at a rate proportional to $(u_\infty^2 - u_b^2)(u_\infty - u_b)$, where u_∞ is the ambient cross-shelter wind speed and u_0 is wind speed through a porous shelter. Figure 6 shows that the following peak turbulence levels are likely to result:

Shelter Type	Approximate Porosity (%)	Approximate Density (%)	Relative Turbulence Intensity (%)
Solid wall	0	100	100
High density	25	75	83
Medium density	50	50	57
Low density	75	25	53

As an approximation, turbulence levels in the lee of a stationary shelter having an effective porosity typical of that for a heavily traveled roadway may be about one-half those in the lee of a solid wall. For low- to medium-density shelters, turbulence values are relatively insensitive to porosity changes.

These shelterbelt concepts are useful, inasmuch as they provide some insight into the dispersion effects generated by simple, stationary obstructions. The roadway situation is more complex for several reasons, particularly because the drag flow created by traffic motion makes the problem three-dimensional and the relatively simple picture given above may not strictly apply. Analysis of these effects is incorporated implicitly into the ROADMAP dispersion methodology, together with the effects introduced by the configuration of the roadway.

ROADMAP

The foundation of the ROADMAP model is the approach used to represent the dispersion of pollutants from an extended line source (end effects are not considered). The model treats the total dispersion as the vector sum of two components: one is the dispersion along the horizontal wind component perpendicular to the roadway, the other is the dispersion along the horizontal wind component parallel to the roadway:

$$\chi_T U/Q_\ell = \vec{i}\,(\chi_n u/Q_\ell) + \vec{j}\,(\chi_p v/Q_\ell) \qquad (5)$$

where

$\vec{i}$ = unit vector normal to roadway,
$\vec{j}$ = unit vector parallel to roadway,
U = vector wind speed (m/s),
u = wind component normal to roadway (m/s),
v = wind component parallel to roadway (m/s),
Q_ℓ = line source emission flux density [(g/m)/s],
χ_T = total pollutant concentration (g/m^3),
χ_n = concentration from lateral dispersion (g/m^3), and
χ_p = concentration from longitudinal dispersion (g/m^3).

When Θ is introduced as the angle between the longitudinal axis of the line source and the wind vector, then

$$u = U \sin \Theta \qquad (6)$$

and

$$v = U \cos \Theta \qquad (7)$$

Substituting Equations 6 and 7 into Equation 5 and squaring both sides,

$$(\chi_T U/Q_\ell)^2 = (\chi_n U \sin \Theta/Q_\ell)^2 + (\chi_p U \cos \Theta/Q_\ell)^2 \qquad (8)$$

For convenience, the first right-hand term in Equation 8 is designated the perpendicular term and the second is called the parallel term.

The form of the perpendicular term is specified in analogy to the Gaussian line source equation for a perpendicular wind,

$$\chi_n U/Q_\ell = \sqrt{2/\pi}/k\sigma_z \Big(\exp\{-\tfrac{1}{2}[(z + z' - H)/\sigma_z]^2\} + \exp\{-\tfrac{1}{2}[(z + z' + H)/\sigma_z]^2\}\Big) \qquad (9)$$

where

k = constant ($H = 0$, $k = 2$; $H \neq 0$, $k = 1$),
σ_z = vertical Gaussian dispersion function (m),
z = height above grade level or above roadway (i.e., depressed section) (m),
z' = height offset from plume rise (m), and
H = roadway height above grade level (m).

A unique feature of Equation 9 is the term z', which serves as a height-modifier to represent the possible change in the height of the plume centerline as a function of distance downwind. This offset could result either from the aerodynamic influence (i.e., shelterbelt) of the traffic stream or from the buoyancy effect of vehicular waste heat emissions. In principle, both σ_z and z' may vary both with distance (x) away from the roadway and atmospheric stability, but not with height.

The parallel dispersion term was formulated to represent the general features of the Gaussian point-source equation when the latter is integrated for a wind aligned parallel to a semi-infinite line source (4). The resulting formulation may be thought of as a type of expanding-box model, where the sides and top of the box are given as exponential functions of height (z) and cross-roadway distance (x). The form chosen assumes the same functional dependence on height as the perpendicular term, but a different cross-roadway dispersion representation (f),

$$\chi_p U/Q_\ell = 1/k\sigma_{z-0}\, f\Big(\exp -\tfrac{1}{2}\{[(z + z' - H)/\sigma_z]^2\} + \exp\{-\tfrac{1}{2}[(z + z' + H)/\sigma_z]^2\}\Big)' \qquad (10)$$

where

$\sigma_z = \sigma_{z\text{-}o} + a_1 x^{b}1$,
$z' = z'_o + a_2 x^{b}2$,
$f = a_3(c_3 + 2x/W)b_3$, and
W = roadway width (m).

When the model is applied to both traffic streams, W is defined as the total roadway width (i.e., from shoulder to shoulder). On the other hand, physical separation of the traffic streams or marked dissimilarities in the traffic volumes (and hence emissions) may suggest application of the model separately for each direction. In this case, W would, of course, be redefined accordingly.

Model Evaluation Procedure

A least squares technique was used to estimate the coefficients of the model. Suppose the generalized nonlinear equation is of the form

$$Y + f(X_1, X_2, \ldots, X_K, \beta_1, \beta_2, \ldots, \beta_p) \qquad (11)$$

where f is a nonlinear function of k independent variables $X_1, \ldots, X_K$ and p coefficients $\beta_1, \ldots, \beta_p$. We want to choose estimated values of the coefficients such that the sum of squared errors is minimized. If we have T observations on Y, $X_1, \ldots, X_K$, then the sum of squared errors is

$$S = \sum_{t=1}^{T} [Y_t - f(X_{1t}, \ldots, X_{Kt}, \beta_1, \ldots, \beta_p)]^2 \qquad (12)$$

To minimize S with respect to the β's, we differentiate the right side of this equation with respect to each coefficient and set the derivatives equal to 0:

$$\sum_{t=1}^{T} 2[Y_t - f(X_{1t}, \ldots, X_{Kt}, \beta_1, \ldots, \beta_p)]\, \partial f/\partial\beta_i = 0, \text{ for } i = 1, \ldots, p \qquad (13)$$

Rather than solving these equations simultaneously, the statistical package for the social sciences (SPSS) program (5) employs the steepest-descent method, an iterative process, to find the minimum value of S. This method moves from one set of coefficient values for $\beta_1, \ldots, \beta_p$ to a new set in such a way that the derivatives (calculated numerically) $-\partial S/\partial\beta_1, \ldots, -\partial S/\partial\beta_p$ are as large as possible, so that those values of $\beta_1, \ldots, \beta_p$ that minimize S are reached rapidly.

Two potential pitfalls exist with this method: (a) the minimum value of S found may be a local rather than a global minimum and (b) the coefficient estimates may not converge at all. Because of the form of the partial derivatives, it may be impossible to obtain coefficient estimates that represent even a local minimum of the sum of squared errors.

The only measure of the efficiency of the solution provided by the SPSS program (aside from the explained variance) is the number of digits of accuracy (d). Let $\Phi(\beta)$ be the sum of squared errors at the point $\beta = (\beta_1, \ldots, \beta_p)$. A point $\beta^* = (\beta_p^*, \ldots, \beta_p)$ is a d-digit solution if $\Phi(\beta^*) < \Phi(\beta)$ for all β that satisfy: $10^{-d} < \mathrm{rel}_{AX}(\beta^*, \beta) \leq 10^{-d+1}$, where

$$\mathrm{rel}_{AX(\beta^*,\beta)} = \max_{1 \leq i \leq p} \{ (|\beta_i^* - \beta_i|) / [\max(|\beta_i^*|, |\beta_i|, AX)] \} \qquad (14)$$

In the runs of the program to estimate the model, AX was set equal to 0.1 and d equal to 3. When a three-digit solution is impossible because of rounding errors or the nature of the model, the program stops and prints an accuracy estimate with the final coefficients.

In practice, the procedure to evaluate the nine coefficients of the model ($a_1, b_1, \sigma_{z\text{-}o}, a_2, b_2, z_o', a_3, b_3,$ and c_3) consists of the following four steps:

1. Step 1—The experimental tests are first stratified according to atmospheric stability. All wind tunnel tests are representative of neutral conditions. The atmospheric tests include stable, neutral, and unstable conditions.
2. Step 2—Coefficients $a_1, b_1, \sigma_{z\text{-}o}, a_2, b_2,$ and z_o' are estimated using Equation 9 and those test data with near-orthogonal wind-roadway angles (Θ). For the wind tunnel tests, Θ values $\geq 60°$ are used, and for the atmospheric tests $\Theta \geq 63°$. The variance (R^2) explained by the estimated coefficients and Equation 9 are also determined for the large-Θ cases.
3. Step 3—Next, coefficients $a_3, b_3,$ and c_3 are estimated using Equation 10, the other coefficient estimates from Step 2, and those test data with near-parallel wind-roadway angles. For the wind tunnel tests, Θ-values $\leq 15°$ are used; for the atmospheric tests $\Theta \leq 24°$. Again, R^2 is determined.
4. Step 4—Equations 9 and 10 are substituted into the general model form, Equation 8, together with the nine coefficient estimates from steps 2 and 3. In this way, the component ROADMAP model is used to predict normal concentrations for all observed data. Observations and predictions are then compared for all data, as well as for various subsets including those cases not included in the coefficient estimates of steps 2 and 3; the latter provide an independent test of ROADMAP performance.

Model Performance

Step 4 of the model evaluation procedure provides the basis for an independent test of ROADMAP. In this step, the dispersion coefficients estimated from the near-parallel and near-perpendicular wind direction cases are used in the model to predict normal concentrations at each of the downwind sampling locations. This procedure is applied to all wind tunnel and atmospheric tests. The stability for all wind tunnel tests is neutral, whereas the atmospheric data include diabatic conditions as well.

Three meteorological parameters measured upwind of the roadway are used to classify stability for the grade-level test data; unfortunately, none of the three is consistently successful by itself and it is necessary to consider the three jointly. The three parameters used included: (a) standard deviation of the horizontal wind direction (σ_Θ), (b) standard deviation of the vertical wind direction (σ_ϕ), and (c) gradient Richardson number (Ri). As only 45 h of data were available at the grade-level site, it was necessary to stratify the data into three broad stability classes, simply referred to as unstable, neutral, and stable. Tabulated below are the ranges of each parameter for each stability class:

Class	Number of Hours	$\sigma(e)$ (degrees)	$\sigma(\phi)$ (degrees)	Ri, n.d.
Unstable	9	16.8 to 40.9	7.4 to 22.2	-4.61 to -0.03
Neutral	17	5.6 to 15.6	2.9 to 12.5	-0.83 to 0.37
Stable	7	17.1 to 47.9	4.4 to 24.0	0.00 to 0.12

In addition to using these three parameters in an objective way, qualitative use was made of the temperature lapse rate, time of day, and cloud cover in assigning the hourly periods to the three stability classes. Even so, 12 h did not fit even these loose criteria and were not included in the analysis.

Before testing the model's performance, two aspects of the stability categorization should be stressed, particularly as stability is an important determinant of the dispersion process. First, the values of σ_Θ for stable conditions are very large, ranging from 17° to 48°. Much larger, for example, than the usual range of 5° to 10° reported in the air pollution literature (6). Note, however, that the accompanying wind speeds were very light (in the range of 1-3 m/s) and that a slow meander of the wind direction is common under these conditions. Second, the large magnitude of these horizontal wind fluctuations has no appreciable effect on dispersion from an extended line source with an oblique wind direction. But when the wind is near-parallel to the roadway, the effect is to significantly enhance the lateral dispersion and reduce the pollutant concentrations well below what would be estimated using the standard range of σ_Θ. This is a particularly significant aspect of line-source dispersion and the accurate assessment of σ_Θ is critical for wind directions with a significant component parallel to the roadway.

The results of the ROADMAP evaluation are summarized in Table 2 for each of seven cases of atmo-

Table 2. Summary of ROADMAP evaluation with independent data from atmospheric and wind tunnel experiments.

Test Description	θ-Range (degrees)	Number of Data Periods	Number of Data Points	Statistics			
				r	r^2	m	s
Atmospheric tests							
Grade-level, neutral stability	19 to 62	6	90	0.908	0.824	0.084	1.06
Grade-level, stable atmosphere	≤68	5	75	0.666	0.444	0.000	0.51
Grade-level, unstable atmosphere	25 to 66	5	75	0.803	0.645	0.035	0.71
Wind tunnel tests							
Vertical-wall cut	30	4	60	0.692	0.479	0.076	0.71
Slant-wall cut	30	4	60	0.836	0.699	0.054	0.50
Fill section	30	4	60	0.934	0.873	-0.011	2.42
Viaduct section	30	4	60	0.917	0.841	-0.010	2.57

Notes: r = linear correlation coefficient.
r^2 = fractional variance explained.
m = regression intercept (m^{-1})
s = slope of linear regression

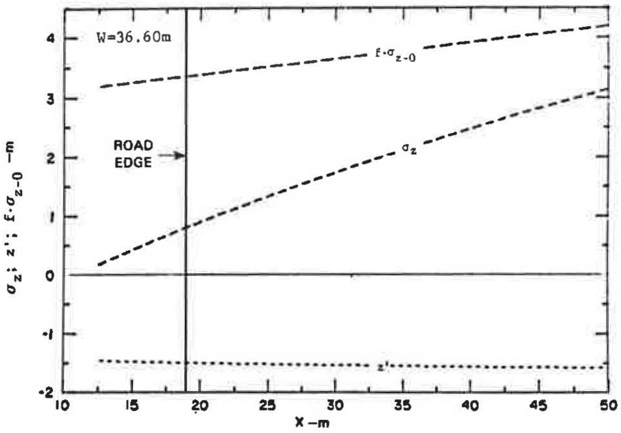
$$\left.\begin{array}{l} m \\ s \end{array}\right\} \left(\frac{\chi u}{Q}\right) = m + s\left(\frac{\chi u}{Q}\right)_{calc}$$

spheric stability and roadway configuration. The results are very encouraging, although it would be both informative and constructive to test the model with a larger data set as well as with data from other, similar sites.

Dispersion Patterns

The derived dispersion coefficients (σ_z, z', and $f\sigma_{z\text{-}o}$) and the model provide an effective means for synthesizing ing the dispersion characteristics of the test data and for obtaining a generic picture of the overall dispersion pattern. Figure 7 shows the variation of the three dispersion coefficients with distance from the roadway. These curves were derived from the CO concentration data; as the evaluation process does not consider variations in CO emission rates among the six lanes (or two directions either), it is not appropriate to attach significance to those portions of the curves that extend over the roadway surface. Perhaps most significant is the sign and magnitude of the z' term. The nearly constant and negative value indicates that the centerline of the exhaust plume is found about 1.5 m above ground downwind of the roadway. This lifting of the plume may reflect the impact of either the waste-heat or shelterbelt effects discussed earlier.

Figure 7. ROADMAP dispersion parameters—grade-level roadway, smooth terrain, and neutral atmospheric conditions.



The dispersion coefficients illustrated in Figure 7 have been used as input to ROADMAP to construct isopleths of normal pollutant concentrations for joint variations in the wind-roadway angle (Θ) and road-receptor separation (x). Figure 8 is such a contour plot and is appropriate to neutral atmospheric stability and a 1-m receptor height. A noteworthy feature of the plot is the lack of a strong dependence of $\chi u/Q$ on Θ; as discussed earlier, this reflects the significant lateral diffusion that can occur as a result of wind meander, which thereby retards the increase in concentration levels when the wind direction becomes nearly parallel to the roadway. The contours obtained from computations made with the U.S. Environmental Protection Agency (EPA) HIWAY model are in contrast to this moderate Θ-dependence (see Figure 9). Not only is there a strong concentration gradient, but the HIWAY model also predicts significantly larger concentration levels than does ROADMAP. The difference between the two models can be explained by the height-offset term (z'), which is not a feature of other line-source models, such as HIWAY (1), as well as the large lateral dispersion values used in ROADMAP. When the HIWAY model was evaluated against the US-101 data, it consistently overpredicted (3) concentrations when the cross-roadway wind component was less than 1.5 m/s. We, therefore, conclude that the current

Figure 8. ROADMAP values of normal concentrations near ground level for at-grade roadway, smooth terrain, and neutral atmospheric stability.

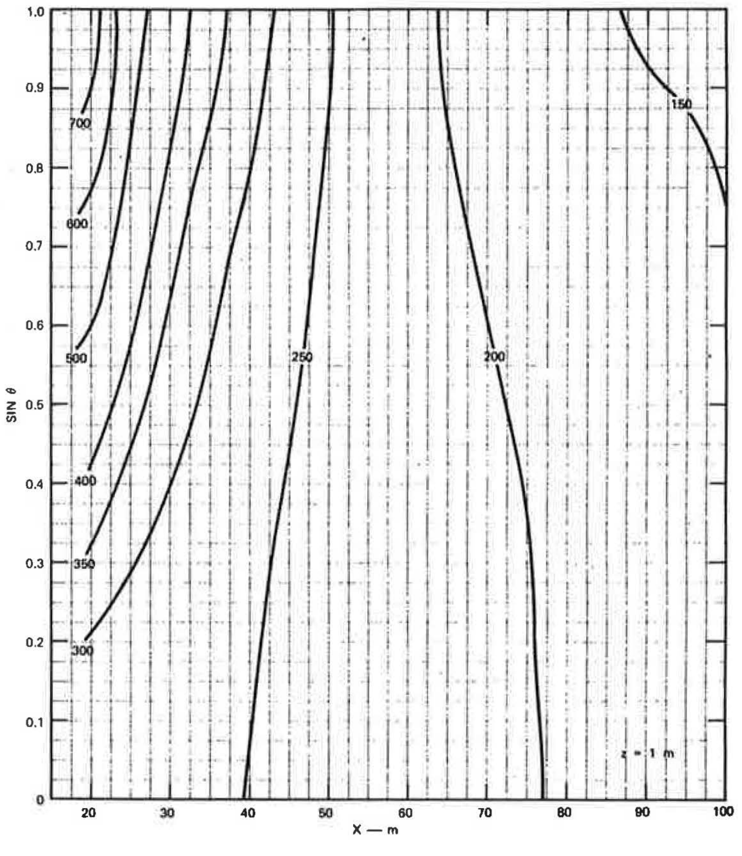


Figure 9. HIWAY values of normal concentrations near ground level for at-grade roadway, smooth terrain, and neutral atmospheric stability.

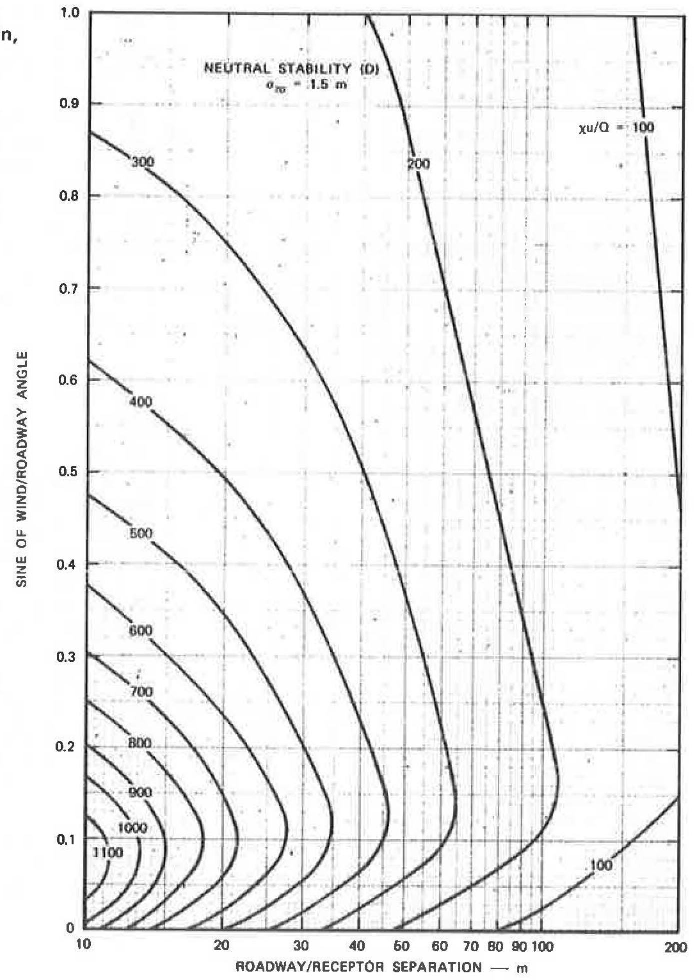
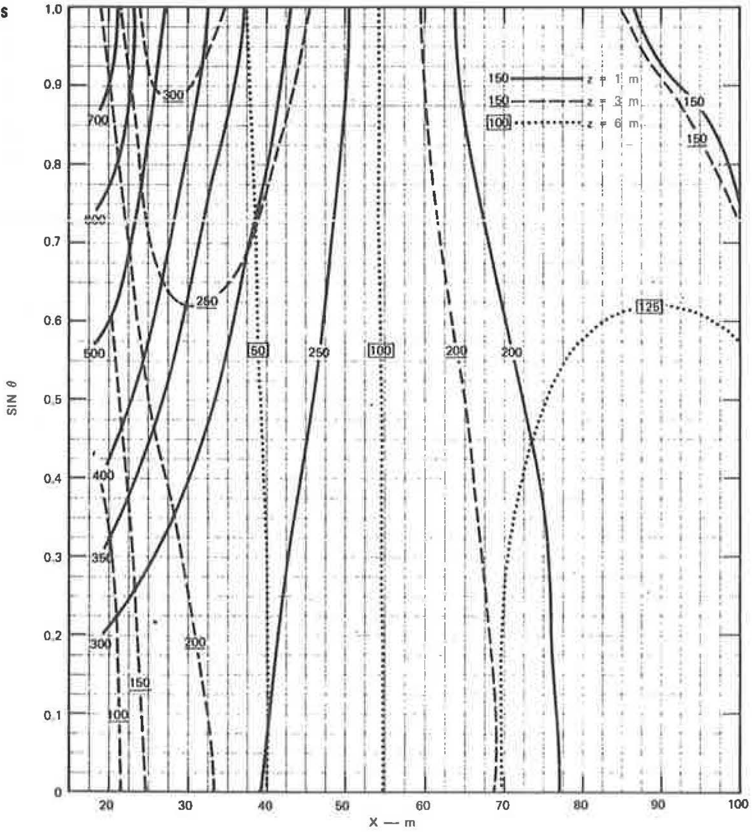


Figure 10. ROADMAP values of normal concentrations at three heights for at-grade roadway, smooth terrain, and neutral atmospheric stability.



body of data both indicates a better performance by ROADMAP, and implicitly supports the value of the concepts incorporated within the height-offset and lateral diffusion terms.

Applying ROADMAP to greater heights, we generate the composite contour plot seen in Figure 10. Using three different line types, the figure illustrates the isopleths of normal concentration at heights of 1, 3, and 6 m.

Wind Tunnel Data

Before exploring the implications of the wind tunnel tests, we first examine the representativeness of the data. That is, a comparison of the dispersion patterns obtained from the atmospheric study of US-101 with data from a comparable configuration in the wind tunnel is desirable. This scale model test was not intended to duplicate precisely the atmospheric test, and as such a few discrepancies are noted:

1. The scale model has four traffic lanes to six for the atmospheric site;
2. There is no azimuthal meander of the wind direction in the wind tunnel; and
3. The uniformity of the traffic speed, volume, and emissions is in distinct contrast to the atmospheric test conditions.

Figure 11 illustrates the variation of the three dispersion coefficients in the wind tunnel. The σ_z and z' terms are quite similar in shape and magnitude to the atmospheric equivalents shown earlier in Figure 7. In contrast, the lateral term ($f\sigma_{z\text{-}o}$) is markedly different: near the roadway edge it is very small, indicating high concentrations, but further away it increases rapidly, indicating a corresponding drop in concentration. This is consistent with the steady-wind concept (i.e., no meander). In the atmospheric test, $f\sigma_{z\text{-}o}$ is nearly independent of x, indicating a more uniform horizontal χ-distribution with parallel winds—typical of the meander concept.

The dispersion coefficients shown in Figures 7 and 11 are then used in ROADMAP to compute concentration values to compare objectively the dispersion patterns at 16 common receptor locations (see Figure 12). Comparisons were made over a 4 × 4-receptor matrix with z = 1, 2, 4, and 8 m and x = 20, 30, 40, and 50 m; two wind-roadway angles were considered: $\Theta = 0^\circ$ and 90°. Considering first the parallel wind situation, the atmospheric data yield an average $\chi u/Q$ of 0.14/m and the wind tunnel average is 0.124/m. Moreover, the higher-concentration receptors (i.e., small x and z) indicate wind tunnel concentrations about 60 percent greater than their atmospheric counterparts, but further away from the roadway the atmospheric values drop off very little in comparison to the wind tunnel concentrations, which rapidly approach zero. The low correlation value of 0.44 reflects this convolution. Referring to the oblique wind data, the average concentration is nearly two-thirds greater for the atmospheric data and the value of the linear correlation coefficient increases to a very significant 0.87. From these comparisons we conclude that the relative dispersion pattern given by the wind tunnel data is representative of atmospheric conditions when the wind-roadway angle has a strong oblique component, but the lateral dispersion is underestimated in the wind tunnel for near-parallel wind-roadway angles.

Configuration and Stability Effects

Figures 13 to 18 illustrate the x-dependence of the three dispersion coefficients for various roadway configurations and atmospheric stability conditions. Figures 13 and 14 represent the unstable and stable cases for the atmospheric, grade-level roadway experiment. Figures 15 through 18 are from the wind tunnel tests of four roadway configurations: vertical-wall cut, slant-wall cut, fill section, and viaduct section.

CONCLUDING REMARKS

A comprehensive series of atmospheric and wind tunnel aerometric experiments has provided new insights into the effects of vehicular traffic, meteorology, and roadway configuration on the microscale dispersion of vehicular emissions. When the roadway configuration is simple (i.e., smooth, grade-level configuration), two traffic-induced effects are important: (a) vehicular waste heat emissions and (b) the aerodynamic obstruction that the traffic stream presents to the wind flow. To account for these effects and those imparted by the roadway geometry, a new and simple empirical model called ROADMAP has been developed and evaluated. The model's performance and versatility have been shown to be quite encouraging; evaluations against independent data show correlation coefficients that range from 0.67 to 0.93 for a wide range of stability conditions and roadway configurations.

Figure 11. ROADMAP dispersion parameters—grade-level roadway and smooth terrain (wind tunnel test).

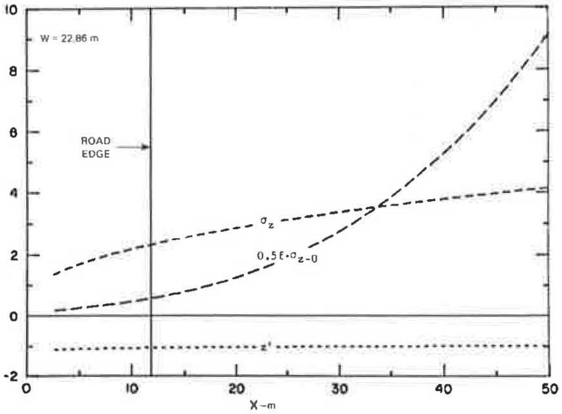
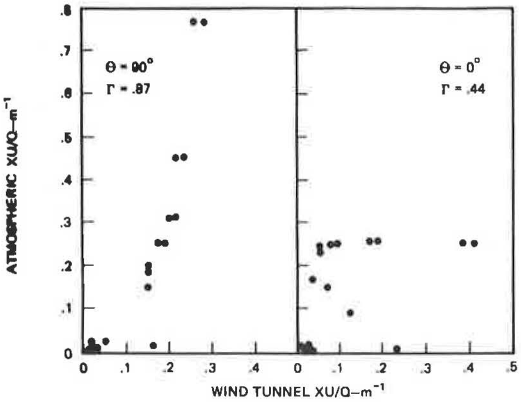


Figure 12. ROADMAP values of normal concentrations from comparable atmospheric and wind-tunnel analyses, neutral stability, and grade-level roadway.



ACKNOWLEDGMENTS

The research reported in this paper was supported by the Office of Research, Federal Highway Administration. The logistical support of the California Department of Transportation and EPA during the atmospheric tests is gratefully acknowledged. In addition, the invaluable and willing assistance of a number of Stanford Research Institute colleagues is greatly appreciated and acknowledged: C. Flohr, D. Marimont, R. Pozdena, R. Ruff, L. Salas, E. Shelar, and A. Smith. The wind-tunnel measurements were made by G. Ludwig and G. Skinner under a subcontract with Calspan Corporation, Buffalo, New York.

Figure 13. ROADMAP dispersion parameters—grade-level roadway, smooth terrain, and unstable atmospheric conditions.

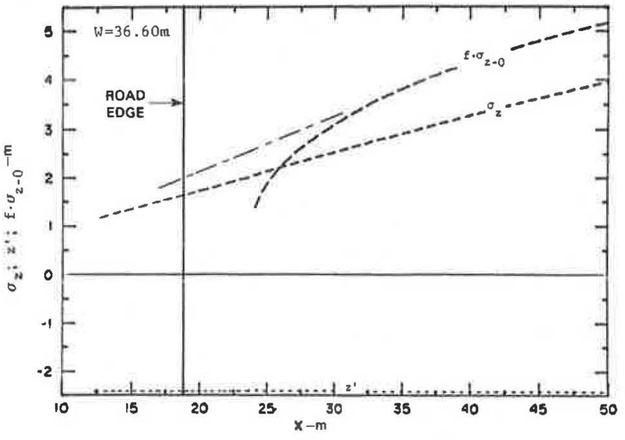


Figure 14. ROADMAP dispersion parameters—grade-level roadway, smooth terrain, and stable atmospheric conditions.

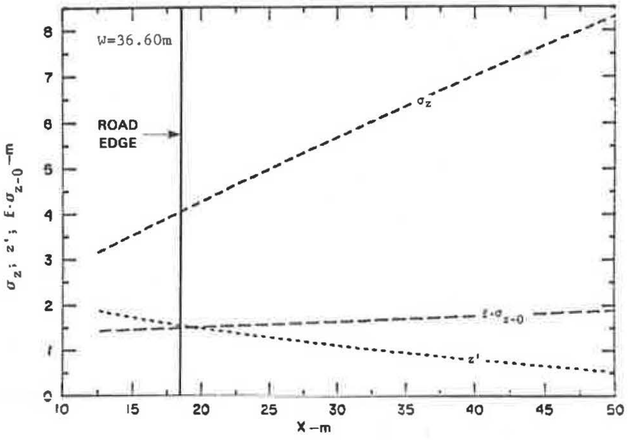


Figure 15. ROADMAP dispersion parameters—cut section with vertical walls and smooth terrain (wind tunnel test).

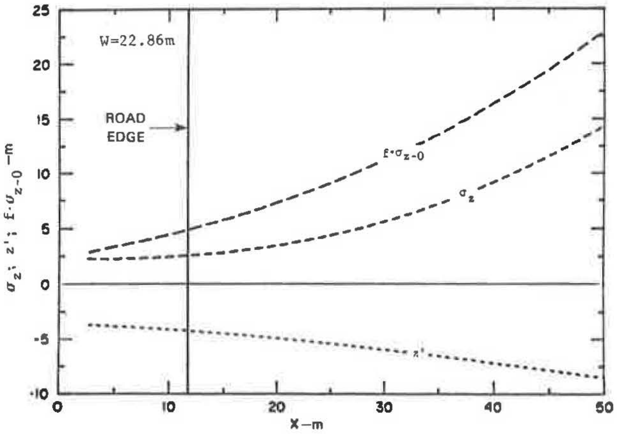


Figure 16. ROADMAP dispersion parameters—cut section with sloping walls and smooth terrain (wind tunnel test).

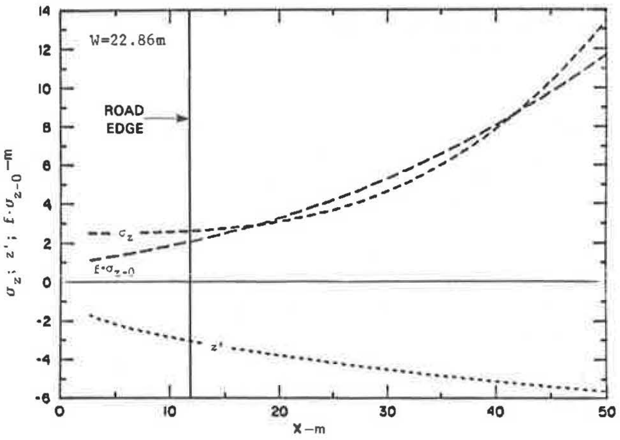


Figure 17. ROADMAP dispersion parameters—fill section and smooth terrain (wind tunnel test).

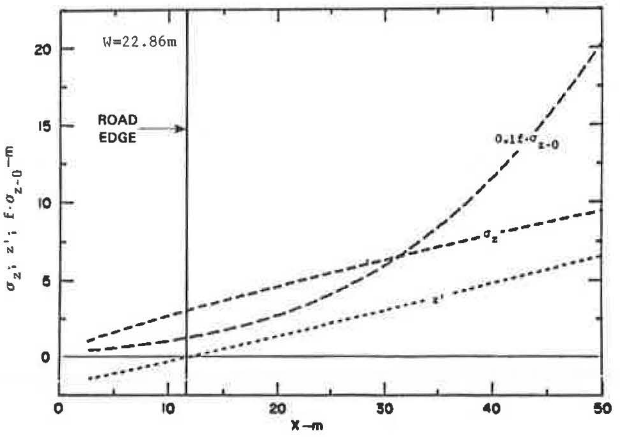
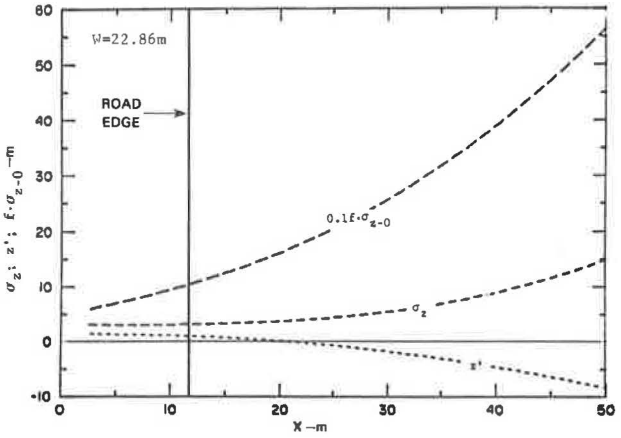


Figure 18. ROADMAP dispersion parameters—viaduct section and smooth terrain (wind tunnel test).



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Overview of the New York State Long Island Expressway Dispersion Experiment

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The objective of this investigation was to collect particulate, gaseous, micrometeorological, and traffic data adjacent to a major highway in a nonurban setting. The experimental site was on a section of the Long Island Expressway that is heavily traveled and where development adjacent to the roadway is relatively minor. The data base is useful for (a) documentation of the distribution of sulfate, lead, total particulate, and carbon monoxide levels at an array of sampling points near the highway; (b) study of the micrometeorological structure adjacent to the highway with special attention to those parameters that are important in the determination of sigma and stability values as well as highway-generated turbulence; (c) reevaluation of highway air pollutant emission factors from the data gathered on tracer gas experiments; and (d) validation of several highway dispersion models. The location of the site and data acquisition techniques are presented. The experimental design of the roadway diffusion study is described and some of the preliminary results of the tracer gas release experiments and sulfate and lead measurements are presented. The data collected in this investigation are being analyzed and a more comprehensive analysis will be presented elsewhere.

Mathematical modeling techniques are being employed to estimate the pollutant concentrations adjacent to highways. A number of mathematical models have been developed for the prediction of pollutant levels, but only a few experimental programs have been undertaken for establishing a sufficiently detailed data base (consisting of traffic, pollutant concentrations, and meteorological data) to be used for model verification. In recent years, such studies were conducted by Stanford Research Institute, General Motors Corporation, and New York State Department of Environmental Conservation. The General Motors study was a controlled experiment on a test track, whereas the Stanford Research Institute and New York State studies were carried out along major highways.

EXPERIMENTAL PROCEDURES

The site chosen on the Long Island Expressway (I-495) is about 25 km east of the city limits of New York City. Figure 1 is a map of the sampling area, which shows nearby residential areas and highways. Recent estimates of vehicles per day as reported by the Suffolk County Highway Department are indicated next to the highways. The area does not contain any major industrial centers; the nearest large point sources are 6 km to the southwest in Bethpage. The highway at the site is fairly flat and straight. The land to the north and the south of the site is a sod farm and is undeveloped and open. Because of the relatively undeveloped nature of the location, the high vehicle density, the flatness of the terrain, and the distance from other highways and point sources, this site closely approximates the assumptions common to all at-grade dispersion models.

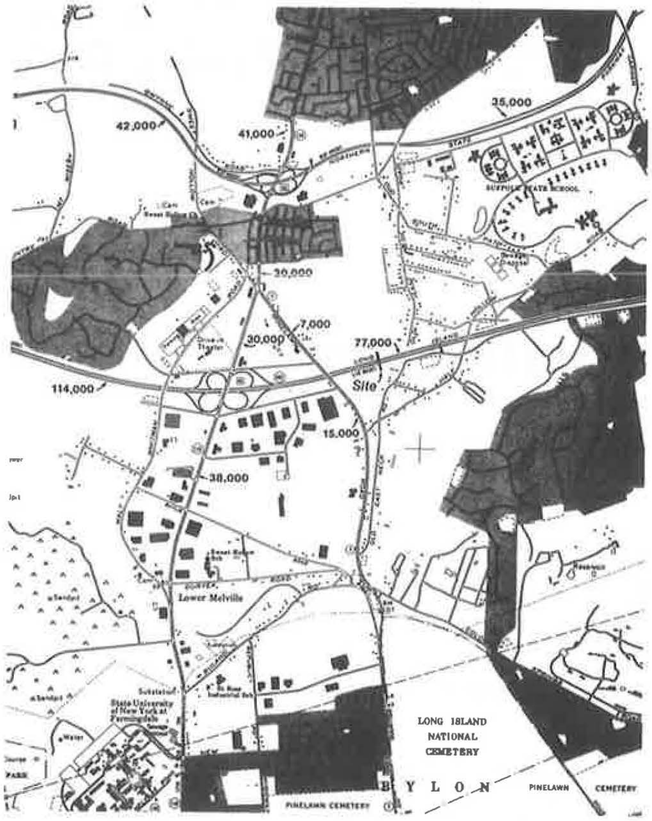
Data Collection and Equipment

A network of towers and sensors was designed and adapted for the project in order to collect data, both upwind and downwind, in a vertical plane perpendicular to the highway. Figure 2 shows the layout of these towers (looking west) and the specific location of air quality and meteorological measurements. A 12-m trailer that housed the instrumentation needed for this study was located about 100 m from the edge of the road and 20 m to the west of the sampling grid on the south side of the highway. This distance was necessary for minimal interference with the wind flow characteristics at the sampling plane. The trailer housed the data acquisition system, the necessary electronic equipment, pumps, carbon monoxide (CO) and meteorological data monitors, as well as heating and air conditioning units.

Particulate Measurements

Eight dichotomous samplers, manufactured by the Environmental Research Corporation, were employed to sample ambient particulates in two size ranges—greater than 3.5 μm and less than 3.5 μm in diameter. Six samplers were located at heights of 2 m and 5 m on towers 5, 9, and 11. The remaining two were located at 2-m height on towers 3 and 12 (see Figure 2). Particulate measurements were taken 5 d/week for a duration of 2 h during the morning and evening peak traffic periods. Fluoropore filters (0.5 micron pore size and 47 mm in diameter) were used to sample particulates in both size ranges. Filters were collected manually, placed in petri dishes, and brought back to Albany at the end of each week for analysis. In addition, total suspended particulates were collected with high-volume air samplers at six locations (three on each side of the highway at various downwind distances) on a 24-h basis for a period of 3 months under a contract agreement with the Federal Highway Administration (FHWA).

Figure 1. Map illustrating the location of the experimental site and nearby residential areas and highways in Long Island, New York.

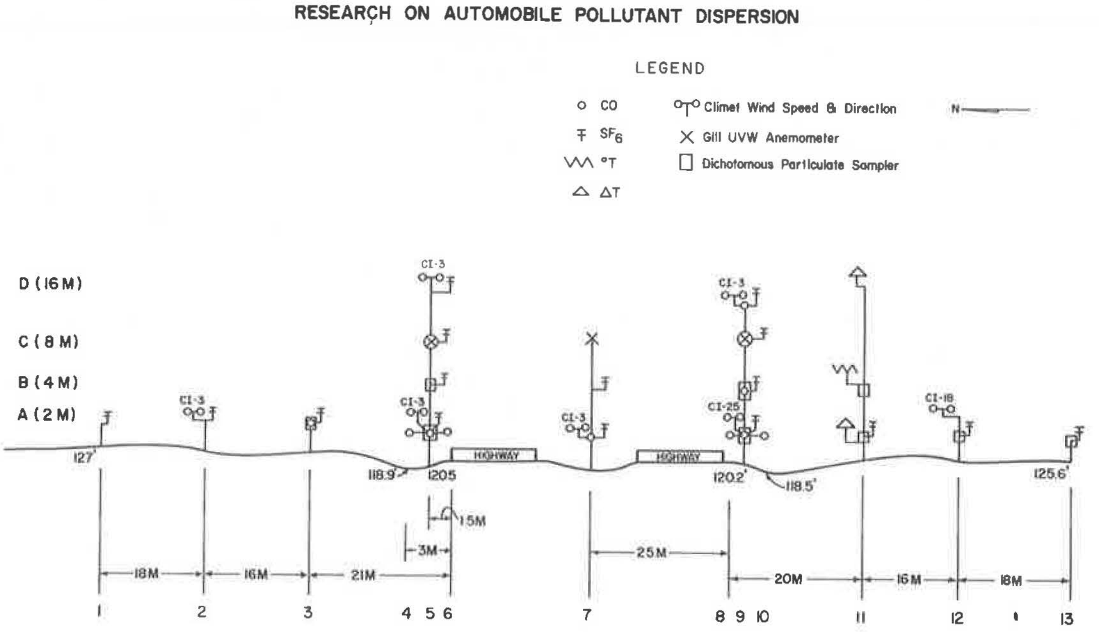


Filters for the dichotomous samplers were weighed before and after the run with a Mettler M-5 microbalance under constant temperature and humidity conditions to determine the particulate mass. Further analyses of these filters for Pb and S were made using x-ray fluorescence (xrf) spectrometry. The xrf unit actually indicated the total S, but in the lower size range of particulate collected by the dichotomous sampler, it was expected that the total S-sulfate (SO_4) ratio would be close to unity. For additional information, soluble SO_4 was analyzed using a liquid ion chromatograph, developed by the Dionex Corporation.

CO Measurement

The locations of the CO measurements are indicated in Figure 2. Sampling was done using nondispersive infrared (NDIR) CO analyzers, manufactured by the Beckman Corporation. Samples were drawn from each specific location through Teflon tubing into a mixing chamber at a fixed sampling rate. The chamber's volume was designed to eliminate any rapid variations in the concentration within the sampling interval without masking any longer period changes. After passing through the averaging chamber, the sample was pumped into the monitor. The electronic output signal was then trans-

Figure 2. The location of the air quality and meteorological data measurements adjacent to the highway.



mitted to the data acquisition system. All NDIRs were automatically calibrated to 0 at least three times a day.

For tower 9, a profile system was designed to allow a single NDIR to measure the concentrations at four points in a vertical line during a 5-min sampling cycle. Flow through these four averaging chambers was produced by either of two pumps, separated by three-way solenoids controlled by the computer. Matched flowmeters were used through the system to assure the same constant flow for each chamber at all times. The main pump drew the samples through a collection tank and was used to maintain uniform flows through each chamber when that particular line was not being analyzed. During analysis, a solenoid was activated that closed that chamber's port to the collection tank and opened another port to the sampling pump and NDIR. Therefore, at any one time, three samples flowed to the collection tank while the fourth went to the NDIR.

Meteorological Measurements

Since dispersion parameters derived from meteorological data are critical in determining pollutant concentrations within 100 m of the highway, multiple measurements of meteorology were made. Four Gill 3-component anemometers were installed at a height of 8 m on towers 5, 7, 9, and 11. Seven Climet sensors were located at various positions, as shown in Figure 2. Temperature and temperature difference measuring systems (manufactured by Meteorology Research, Inc.) were located on tower 11. In addition, solar radiation, relative humidity, and precipitation were also measured.

Traffic Measurements

Each lane on the expressway had a pair of induction loops imbedded in the pavement. A separation distance of 3.5 m was used. These loops were connected to Streeter Amet Model-740 loop detectors. Via interface circuitry, each sensor was polled by the computer periodically for vehicle presence. The length and speed of each vehicle was computed from this information and classified into 5 length and 10 speed categories for each direction. A time-lapse photography system was used once a week to serve as a further check on the traffic measurements made by the computer.

Data Acquisition and Storage

All the electronic signals were transmitted to an 8-K memory NOVA 2 Data General mini-computer. In addition to providing a teletype output of all variables averaged over a sampling period of 10 min, the data were transferred to diskettes for storage and easy retrieval. The final output (10-min averages) of the data acquisition system was as follows:

1. CO concentrations at 11 locations in the sampling plane;
2. Westbound traffic counts in a two-dimensional matrix (50 elements—10 speed and 5 length categories);
3. Eastbound traffic counts similar to the westbound counts;
4. Average horizontal wind speed from seven Climet sensors;
5. Average horizontal wind direction from seven Climet sensors;
6. Average east-west component of wind from four Gill sensors;
7. Average north-south component of wind from four Gill sensors;
8. Average vertical component of wind from four Gill sensors;
9. Average temperature and vertical temperature gradient;
10. Radiation, humidity, and precipitation;
11. Resultant wind speed from the average east-west and north-south components; and
12. $\overline{UW}$, $\overline{UV}$, $\overline{WT}$, $\sigma_{i,j}$, where $i = U, V, W$ and $j = 1, 5, 10,$ and 25 s average time from four Gill sensors (the overbar indicates the mean over the sampling period).

Utilizing the above measured quantities, a data manipulation routine was written to compute Richardson number, flux Richardson number, Monin-Obukhov length, $\sigma\theta$ and $\sigma\phi$ from σ_i for various averaging times, and ratios of eddy diffusivities of heat and momentum.

TRACER GAS RELEASE, SAMPLING, AND ANALYSIS

Simulation of a line source was achieved in the vicinity of the sampling plane by releasing sulfur hexafluoride (SF_6) from six 1976 Plymouth Fury station wagons. The source was 99.99 percent pure instrument grade SF_6 gas contained in T-size cylinders with single stage regulators and gauges for tank and release pressure. This was modified by a third valve and pressure gauge with flowmeter so that close limits could be placed on the flow of SF_6 release. The third gauge and flowmeter were calibrated by Brooks Instruments for operation at 517 MPa. Copper tubing, 0.635 cm from the flowmeter, terminated near the vehicle's exhaust pipe. The SF_6 release set-up is shown schematically in Figure 3.

Sample collection was achieved via small battery-operated pumps mounted at each sampling point. The pumps were modified so that their on-off operation was centrally controlled. Acrylic rubber tubing ran from the pumps to Tedlar sampling bag at ground level. The procedure used in establishing and sampling a line source of tracer gas is described below.

All six automobiles were lined up at point A (see Figure 4), and each automobile left the ramp at intervals of 1.5 min. The SF_6 was released between the two overpasses on either side of the sampling plane. The duration of SF_6 release was recorded for each release. All automobiles travelled at 88 km/h during the release

Figure 3. Design of the SF_6 tracer gas release set up.

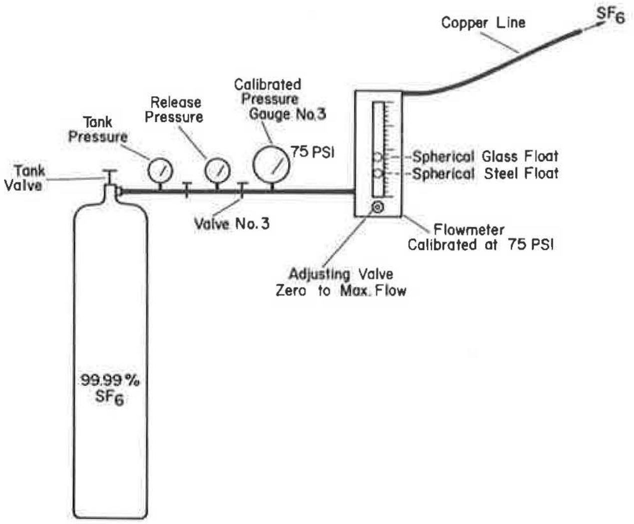
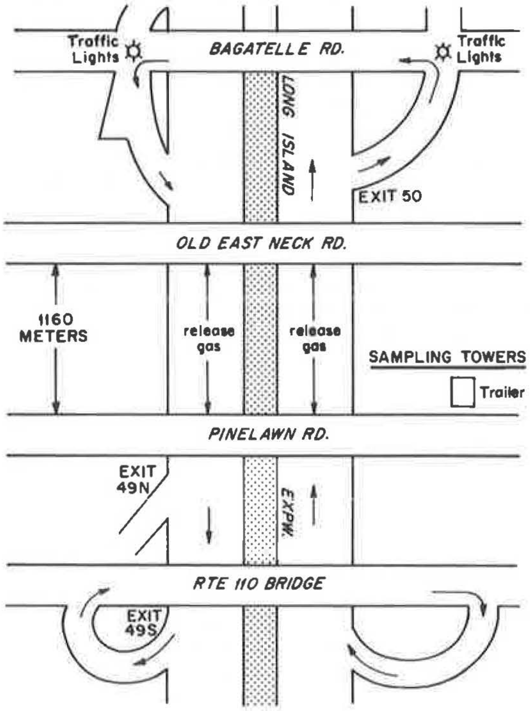


Figure 4. The course for the SF_6 releasing automobiles with respect to the sampling network.



periods and stayed in the center lane. The collection of SF_6 began when the second automobile passed the sampling plane on its eastbound return lap. This procedure was adapted to ensure creation of a line source before the collection of samples. The sampling was continued for 1 h, at the end of which all automobiles were signalled to stop the release of gas. The bags were then sealed and brought to the trailer for analysis. The location of SF_6 measurements is shown in Figure 2. The bags thus collected were analyzed immediately after the experiment using an Analytical Instrument Development, Inc., model 511-06 portable electron capture gas chromatograph and a Supergrator II integrator. The range of electron capture detection used was 0 to 59.6 $\mu g/m^3$. The analyses used three SF_6 standards, 0.596, 5.96, and 59.6 $\mu g/m^3$, which were prepared by Scott Environmental Technology. A total of 23 hour-long experiments were conducted over a period of 3 weeks.

MODEL PREDICTIONS

Two mathematical dispersion models—HIWAY, developed by the U.S. Environmental Protection Agency (EPA), and GM, developed by the General Motors Corporation—were tested to evaluate their capability to simulate dispersion from a line source. Both models are based on the assumption that the pollutant concentration at any given receptor is given by the Gaussian equation. Details on the model formulation and input requirements can be found in Zimmerman and Thompson (1) and Chock (2).

The above models were run for two stabilities using meteorological data from location 7C on the median tower. The wind speed and direction at this height (8 m) are thought to be representative of the advection process adjacent to the highway. Micrometeorological measurements also indicate that the mechanical turbulence generated by the traffic flow extends up to heights of 8 m.

A considerable variation of the atmospheric stability is observed for the same set of meteorological conditions at the site when different methods of estimating atmospheric stability are used. The more commonly used Pasquill-Turner (3) classification yielded neutral stability for almost all the hours during which tracer experiments were conducted. Slade's (4) method of atmospheric stability determination utilizing horizontal sigmas indicated that conditions during most of the tracer runs fall into unstable categories.

Preliminary analysis of the micrometeorological data collected at the site indicates that although neutral stability exists on the mesoscale, the stability in the vicinity of the roadway is dictated by the turbulence generated by the vehicular traffic and change of roughness. Hence HIWAY and GM models were run using both stability 4 (neutral) and stability 2 (unstable) conditions for the same set of SF_6 observations. Wind-road orientation angles in the range 0° to 30° are treated as parallel, 30° to 60° as oblique, and 60° to 90° as perpendicular cases.

Table 1 demonstrates that the HIWAY model yields better correlations using stability 2 criteria than neutral criteria for these experiments. For the GM model, on the other hand, there are no significant differences between the correlations for the two stabilities. This is to be expected because there is little variation in the sigma values for neutral and unstable classes in the GM model. The slope of the regression line, however, is closer to unity for unstable conditions in the GM model. Both HIWAY and GM predict concentrations with some confidence for perpendicular wind conditions. The predictive capability of the HIWAY model seems to decrease as winds deviate from the perpendicular to the roadway.

Table 1. Comparison of two highway dispersion models using the data collected during the tracer gas experiment.

	Atmospheric Stability						
	Neutral			Unstable			
Wind-Road Angle	Correlation r^2	Intercept	Slope	Correlation r^2	Intercept	Slope	Number of Data Points
Perpendicular							
HIWAY	0.70	0.97	0.48	0.88	0.60	0.71	41
GM	0.88	0.43	0.91	0.87	0.51	1.0	41
Oblique							
HIWAY	0.58	0.83	0.44	0.63	0.67	0.71	59
GM	0.59	0.56	0.86	0.58	0.64	0.97	59
Parallel							
HIWAY	0.52	1.78	0.15	0.67	1.35	0.40	40
GM	0.89	0.36	0.70	0.93	0.33	0.92	40
All combined							
HIWAY	0.43	1.74	0.20	0.66	1.07	0.52	140
GM	0.73	0.63	0.76	0.71	0.64	0.93	140

Figure 5. Concentrations of lead and sulfate adjacent to the roadway for parallel and perpendicular wind-road orientations.

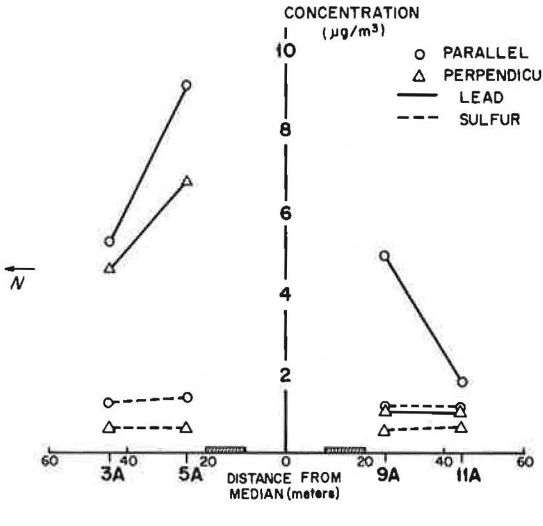


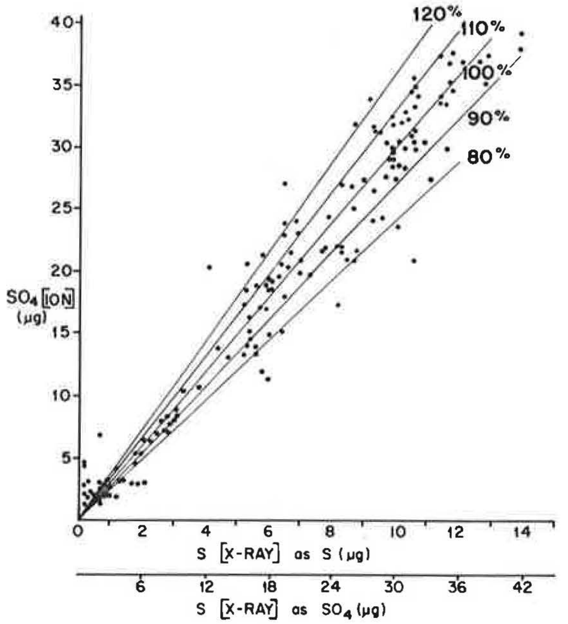
Table 2. Lead, sulfur, and sulfate concentrations for the small-particle fraction.

	Small-Particle Concentrations		
Position	Lead (μg/m³)	Sulfur (μg/m³)	Sulfate (μg/m³)
5A	1.2	1.5	4.8
9A	8.1	1.5	4.9
9B	4.1	1.4	4.8
11A	4.8	1.4	4.6
11B	3.7	1.8	5.4
12A	3.7	1.6	4.9
13A	3.2	1.5	5.7

The GM model, on the other hand, has much higher correlations for both perpendicular and parallel wind-road orientations than for the oblique wind situations. This suggests that the empirical equation used in the GM model to derive the sigma values as a function of downwind distance and wind-road orientation angle needs closer examination. The equation would appear to be satisfactory for perpendicular and parallel wind-road orientations. From the above, one can infer the general observation that a model calibration and validation must be performed segmentally; that is, different wind regimes and stabilities should be examined separately rather than combining all cases together.

The observed SF_6 concentrations and source strength are being used to estimate the vertical diffusion parameter values, and these values are being compared to those used in the above mathematical dispersion models. Preliminary data from this type of analysis indicates that the sigma values applicable to near-roadway dispersion are closer to the vertical sigmas that are prescribed under stability 2 in the HIWAY model. This suggests that the importance of the atmospheric stability in dispersing pollutants near the roadway might be less significant than the effects of the turbulence generated by the vehicular traffic. Work is continuing in this direction to better define the diffusion parameter values applicable to near-roadway dispersion and to identify clearly the roles played by the natural turbulence and the local turbulence generated by the waste heat emissions from the automobile exhaust and the aerodynamic drag of moving vehicles. Also, comparisons of the SF_6 and CO data are under way to see if CO dispersion is similar to that of SF_6.

Figure 6. Comparison of sulfur and sulfate measurements using X-ray fluorescence spectrometry and ion chromatography techniques.



SO_4 AND Pb LEVELS ADJACENT TO THE HIGHWAY

Particulate samples collected with the dichotomous samplers were analyzed for total weight, Pb, S, and SO_4. At the start and end of the study, all the dichotomous samplers were placed at tower 11 and over 20 runs were made sampling the same air mass in order to estimate the range of sampling and analysis errors.

Figure 5 is a plot of the small particle (<3.5 μm) concentrations for Pb and S at the 2-m level. Two cases are presented. Run 1019R2 had a wind-road angle of 90° and a wind speed of 1.9 m/s, and run 1020R1 was a parallel case with an angle of 8° and a wind speed of 1.0 m/s. Table 2 contains the small particle concentrations of Pb, S, and SO_4 at 2-m and 5-m heights for run 1005R2, which had an oblique wind of 32° and a wind speed of 3.1 m/s.

The Pb concentrations for perpendicular and oblique winds reach a maximum immediately downwind of the roadway, with a subsequent decline both vertically and horizontally. As is to be expected, under parallel winds the Pb concentrations increased on both sides of the highway. The S and SO_4 concentrations do not display a similar trend. Their spatial variations show no perceptible pattern and are within the range of sampling error.

At the most, 30 percent of the automobiles on the expressway during sampling were equipped with catalytic converters and, therefore, used nonleaded gasoline. Assuming that each of these automobiles had a SO_4 emission rate of approximately 0.002 g/km, and the rest of the vehicles had a Pb emission rate of approximately 0.04 g/km each, the Pb emission rate on the roadway would be on the order of 50 times greater than the SO_4 emission rate. These estimates are supported by the observed concentrations.

The SO_4 contribution from the roadway is indiscernable at the site; therefore, the magnitudes of SO_4 levels found can be considered representative of ambient concentrations. Figure 6 is a scatter plot of S content of the small particle fraction of particles collected in the dichotomous samplers by xrf versus soluble SO_4 by ion chromatography for the runs taken during the tracer periods. The two methods correspond fairly well, indicating that most, if not all, of the S is in the form of soluble SO_4.

ACKNOWLEDGMENTS

We are grateful to many staff members of the Division of Air Resources for taking part in the tracer gas release experiments and for providing moral support throughout this research program. Dr. G. Wotzak developed the computer logistics for data acquisition. Dr. N. Kolak and S. House, R. Peddada, and H. Whitney have carried out the laboratory analysis of the particulate samples. John Hawkins' frequent checks on the electronics at the site was a great aid throughout the study. Thanks are due to Gerard E. Blanchard for his constructive criticism and constant encouragement throughout the progress of this study. We are indebted to Dr. John Hawley for his continuous guidance during the course of the study. Thanks are extended to Beth Peck for typing the manuscript and Carol Clas for drafting the diagrams. This research was done with the support of the EPA, New York State Department of Transportation, and State University of New York at Albany.

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Integrated Planning and Management of Transportation and Air Quality

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Efforts to implement the transportation control provisions of the Clean Air Act Amendments of 1970 have generated much discussion but little implementation of transportation measures to improve air quality. Reasons for this include conflicts over transportation priorities, inadequate institutional arrangements for combined transportation and air quality planning, and insufficient information concerning the relation between transportation and air quality. The Clean Air Act Amendments of 1977 provide a framework for handling these problems. However, important questions remain to be answered concerning organizational roles in transportation and air quality planning, the structure of the planning process, and the responsibilities of transportation and air quality decision makers.

The Clean Air Act Amendments of 1970 directed the U.S. Environmental Protection Agency (EPA) to establish national ambient air quality standards whose attainment would protect the public health and welfare from the adverse effects of major air pollutants. The pollutants for which health-based air quality standards now exist include carbon monoxide (CO) and photochemical oxidants, whose presence in urban air is primarily attributable to emissions by motor vehicles of CO, hydrocarbons (HC), and nitrogen oxides (NO_x). The areas in which one or more of these air quality standards are exceeded include most large cities in the United States and contain approximately two-thirds of the nation's population. The automobile is the source of roughly 70 percent of the CO, 50 percent of the HC, and 30 percent of the NO_x emitted in urban areas. Other transportation sources are responsible for approximately 20 percent of CO, HC, and NO_x emissions in these areas.

Because of the importance of motor vehicles relative to other sources of CO, HC, and NO_x, the reduction of motor vehicle emissions is a major objective of programs to improve air quality. The principal means of achieving this objective is the control of emissions from new vehicles. However, in many large cities, the current and projected future magnitudes of motor vehicle emissions are such that the CO or oxidant air quality standards cannot be attained and maintained through the control of emissions from new motor vehicles and nonvehicular sources alone. Furthermore, motor vehicles will remain among the two or three largest emissions sources, even after controls on new motor vehicles have become fully effective. In effect, the transportation systems of large cities are now and will continue to be major emissions sources that, like other major sources, must be controlled if the air quality standards are to be achieved.

Emissions from urban transportation systems can be reduced by improving traffic flow conditions and reducing traffic volumes. The measures through which these objectives might be achieved include virtually all of the ones currently encompassed by the term transportation system management. The Clean Air Act refers to transportation system management measures as transportation controls and requires their implementation in areas where they are needed to ensure the attainment and maintenance of the air quality standards.

Efforts to implement the transportation control provision of the Clean Air Act began in 1973. Thus, roughly 5 years of activity have been directed toward the broad objectives of identifying and implementing transportation measures that improve air quality and, conversely, identifying and minimizing the implementation of transportation measures that make air quality worse. This activity has entailed, among other things, much consciousness-raising in both the transportation and air quality professions. The transportation profession, for example, is learning that urban transportation systems are major causes of air pollution and that the problem of controlling transportation systems' emissions must be taken seriously. The air quality profession is learning that transportation planning is not a subspecialty of air pollution engineering and that the problems of controlling emissions from urban transportation systems are different from the problems of controlling emissions from industrial facilities.

Implementation of transportation measures to improve air quality also has created considerable controversy. The issues involved in this controversy range from the highly technical to the highly political and include questions such as: What are the air quality effects of specific transportation measures (for example, priority bus treatment or downtown parking restrictions)? What changes in urban transportation planning and decision-making processes are needed to accommodate the Clean Air Act's implicit requirement that air quality improvement be a major objective of these processes? Is the implementation of transportation measures to improve air quality consistent with the achievement of other transportation objectives, and if not, how should trade-offs be made between air quality improvement and other objectives? The controversy has stimulated a significant quantity of research on the relations between transportation and air quality. Although much remains to be learned about these relations, they are far better understood now than they were in 1973.

The consciousness-raising, controversy, and research that have taken place since 1973 have not been accompanied by significant implementation of transportation measures to improve air quality. There are, of course, many reasons for this. First, increasing the emphasis placed on air quality in transportation planning and decision making requires changing urban transportation priorities. In particular, it requires that increased priority be assigned to developing and implementing measures to reduce traffic volumes. Changes in the lines of authority among organizations involved in transportation and air quality also are likely to be needed. For example, effective air quality planning requires a strong element of regional coordination. Accordingly, it may be necessary to strengthen transportation agencies that have regional responsibilities at the expense of agencies that have more localized concerns. Clearly, such changes in priorities and authority are difficult to achieve, thus making the planning and implementation of transportation measures to improve air quality difficult.

Another source of difficulty in achieving the implementation of transportation measures to improve air quality has been the relative isolation of transportation agencies from the air quality planning process. Air quality planning and transportation planning typically have been done by different agencies, often at different levels of government. Air quality agencies tend to be state-level organizations and usually are oriented toward industrial pollution control. They have neither expertise in nor responsibility for urban transportation. Urban transportation planning, on the other hand, tends to be the responsibility of local agencies that, until recently, have had little expertise in air quality matters and have felt little need to be involved in these matters. The Clean Air Act Amendments of 1970 assigned the principal responsibility for planning and implementation of air quality improvement measures to state governments. State governments, in turn, tended to assign the responsibility to state air quality agencies. These agencies frequently failed to involve local transportation agencies in the air quality planning process. Moreover, in the relatively few areas in which transportation agencies were involved, problems of achieving cooperation between different levels of government and among agencies that were unfamiliar with one another's responsibilities, objectives, and operations hindered effective planning of transportation measures to improve air quality.

Finally, the method for identifying, evaluating, and gaining public and political acceptance of coherent packages of transportation measures that both improve air quality and serve other community objectives is unclear. This problem is, to a large extent, a consequence of the relative newness of air quality as a transportation issue and the resulting lack of information, technical tools, and institutional processes to deal with it. The problem was aggravated, however, by the Clean Air Act Amendments of 1970, which failed to recognize either the need for or the complexity of the various technical and political activities associated with planning and implementing transportation measures to improve air quality. The amendments established a schedule for air quality improvement that did not provide time for even the most rudimentary activities.

The problems of implementing transportation measures to improve air quality have received widespread recognition, including that of the Congress, and one of the consequences of this has been the Clean Air Act Amendments of 1977. These amendments contain several provisions that are designed to encourage the integration of transportation and air quality planning and to alleviate the problems that have prevented this integration in the past; for example,

1. They require that transportation planning and air quality planning be coordinated at the local level;
2. They specify that, where possible, planning for the control of transportation-related air pollutants be conducted by an organization of elected local officials in each affected metropolitan area, and they encourage the designation of either the metropolitan planning organization (MPO) or the air quality maintenance organization (AQMO) for this purpose;
3. They place increased emphasis on process-related activities (such as evaluation of options, consultation with the public, involvement of elected officials, and programming) and they provide additional time (although perhaps not enough) for these activities to take place; and
4. The amendments require federal agencies whose programs affect transportation and air quality to give priority to implementation of transportation plans to improve air quality.

The Clean Air Act Amendments of 1977 provide a framework for an improved transportation and air quality planning process. However, it is only a framework; many complex issues still must be resolved. One such issue concerns the designation of regional agencies to plan for the control of transportation-related air pollutants. Transportation systems are not the only sources of these pollutants. Therefore, if an MPO is the designated planning agency, how will it arrange for the planning of stationary-source controls? Conversely, if an AQMO is the designated agency, what arrangements are needed to coordinate its activities and those of the MPO?

Another set of issues concerns the structure of the transportation planning process. How does one identify transportation measures that improve air quality? How does one combine these measures into coherent packages that both improve air quality and serve other community objectives? How should potential measures and packages of measures be evaluated? When and how should elected officials and the public be consulted?

A final set of issues concerns decision making and priorities. What criteria should be used to determine whether the transportation sector is making an adequate contribution to air quality improvement? Who should apply these criteria? How should conflicting claims on scarce planning resources by air quality planning activities and other planning activities be resolved? How should decisions be made as to the relative priorities of improving air quality and achieving other objectives when trade-offs must be made?

There clearly are no simple answers to these questions. Attempts to answer them must rely heavily on the experience of people who have dealt with them. The sharing of experience in transportation and air quality planning will contribute to an improved, integrated transportation and air quality planning process.

Experience With Consistency Reviews in Four Metropolitan Areas

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This paper reviews the experience of Region 3 of the U.S. Environmental Protection Agency in enforcing the section 109j consistency review process. After a description of the process, U.S. Environmental Protection Agency and Federal Highway Administration positions on consistency are examined and some reasons for differences are discussed. U.S. Environmental Protection Agency's experience in reviewing consistency in the Delaware Valley Region (Philadelphia), Southwest Pennsylvania Region (Pittsburgh), Baltimore Region, and National Capital Region is discussed. An assessment is then made of the status of the consistency process and future directions for consistency review are proposed. Although some progress has been made, the section 109j consistency review process has been generally ineffective. Some basic changes in attitudes and policies of metropolitan planning organizations and state and federal agencies are needed if the consistency review process is to become a useful tool for improving air quality.

The Federal-Aid Highway Act of 1970 added section 109j to title 23 of the U.S. Code, which requires that all highways constructed with federal funds be consistent with state implementation plans (SIPs) to attain and maintain national ambient air quality standards (NAAQS). In 1974 the Federal Highway Administration (FHWA) published regulations (1) for determining consistency with state air quality plans. These regulations set out the procedure that the state highway agency and metropolitan planning organization (MPO) first assess consistency and solicit comments from state and local air pollution control agencies. Differences should be identified and, if possible, resolved. The MPO annually makes a determination of consistency. This determination is forwarded through the state to the FHWA. FHWA, in consultation with the U.S. Environmental Protection Agency (EPA) annually assesses the degree of coordination between transportation and air quality planning and reviews the determination of consistency. Significant deficiencies are grounds for FHWA to withhold planning certification.

In 1975, FHWA and EPA published joint guidelines for analysis of consistency between transportation and air quality plans (2). The guidelines were intended to identify levels of technical analysis required, commensurate with the severity of the air pollution problem in an urban area. The guidelines also set out five criteria that transportation plans and programs should meet in order to be consistent with SIPs. These criteria are

1. MPO transportation plans and programs must not exacerbate any existing violations of the NAAQS.
2. MPO transportation plans and programs must not contribute to a violation of the NAAQS for a pollutant for which no concentrations in violation of the NAAQS have been measured.
3. MPO transportation plans and programs must not delay the attainment of NAAQS.
4. MPO transporation plans and programs must not interfere with maintenance of the NAAQS once the standards are attained.
5. MPO transportation plans and programs must include all appropriate portions of state plans to implement NAAQS, including transportation control measures either adopted by a state or promulgated by EPA to reduce vehicle miles of travel (VMT), such as exclusive buslanes or carpool matching programs.

POSITIONS ON CONSISTENCY

After several years of experience reviewing consistency of urban transportation plans, it has become apparent that there are significant differences in the way EPA and FHWA interpret section 109j, despite the existence of joint EPA-FHWA guidelines. These differences have made the section 109j process ineffective as a device for improving air quality. The major issues on which EPA and FHWA differ are

1. Definition of consistency,
2. Responsibility for air quality,
3. Adequacy of models, and
4. Corrective action required.

The five criteria contained in the FHWA-EPA guidelines are too general. FHWA's position is that consistency should be judged only on whether the transportation plan and program are consistent with the approved SIP. Although section 109j uses the word "approved", EPA believes that an inadequate SIP does not relieve the transportation planning process of responsibility for air quality. EPA's position is that a simple comparison of measures in the approved SIP with the transportation plan and program is not adequate.

FHWA believes that primary responsibility for attainment and maintenance of the NAAQS rests with air pollution control agencies. The transportation planning process has no responsibility to actively undertake measures to improve air quality, although FHWA believes such measures are desirable. EPA's position is that the transportation planning process and the resulting plan and programs must assume responsibility for at least a portion of the emission reductions needed for attainment and maintenance of the clean air standards.

FHWA's position is that currently available models are not adequate to make determinations of the attainment and maintenance status of air quality standards. EPA recognizes the shortcomings of current models, but believes that they exhibit at least the same degree of confidence as transportation planning models and are adequate for making decisions about air quality standards.

FHWA believes that strong encouragement of MPOs to consider air quality measures as transportation systems management (TSM) improvements is adequate. EPA believes that much stronger action is required because experience has shown that MPOs do not place a high priority on air quality.

Areas where EPA and FHWA have reached substantial agreement can be summarized as follows:

1. Complete implementation of control measures for both stationary and mobile sources will be required to attain and maintain air quality standards. EPA and FHWA agree that the transportation plan and program should not be solely responsible for attainment and maintenance of air quality standards. However, the degree of responsibility that transportation should assume is still a subject of disagreement.

2. The transportation portion of the SIP should be developed as part of the federal urban transportation planning process. One failure of the first transportation control plans (TCPs) is their lack of coordination with the existing transportation planning process. Transportation control measures for the first TCPs were developed by EPA and state and local air pollution control agencies. Attempts were then made to incorporate these measures into the transportation plan and program. The proper way to develop a new TCP is for the MPO to develop the measures and have the state incorporate them in the SIP.

3. FHWA and EPA should not dictate future land-use patterns. Major changes in land-use patterns may be necessary to attain and maintain the air quality standards; however, FHWA and EPA agree that land-use decisions should not be made by the federal government.

REASONS FOR DIFFERENCES

Some of the differences in EPA and FHWA positions exist because of the differing nature of each agency's responsibilities. The Clean Air Act Amendments of 1970 require EPA to approve SIPs. Federal highway legislation does not give the FHWA authority to approve plans. The Clean Air Act requires that SIPs result in attainment of NAAQS. Federal highway legislation does not contain any specific standards that transportation plans must meet. The Clean Air Act Amendments of 1970 give no direct responsibility to FHWA for attainment of NAAQS. The Clean Air Act Amendments of 1977, however, have given FHWA authority to invoke funding sanctions in areas where adequate SIPs are not developed. The EPA is a regulatory agency and has no funds to implement transportation measures. EPA must, therefore, rely on other agencies for such implementation. FHWA is not a regulatory agency. It has responsibility to administer federal-aid highway funds.

CONSISTENCY REVIEW

Region 3 of EPA contains four major MPOs. The Delaware Valley Regional Planning Commission (DVRPC) is responsible for five counties in Pennsylvania and four in New Jersey; Philadelphia is the only major city. The Southwest Pennsylvania Regional Planning Commission (SPRPC) performs planning for six counties; Pittsburgh is its major city. Regional Planning Council (RPC) in Maryland is responsible for planning in the Baltimore area. The Transportation Planning Board (TPB) is the MPO for the Washington area, which is composed of the District of Columbia and portions of Maryland and Northern Virginia. The first year for MPO consistency determinations was 1974-1975.

Delaware Valley Region

The 1974-1975 assessment of consistency was based on an emissions burden analysis for carbon monoxide (CO) and hydrocarbons (HC) and contained some positive discussion on the implementation of the TCP. FHWA concurred with DVRPC's determination of consistency. Based on the submission, EPA's response was that, with the information given, a determination of consistency between transportation and air quality planning was not possible. The substantive issues of meaningful coordination between air and transportation planning and the responsiveness to air quality by the process were not addressed.

In 1975-1976, DVRPC performed a detailed diffusion modeling analysis for CO using the APRAC air pollution model and a burden analysis for HC. Also contained in the submission was a discussion of the Delaware Valley Region's active implemention of the TCP. FHWA in their letter to EPA expressed satisfaction that the transportation plan and program were consistent with the SIP. EPA responded by saying that the plan was inconsistent with respect to air quality and violations of the standards continued while the substantive planning issues were not addressed. EPA recommended that FHWA withdraw certification of DVRPC until the transportation plan was revised to be consistent with the SIP. Three meetings were held to discuss the technical issues on which EPA and FHWA disagreed. Little was resolved. FHWA strongly urged

DVRPC to consider air quality in their planning, but unconditionally certified DVRPC.

The 1976-1977 assessment of consistency again used APRAC to better define the air quality problem through the use of a hot spot analysis. The report was a fair assessment of the air quality problem: It noted the violation of air quality in the region and indicated failures in implementation of the TCP. The resolution adopted by the DVRPC board, however, gave little recognition that transportation plays a major part in the CO and oxidant problem. The board made no commitment to work actively to solve the problem. After further consideration of the air quality problem, however, the DVRPC board adopted a stronger resolution, which states in part:

> ...The DVRPC Board...recognizes that air quality standards for the Region are not being met and that existing transportation plans will not by themselves result in attainment and maintenance of the carbon monoxide and photochemical oxidant standards. However, the Board also recognizes that attainment of these standards is directly tied to the long-range regional comprehensive planning process now underway and the Board confirms its commitment to develop functional plans and programs with achievement of national air quality standards as a goal. This will be done in close coordination with responsible air quality control agencies. Additionally, in the further refinement of the TSM element, full consideration will be given to measures that will aid in improving air quality. In view of these efforts, the Board finds the transportation planning process generally consistent with the state implementation plans.

In responding to FHWA, EPA stated that it was encouraged by the resolution and believed that implementation of the commitments would eventually result in a consistent plan, program, and process. EPA asked FHWA to monitor progress closely in carrying out the commitments and consider failure as grounds for withdrawal of certification.

Southwest Pennsylvania

The assessment of consistency for both 1974-1975 and 1975-1976 was based on a CO and HC emissions-burden analysis and some discussion of the implementation status of the TCP. In neither year was an adequate demonstration of consistency made. The substantive planning issues and meaningful coordination between air quality and transportation planning were not addressed. FHWA's determination for both years was that the planning process was consistent and adequately considered air quality. EPA did not agree with this determination and, in 1976, EPA recommended that FHWA withdraw certification of SPRPC until the plan is revised to be consistent with the SIP. FHWA did not accept this recommendation and certified SPRPC. FHWA, however, has been strongly urging SPRPC to perform adequate air quality analysis. The 1976-1977 determination has been delayed because of FHWA's dissatisfaction with SPRPC's technical evaluation.

Regional Planning Council (Baltimore)

The 1974-1975 statement on consistency between the regional transportation plans and programs and the air quality implementation plan for the Baltimore Region was approved by the Baltimore Region Transportation Steering Committee on June 26, 1974. The resolution by the committee found the plans to be generally consistent. The statement was based on some projections in the Baltimore Regional Environmental Impact Study and the TCP analysis that showed standards would not be met in 1977. Using this as a basis, RPC concluded that no change in the highway construction programs would help achieve standards. EPA found the transportation plans and programs were inconsistent with the applicable SIP. FHWA did not agree and certified RPC.

The 1975-1976 statement was a reaffirmation of the earlier determination based on an update of status of implementation of some items of the TCP. EPA again found the transportation plans and programs to be inconsistent with air quality goals and recommended that FHWA withdraw certification of RPC. FHWA did not agree with the recommendation and certified the transportation planning process, but added a strong request that air quality be considered.

The 1976-1977 submission by RPC did not address previous concerns expressed by EPA. However, EPA noted that the draft general transportation plan and the recommended transportation system management elements indicated that the planning process was beginning to be responsive to air quality concerns. Although the plan was still inconsistent, EPA recommended that FHWA monitor progress carefully.

Washington Area

The 1974-1975 statement on consistency for the Washington, D.C., urban area was based on an emission analysis of the long-range transportation plan for the year 1992 and a working paper that reviewed the status of implementation of the control strategies. The FHWA submitted the determination to EPA and expressed the conclusion that the transportation plans and programs were generally consistent with the SIP with the exception that the plans and programs did not provide for the maintenance of NAAQS.

In the 1975-1976 determination of consistency, the supporting materials consisted of an air quality analysis for 1992 and a status of implementation of the TCP-related measures in the short-range plans. The analysis indicated that in 1992 microscale violations of the CO standards may occur in those areas of heavily congested traffic in central Washington. Also taken into account by EPA was the analysis of air quality data to determine the adequacy of SIP to attain and maintain the NAAQS, which resulted in a notification of the appropriate elected officials in the Washington, D.C., region that the SIPs needed revision. After consideration of these documents, EPA concluded that the highway portion of the plan was inconsistent with air quality goals and recommended that FHWA withdraw certification of the TPB. FHWA did not concur with EPA's recommendation and unconditionally certified the planning process. FHWA urged TPB to continue development of transportation measures to improve air quality.

In 1976 to 1977, EPA again found the plan and program inconsistent with air quality goals. EPA was encouraged, however, by TPB's endorsement of the need for continual refinement of plan elements to complement air quality planning. EPA asked FHWA to monitor implementation of this policy.

STATUS OF CONSISTENCY PROCESS

The experience of EPA Region 3 with consistency reviews in the four major metropolitan areas leads to several conclusions regarding the status of the consistency process.

1. The quality of the technical analysis has improved. The four MPOs are developing staff expertise to deal with air quality issues in transportation planning. This is an important step because of the need to know the air quality impacts of transportation plans and programs.

2. MPO policy boards are beginning to recognize air quality issues. They are starting to understand that transportation systems have significant impacts on air quality.
3. FHWA and EPA are continuing their open dialogue on air quality issues. The Region 3 offices of EPA and FHWA have initiated joint meetings with MPOs to review air quality issues. EPA is active on the Region 3 intermodal planning group and comments on unified work programs. FHWA has been very responsive to these comments.

The Clean Air Act Amendments of 1977 substantially strengthen the role of local governments in development of transportation measures for air quality. Section 174 authorizes the designation of MPOs to develop transportation plans. Section 175 authorizes Congress to appropriate funds for the planning process. If the funds become available, the consistency review process as it now exists will be changed radically. TCPs will be developed through the federal transportation planning process and be incorporated by the state as part of the SIP. Whether or not additional funds become available, changes must occur to make air quality a regional goal.

1. MPOs must recognize that attainment and maintenance of air quality standards are not optional;
2. MPOs must accept responsibility for a portion of the emission reductions needed for attainment and maintenance of the air quality standards; and
3. Federal policies must require complete integration of functional planning (transportation, water quality, and housing) with air quality as a constraint.

The Clean Air Act Amendments of 1977 allow until 1987 for attainment of CO and HC standards. If those dates are to be met, state and federal agencies and MPOs must make a commitment to do everything reasonable to attain standards. The first step is the development of an adequate planning process.

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1. Federal-Aid Highway Program Manual, Vol. 7, Chapter 7, Section 9. Federal Highway Administration, Transmittal 105 HEV-10, Nov. 26, 1974.
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Air Quality Considerations in Transportation Planning

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For the past 5 years, transportation control plans and related air quality analyses of transportation projects have been the major focus of air quality considerations in transportation planning in metropolitan areas. Experience with control plans has been mixed: In many areas, tight deadlines, weak intergovernmental coordination, limited analysis of the costs and effectiveness of measures, and lack of public support for the plans combined to limit implementation of control measures. The Clean Air Act Amendments of 1977 include provisions to correct these problems. The amendments call for the development and implementation of plans to attain the national ambient air quality standards by 1987 under procedures that emphasize metropolitan, state, and local participation, consultation with elected officials and the public, and incremental progress in implementing transportation measures that improve air quality. The amendments authorize $75 million for planning grants to nonattainment areas and forbid federal agencies to approve or fund any activity that does not conform to the plan approved by the U.S. Environmental Protection Agency. Federal agencies also must give priority to plan implementation. The amendments point to a process in which air quality considerations are an integral and continuing part of transportation planning. Wherever possible, the metropolitan planning organization would coordinate transportation air quality activities as part of the continuing, cooperative, comprehensive transportation planning process for the area. The unified work program, the long-range and transportation systems management elements of the transportation plan, and the transportation improvement program would document the actions being planned or programmed to improve air quality. Periodic reviews of procedures being followed and progress in implementation would serve as the basis for determinations of conformity and for funding decisions. A major unresolved question is whether the transportation planning process can be shifted away from consideration of air quality to the implementation of air quality improvement measures. This implies that the role of the metropolitan planning organization may have to evolve from coordinating and summarizing planning activities to orchestrating and catalyzing action. Next is the question of whether the incentive of planning funds and the threat of possible loss of federal assistance will be sufficient to induce agencies to experiment with those measures that often are perceived as visiting very clear inconveniences or costs on the public to reduce diffusely perceived threats to health and welfare. Finally, there are great uncertainties about whether and how a combined transportation and air quality planning process would be evaluated and whether pressures for responsiveness could be brought to bear effectively.

In recent years Congress has enacted legislation and the U.S. Department of Transportation (DOT) and the U.S. Environmental Protection Agency (EPA) have issued regulations to improve the quality of the ambient air in our cities through judicious management of the transportation system. To date, however, the results of these initiatives have been mixed. The goal of attaining national air quality standards by 1977 (enunciated in the Clean Air Act Amendments of 1970) could not be met in a number of metropolitan areas, so Congress responded by enacting the Clean Air Act Amendments of 1977. The 1977 amendments contain major provisions that will have a significant and direct impact on the process by which air quality is considered in transportation planning.

EXPERIENCE WITH AIR QUALITY CONSIDERATIONS IN TRANSPORTATION

Transportation control plans (TCPs) developed in response to requirements of the Clean Air Act Amendments of 1970 have been the predominant factor in the transportation-air quality interface in most large urban areas. The plans, which at least initially included measures ranging from transit improvements to traffic management and, in some cases,gasoline rationing, became controversial from the moment they were announced. Experience in implementation has been mixed.

The problems TCPs have faced can be summarized: Extremely tight deadlines for plan development and promulgation took their toll on the quality of the plans that were produced. Rapid adoption of proposals for some very substantial and, in some cases,disruptive changes in urban transportation systems did not allow for adequate exploration of the social and economic consequences of the proposed measures, nor did it allow for adequate participation of metropolitan, state, and local agencies and officials in the planning and decision-making process. Limited or nonexistent experience with many of the proposed measures left doubts about their feasibility and cost-effectiveness. The 1977 deadline for attainment of the air quality standards allowed little time for investigation of alternatives, for experimentation with untested measures, and for accommodating the proposals within the budgetary and programming processes of the affected areas. Furthermore, the pressures of the attainment date forced the inclusion in the plans of measures that were universally agreed to be not only infeasible, but undesirable (gas rationing is the best example). These problems combined with a public perception that the benefits to be gained were uncertain, indirect, diffuse, and long term, whereas the costs were perceived to be immediate and,frequently, severe. The net result was opposition not only to some of the proposed measures, but in large part to the process by which TCPs were promulgated. In short, TCPs were viewed as constraints being imposed on the public, rather than as improvements being proposed for the public.

The TCP experience has not been without its successes. In fact, most urban areas have implemented several components of their TCPs, including preferential treatment of high-occupancy vehicles, employer-based carpooling programs, traffic flow improvements, and parking management actions. TCPs have been revised to eliminate many of the more controversial measures, and great emphasis has been placed on developing transportation actions that improve air quality through the normal transportation planning processes. Nevertheless, the TCP experience has highlighted the difficulties of achieving a specific environmental objective through modifications to the transportation system, particularly over the short term.

DOT Requirements and Activities

It is useful to review two other DOT requirements that are relevant to air quality considerations in transportation. One is section 109j of title 23, U.S. Code, the Federal Highway Administration (FHWA) consistency determination requirements. The other is DOT's transportation improvement program-transportation systems management (TIP/TSM) regulations, which govern the planning and programming of urban transportation improvements administered by FHWA and Urban Mass Transportation Administration (UMTA).

Section 109j directed DOT to develop and promulgate guidelines to assure that highways constructed through the use of federal funds are consistent with the applicable plan to achieve the ambient air quality standards. The FHWA regional administrator, after consultation with the EPA regional administrator, is responsible for making consistency dermination annually, based on information and analysis provided by the metropolitan planning organization (MPO). A finding of inconsistency can lead to decertification of the MPO's transportation planning process and eventual withholding of federal highway funds.

FHWA and EPA have published joint guidelines for determining consistency. The guidelines state that a highway plan or program should not cause or exacerbate a violation, delay attainment, or interfere with maintenance of an air quality standard, and should contain all appropriate transportation measures from the plan to improve air quality. Interpretation of the guidelines is still being sorted out, and disagreements have surfaced over data and modeling for consistency determinations and over what response is appropriate when certain inconsistencies appear. Moreover, FHWA has based its determinations primarily on whether an adequate process for consultation with air quality agencies and for evaluation of air quality impacts has been established and followed. EPA has lobbied for greater emphasis on results—whether the process has led to decisions and actions that would improve air quality. This significant difference in the orientation of the two agencies highlights a major issue in the air quality-transportation interface: Is thorough consideration of air quality sufficient, or must that consideration result in decisions to take actions to improve air quality? The 1977 amendments partially address this issue. In any case, however, the consistency requirement explicitly links highway planning and air quality objectives by requiring assessment of the air quality impacts of proposed highway actions.

The TIP/TSM regulations, which were promulgated in September 1975, are less explicitly linked to air quality, but in fact hold great potential for integrating air quality and transportation planning by setting forth DOT policies and objectives that overlap to a considerable extent with EPA's. The regulations call for the annual development by the MPO of a transportation systems management plan designed to meet the short-term transportation needs of the urban area and emphasize the efficient use of existing facilities. TSM measures identified by DOT include many of the same measures proposed by EPA for their potential air quality benefits: preferential treatment of high-occupancy vehicles, carpooling programs, improved transit service, traffic flow improvements, automobile-restricted zones, parking management. TSM plans thus consider a variety of locally initiated policies and programs to bring about a more responsible and balanced use of the private automobile and a more effective utilization and organization of public transportation facilities and services. Although the major emphasis in the TSM regulations is on transportation efficiency, air quality considerations are listed as one of the criteria for TSM decisions.

The TIP requirement calls for the continuing development of a program of projects recommended from the TSM, long-range elements of the transportation plan, and plans scheduled for implementation over the short to medium range (3 to 5 years or more). UMTA requires programming and progress in implementation of selected TSM measures in urban areas that have a population of 200 000 or more (FHWA has not yet required TSM programming). Thus, the TIP is the link between planning and implementation in metropolitan areas. Like the TSM requirement, the TIP requirement is of great interest to EPA because it provides for the orderly progression of projects from planning to actual funding, a mechanism sorely needed if proposals to improve air quality are to become realities.

EPA views the TSM and TIP requirements as holding great promise for the implementation of air quality measures. But currently there are basic differences between the DOT requirements and EPA's needs:

1. DOT neither requires that specific criteria be met nor sets deadlines for attainment of objectives. EPA, in contrast, is responsible for ensuring that the air quality standards as well as the attainment deadlines are met.
2. DOT approves the process leading to plans and programs, not the MPO's plan and program measures. (UMTA capital grants are a clear exception.) EPA must approve the adequacy of the air quality plan's measures, in addition to the process.

Thus, although the TIP/TSM regulations are compatible with EPA's air quality program needs, they do not by themselves tie transportation and air quality planning together neatly.

Provisions of the Clean Air Act Amendments of 1977

The Clean Air Act Amendments of 1977 make sweeping changes to the procedures through which transportation-based air quality improvement measures are to be developed and implemented. Many of the new provisions were designed to avoid problems that occurred in transportation control planning under the 1970 amendments. Other provisions clarify the responsibilities of DOT and other agencies in support of actions to reduce air pollution.

The new amendments extend to 1987 the time for attainment of the standards for carbon monoxide (CO) and photochemical oxidants (section 172). By 1987, state, regional, and local officials in nonattainment areas must determine jointly the planning, implementation, and enforcement responsibilities that each level of government will assume. Where feasible, the MPO or the air quality maintenance organization should be responsible for the air quality planning process (section 174). An implementation plan remains the foundation for transportation-related air quality attainment; the amendments encourage the inclusion of programs for improved transit, exclusive bus and carpool lanes, street parking control, park-and-ride facilities, road user charges and tolls to discourage single-occupancy automobile trips, improved traffic flow, bicycle lanes and facilities, and employer participation in carpooling, vanpooling, bicycling, and walking incentive programs (section 108). Section 105 requires EPA to develop guidelines for planning transportation and air quality improvements, in consultation with DOT, U.S. Department of Housing and Urban Development (HUD), and state and local governments, and authorizes $75 million for planning grants to the MPOs (to the designated agencies) for developing a planning process to link air quality planning to transportation and urban development planning.

By July 1, 1979, nonattainment areas must submit implementation plans that either show attainment of the CO and oxidant standards by 1982 or demonstrate to the satisfaction of EPA that such attainment is not possible despite the implementation of all reasonably available measures. In the latter case, a plan must be submitted by 1982 to demonstrate attainment as expeditiously as practicable but not later than 1987. The plan provisions must be adopted or promulgated after notice and reasonable public hearing (sections 172 and 178). After July 1, 1979 or 1982 (depending on the attainment status), if a nonattainment area has not submitted or made reasonable efforts toward submitting a plan, EPA cannot approve projects or award grants authorized by the amendments and DOT cannot approve projects or award grants under title 23, U.S. Code, other than for safety, mass transit, or transportation improvement projects related to air quality improvement or maintenance in that area (section 176). The plans submitted to EPA must include not only measures to ensure attainment and maintenance of the standards, but also schedules and timetables for compliance (section 110) and other evidence of the necessary commitments to implement and enforce the plan provisions (section 174).

Two provisions of the amendments should increase the likelihood that the plans developed will be implemented. Section 108 provides that EPA, after consultation with DOT, HUD, and state and local officials, shall publish guidelines on:

1. Methods to identify and evaluate alternative planning and control activities;
2. Methods to review plans on a regular basis as conditions change or new information is presented;
3. Identification of funds and other resources necessary to implement the plan, including interagency agreements on providing such funds and resources;
4. Methods to assure participation by the public in all phases of the planning process; and
5. Such other methods as the administrator determines necessary to carry out a continuous planning process.

Section 108 also calls for EPA to publish information (in cooperation with DOT) on a variety of methods and strategies that will contribute to the reduction of automobile-related pollutants and on the effectiveness and impacts of such methods.

Section 176 adds the provision that all agencies of the federal government that have authority to conduct or support any program having air quality-related transportation consequences shall give priority in the exercise of such authority to implementation of air quality plan provisions, and specifies that the section extends to authority exercised under the Urban Mass Transportation Act of 1964, title 23, U. S. Code, and the Housing and Urban Development Act of 1965. Furthermore, section 176 stipulates that no federal agency shall engage in, support, financially assist, license, or approve any action that does not conform to an air quality plan, nor shall any MPO approve any nonconforming plan, program, or project.

THE EMERGING TRANSPORTATION AND AIR QUALITY PLANNING PROCESS

The transportation and air quality planning process that is taking shape as a result of the experience of the past few years and the provisions of the Clean Air Act Amendments of 1977 has several general characteristics. As experience in planning and implementing measures to improve air quality has accumulated, there has been a growing movement to locate primary responsibility for most transportation and air quality programs at the regional level, consistent with air quality control region designations and with transportation planning and funding practices. The 1977 amendments should accelerate this trend by assigning to the MPO (or air quality maintenance agency) lead responsibility for the air quality plan revision process.

The 1970 amendments assigned TCP responsibilities to state agencies, creating an inability to tie plan elements to programming and funding processes at the regional and local levels, vagueness about implementation and enforcement responsibilities, and a lack of local and regional agency commitment to policies and programs developed largely without their input. Here too, the trend has been toward greater sharing of planning and decision-making responsibilities consistent with existing institutional lines of authority. The 1977 amendments formalize this sharing by calling for state and local agencies to determine jointly which agency and levels of government shall have responsibility for each element of the vast array of planning, implementation, and enforcement actions necessary to carry out an adequate air quality plan. Furthermore, provisions of the amendments that call for continuing consultation and for evidence of ability to carry out the plans emphasize the need for a clearly defined, participatory planning process.

A major criticism of the first round of TCPs was that insufficient attention was given to alternative planning and control actions, to the identification of social and economic impacts, and to cost-effectiveness. The amendments not only require the development of information on these issues but also call for a planning process in which such information is developed and weighed in reaching decisions about appropriate courses of action. Furthermore, public involvement in the process and the provision of information to the public about air pollution problems and potential solutions should help make the alternatives analysis more meaningful.

The 1970 amendments set a tight deadline for attainment of the air quality standards but were mostly silent about procedures for meeting the deadline and about interim results. In contrast, the 1977 amendments set a more reasonable attainment date, but also call for expeditious implementation and incremental progress in the years preceding the deadline.

Under the 1970 amendments, EPA stood virtually alone in its responsibility for assuring that transportation control plans were implemented. The new amendments assign the major federal responsibility to EPA but also call for DOT and HUD support, not only in the development of guidance for the planning process but also through their approval and funding of transportation activities and other programs with air quality impact.

As the experience of the past 5 years has proven, the planning of transportation and air quality improvements overlaps to a considerable extent with ongoing transportation planning activities, and efficiency and effectiveness considerations indicate that at least some degree of merger is appropriate. The policy in many metropolitan areas is to develop air quality improvement measures through the ongoing transportation planning process. The new amendments affirm this practice, requiring coordination with the federal urban transportation planning process, and go further to require both compatibility between the air quality plan and other plans, programs, and projects that receive federal assistance, and priority assignment to air quality plan elements.

The process that is emerging thus creates a two-way link between air quality planning and transportation planning by requiring not only that the air quality planning process be consistent with the transportation planning process, but also that the transportation planning process support and assist air quality improvement efforts.

Proposed Guidelines

In response to section 108 of the Clean Air Act Amendments of 1977, EPA prepared draft guidelines on the planning process for developing transportation components of air quality plans. The guidelines, which are being prepared with considerable input from representatives of state and local governments and federal agencies, emphasize the continuing development and implementation of transportation projects and transportation system management measures that provide incremental reductions in emissions from mobile sources as expeditiously as possible. The guidelines are designed to allow sufficient flexibility to accommmodate the characteristics and practices of a variety of institutional arrangements.

The guidelines contain five major sections. The first section calls for the modification of the transportation planning process specified in DOT regulations to incorporate the air quality-related provisions of the Clean Air Act Amendments of 1977. Consistent with those amendments, the guidelines also call for strengthening certain elements of the existing process, including involvement of elected officials, assignment of responsibility to state, regional, and local agencies, alternatives development and analysis, public participation, and plan implementation.

The next sections of the guidelines address documentation of the transportation and air quality process in the transportation planning work programs, plans, and programs of projects, as well as in the air quality plan for the area. The guidelines recommend that the prospectus include a discussion of the transportation-related air quality issues facing the area and a summary of the planning program. The unified work program would include all air quality-related transportation planning activities anticipated for the metropolitan area, including planning to be funded by EPA grants.

The TSM element of the transportation plan would document the area's consideration of all short-range measures that have the potential of reducing transportation emissions; the long-range element would summarize the consideration of major changes to reduce emissions. The TIP, including the annual element, would specify the projects being programmed and implemented that would improve air quality; priority would be given to such projects in compliance with the 1977 amendments.

The revised air quality plan would be based on these modifications and inclusions to the transportation documents. In addition, an emissions inventory and a description of programs for citizen participation, interagency coordination, and involvement of elected officials would be included in the air quality plan.

The next section of the guidelines calls for periodic progress reports on the status of the unified work program and the transportation improvement program. The progress reports would be used as the basis for determining continued eligibility for EPA planning grants and to assist the determination of compliance with the conformity, priority, and reasonable progress provisions of the 1977 amendments.

Finally, the guidelines describe the process for progress and conformity determinations. The determinations would be based on a review of the transportation plan and program documents, the progress reports, and the area's consistency analysis. After consultation with the states, the responsible agency, FHWA, and UMTA, EPA would make a finding of conformity and determine that satisfactory progress could be achieved by taking specified corrective actions or would find that serious deficiencies require adjustment or termination of EPA funding or other actions.

The emerging process, then, would have self-enforcing provisions for the compatibility of air quality planning and transportation planning: the two plans would be, simply, documentation of the same planning process and implementation activities. And the process would include a system of procedures, incentives, and sanctions designed to ensure that reasonable progress in implementing air quality improvements actually would occur.

Unresolved Issues

Although the emerging transportation-air quality process offers greatly increased potential for success, several nagging questions remain. The major objective of the proposed process is to shift transportation planning away from mere consideration of air quality toward actual implementation of air quality improvement measures. If this objective is to be attained, several issues must be resolved favorably.

The Role of the MPO

Currently, most MPO staffs perform feasibility studies and conduct certain area-wide planning efforts, but primarily they summarize and compile the planning and programming activities of local and state agencies and operators. In order to achieve the goal of regional and subarea air quality improvement, however, these disparate agencies and organizations will have to be mobilized for coordinated action. As planning agencies, MPOs simply do not have the authority (nor do they have the mandate) to direct other agencies to conduct studies or implement measures. Therefore, if coordinated action on air quality is going to occur, it will be largely dependent on the MPO in its role as a consortium of local (and state) officials reaching agreement that the members individually will take responsibility for air quality improvements.

MPO can offer valuable assistance, ranging from lend-a-planner programs and pass-through funding earmarked for particular studies or projects to studies of promising actions and identifications of the local or state agencies and officials who appropriately would perform further investigation of the actions. Many measures are appropriately planned and carried out by MPO staff (such as development of employer-based ridesharing programs). Nevertheless, the proposed process would necessitate goal-oriented commitment and responsibility on the part of local agencies and officials to a greater degree than has typically occurred in the past, plus stronger direction from the MPO as a forum and as a planning staff than has been common. Whether or not the incentives and sanctions of the proposed process will be sufficient to catalyze these changes remains to be seen.

The Problem of Perceived Costs

The transportation control planning experience of the past 5 years demonstrates the difficulties of implementing measures that are perceived by the public as imposing direct and immediate costs or inconveniences in return for modest reductions of dangers that are uncertain, indirect, diffuse, and long term. Although the proposed transportation-air quality planning process includes provisions for informing the public about air pollution problems, on one hand, and for selecting the most cost-effective, least disruptive measures possible, on the other, there is little reason to believe that political resistance to at least some of the proposed measures (automobile restraints, for example) will fade away. In some areas, attainment by 1987 may be possible through some combination of reduced emissions from a better controlled and maintained vehicle fleet, with only a modicum of voluntary programs and transit improvements for good measure. In the metropolitan areas having the worst air pollution problems, however, attainment may necessitate the implementation of measures that do impose certain restrictions on automobile mobility, increase costs, or both. No doubt these measures would be controversial, and judicious use of incentives, sanctions, and lobbying would be necessary to achieve implementation.

Progress Evaluation and Sanctions

Implementation of transportation measures to improve air quality is likely to be heavily dependent on periodic evaluations of progress and threats of sanctions, as specified in the 1977 amendments. The assessment of how much progress is reasonable is always dependent on facts and circumstances and in each case will depend on intensive and complex negotiations, lobbying, and compromises. Sanctions are more difficult: for example, although the law specifies that DOT must give priority to air quality improvements and must not fund incompatible activities, it is vague on who actually determines what giving priority means and what constitutes incompatibility. For that matter, what does it mean to give priority to the implementation of certain projects, when the DOT approval process focuses on process adequacy, not plan and program specifics? The implication may be that in order for DOT to find the process adequate, that process will have to produce programming and implementation decisions that are in accord with the air quality plans. Such an interpretation is speculative, however. Moreover, the effectiveness of imposing sanctions on an MPO in instances where responsibilities assigned to state and local agencies and officials have been neglected is questionable. Thus, perhaps the greatest uncertainty is whether the driving force of the process (periodic evaluation, incentives, and sanctions) can be designed in a way that produces sufficient pressures to assure real action.

In summary, the outlook for improved consideration of air quality in transportation planning is promising, but the potential for controversy and conflicting objectives remains. The emerging process should correct many of the problems that occurred in the past, but a great deal of work is ahead for regional, local, and state agencies and officials in establishing the process and for EPA and DOT in managing it. Where air quality problems are worst, the success or failure of the process will depend, as it always has, on whether or not the public can be persuaded that cleaner air is worth certain sacrifices and that transportation actions can in fact improve air quality.

ACKNOWLEDGMENTS

Many of the ideas presented in this paper were developed during a study conducted at the Massachusetts Institute of Technology and funded by the U.S. Environmental Protection Agency. The opinions and conclusions expressed herein are mine, however, and are not necessarily those of the EPA. I take full responsibility for any inaccuracies and omissions.

Role of the Federal Highway Administration Under the Clean Air Act Amendments of 1977

Ali F. Sevin, Community and Environmental Planning Branch, Federal Highway Administration

The Federal Highway Administration first became involved in air quality planning in the summer of 1973 when it assisted the U.S. Environmental Protection Agency in the review of transportation control strategies. Later the two agencies worked together to implement the consistency requirements of section 109j of title 23, U.S. Code. Cooperation in the development of analysis techniques, handbooks and manuals, technical conferences, workshops, and courses created the foundations for better understanding between air quality planners and transportation planners. This new understanding improves the chances of success under the Clean Air Act Amendments of 1977. The Clean Air Act Amendments of 1977 (Public Law 95-95) reveal that (a) the transportation control planning approach failed because of a lack of institutional mechanisms and inadequate technical evidence to justify the requirement of politically unacceptable measures; (b) the specification of the end product is not enough: The political, institutional, administrative, and technical processes must also be emphasized; (c) each federal agency should participate more actively in cleaning up the air; and (d) more emphasis should be given to the costs and economic consequences of proposed transportation measures. The responsibilities of the Federal Highway Administration under the new amendments include (a) assistance to the U.S. Environmental Protection Agency in developing guidelines for transportation control plans; (b) ensurance that transportation control planning is properly incorporated into the comprehensive, cooperative, and continuing urban transportation planning process; (c) ensurance that no highway projects are delayed because state implementation plans are not submitted on time; (d) ensurance that transportation plans and programs of metropolitan planning organizations conform to state implementation plans; (e) ensurance that all highway projects conform to the appropriate state implementation plan; and (f) ensurance that priority is given to the implementation of pertinent portions of the state implementation plans in the exercise of its authority.

The Federal Highway Administration (FHWA) first became involved in air quality planning in the summer of 1973 when it assisted the U.S. Environmental Protection Agency (EPA) in a review of the first round of transportation control strategies. At about the same time, FHWA began a series of consultations with EPA to develop the instructions for implementation of section 109j of title 23, U.S. Code, which requires consistency between highways constructed under that title and the approved state implementation plans to meet the ambient air quality standards.

The first round of transportation control strategies in the state implementation plans (SIP) were developed by air quality planners under extremely tight deadlines, with little advice from transportation planners. These strategies proved difficult to implement because they were, in essence, wish-lists of strategies that could only be implemented if clean air were the only objective being pursued. There was a clear need to sensitize air quality planners to the multitude of other urban objectives worthy of achievement. Transportation planners, on the other hand, needed a better understanding of how the development and operation of transportation facilities could help attain and maintain clean air in urban areas.

The air quality guidelines implementing section 109j were issued in the Federal Register on December 24, 1974, and codified in part 770 of the Code of Federal Regulations. The most important element of these guidelines for long-term effect has been the continuing review procedure that each federal urban transportation planning agency is required to establish with the cognizant air pollution control agency. Thus, transportation planners and air quality planners have been working together for a couple of years. They are beginning to appreciate each other's roles, responsibilities, and obligations.

Experience under the section 109j consistency requirement also sharpened the technical capabilities of planners in analyzing air quality impacts of transportation facilities. We are better prepared for quantitative analysis of transportation proposals and less likely to be lured into solutions that look good on paper but prove counterproductive in application.

The SAPOLLUT computer program probably has been the tool used most extensively to analyze quantitatively the air quality impacts of transportation plans. Several other computer techniques have been modeled after SAPOLLUT. Other computer programs, such as the California Line Source model, the Kansas Air Pollution Package, APRAC-1A, and more recently APRAC-2, have proved to be very helpful to both transportation and air quality planners.

The requirements of section 109j have also provided the impetus for a surge of research activity within FHWA and by state departments of transportation. The majority of this activity has been concerned with developing more sophisticated analysis techniques, such as air quality simulation models for photochemical oxidants. Numerous technical conferences, workshops, and courses have also been held. A variety of handbooks and manuals have been developed. We can safely say that transportation and air quality analysts now speak the same language and understand each other.

The Clean Air Act Amendments of 1977 (Public Law 95-95) will produce more realistic, practical, and technically sound results because it will be implemented in a more mature environment. There is little room for optimism, however, in hoping that the transportation control plans (TCP) will have a dramatic effect on air quality. The evidence shows that even under the most ambitious assumptions, improvements beyond a 2 to 5 percent level will not be forthcoming from transportation management schemes because the measures with greater yields are not yet feasible in a practical or political sense and their impact on our lifestyles is too drastic.

THE CLEAN AIR ACT AMENDMENTS OF 1977

The Clean Air Act Amendments of 1977 tell us that the TCP approach failed because (a) the institutional mechanisms were lacking, (b) there was inadequate technical evidence to justify requiring TCPs, and (c) the proposed measures were politically unacceptable. Thus, the law requires a clear-cut definition and assignment of responsibilities at the local level, introduces a direct role for the metropolitan planning organizations (MPO), requires coordination with transportation planning, and directs EPA to issue regulations governing consultation between governmental units. On the technical side, the law requires EPA, in cooperation with the U.S. Department of Transportation (DOT), to issue information on 18 specific transportation proposals to reduce mobile source pollutants, including assessments of effectiveness and impacts on transportation, economy, energy, and the environment. Further, EPA is directed to develop guidelines in consultation with DOT to govern a continuing TCP process for air quality. These guidelines will help focus both the institutional and the technical processes.

The law also tells us that specification of the end product is not enough and that the air quality agencies at the federal, state, and local levels should concern themselves with the political, institutional, administrative, and technical processes. Thus, the law mandates reasonable public notice and hearings (section 129), continued planning (section 105), consultation (section 119), periodic review of ambient air quality standards (section 106), and systematic deferrals of attainment dates with incremental conditions (section 129).

The law directs each federal agency to be a more active participant with EPA in cleaning up the air. Thus, each department, agency, or instrumentality of the federal government is directed to conform with SIP in administering its program and to give priority to projects that are proposed for improving air quality (section 129).

Lastly, the law focuses on the costs and economic consequences of measures proposed to reduce air pollution. Apart from the new section on economic impact assessment (section 307), which applies to EPA regulations on standards and significant deterioration, the law is sprinkled with requirements that direct attention to economic impacts. Thus, the Secretary of Labor is directed to study the potential employment dislocations due to EPA's programs (section 403). Step-wise extensions are provided for areas in which the standards for photochemical oxidants or carbon monoxide (CO) cannot be met by available measures (section 129). EPA is directed to disseminate information on methods of pollution reduction and document the energy and economic impacts in addition to the environmental impacts of these methods (section 105). EPA is directed to study the increased use of cost-effectiveness analyses in devising strategies to control pollution and report to Congress not later than January 1, 1979 (section 223).

The continuing review procedures established to achieve consistency between transportation plans prepared by the MPOs and the SIPs prepared by the air quality agencies have set the stage for implementing the new requirements of the Clean Air Act Amendments of 1977. Congress appears to have used the experience accumulated under section 109j as a model in writing the transportation control planning requirements into law. The states are urged to cooperate with local officials and designate, where feasible, the MPO as the responsible agent to prepare TCPs. In any case, preparation of the implementation plans shall be coordinated with the federal urban transportation planning process required under section 134 of title 23, U.S. Code.

Transportation control planning under the Clean Air Act Amendments of 1977 should consist of a natural extension of the procedures begun under section 109j of title 23, U.S. Code. It would be fortunate indeed if in all areas needing transportation control planning the MPOs were designated as the responsible agencies. The federal oversight would be minimized because the transportation implementation programs and TCPs would be one and the same and, therefore, consistent by definition. The quality of planning should also improve because of new funding from EPA for transportation control planning.

In those areas in which some other agency is designated for transportation control planning and the MPOs are required to conform to the measures established by this agency or promulgated by EPA, one can expect duplication in the planning work, miscommunications, increased federal oversight, a delay in the implementation of any measures, and a general diffusion of the planning dollar. Any measure not developed through the federal urban transportation planning process cannot be built with federal-aid highway or Urban Mass Transportation Administration (UMTA) funds. Therefore, any measure developed by the air quality agency that requires capital from either FHWA or UMTA programs must be included in the MPO's program. The air quality planning agency must pay particular attention to cultivating open, cooperative relations with the MPO.

The consistency determinations under section 109j of title 23, U.S. Code, will continue until at least January 1, 1979, when new SIPs are due. After the new SIPs become effective, transportation plans and programs developed by MPOs will be required to conform to the SIPs, and FHWA and UMTA must be certain that any projects utilizing their funds also conform to the SIPs. At that stage, the existing consistency determination and the conformance finding should be one federal action.

FHWA'S RESPONSIBILITIES UNDER THE CLEAN AIR ACT AMENDMENTS OF 1977

To delineate the FHWA's responsibilities under the 1977 amendments, we should view the requirements of this piece of legislation against the backdrop of title 23, which is the legislative source of the Federal-Aid Highway Program. The following list enumerates FHWA's role:

1. FHWA must assist EPA in developing guidelines for transportation control planning by utilizing its expertise, which resides both in its field organizations and the headquarters office. FHWA must ensure that the guidelines are realistic and workable.
2. Together with EPA, FHWA must publish sound technical information on processes, procedures, and methods to reduce pollutants as an aid to those responsible for proposing and implementing transportation measures to help reduce mobile source pollutants.
3. FHWA must ensure that transportation control planning is incorporated into section 134 planning required under title 23, U.S. Code. The unified work program reviews provide the framework for this activity. FHWA should encourage the continuing involvement of EPA regions in the intermodal planning groups and the incorporation of EPA-funded planning studies in the unified work program.
4. FHWA must ensure that no highway projects are delayed because SIPs are not submitted on time. This will entail getting together with state and local officials to assist EPA in writing the consultation regulations required by the Clean Air Act Amendments of 1977, such that the continuing review procedures established under section 109j of title 23, U.S. Code, are reinforced and plans are developed on time.
5. FHWA must ensure that transportation plans and programs submitted by an MPO conform to an SIP that has been approved or promulgated under the Clean Air Act.
6. FHWA must ensure that all highway projects approved under title 23 conform to the appropriate SIP that has been approved or promulgated under the Clean Air Act.

FHWA must give priority to the implementation of pertinent portions of the SIPs in the exercise of its authority, consistent with statutory requirements under title 23, which specify priorities also in other areas. For example, title 23 directs the secretary to give priority to projects that: (a) expedite completion of Interstate highways (section 105c), (b) provide safety benefits (section 105f), (c) provide access to air and water ports (section 105g), and (d) improve traffic flow (section 135). The priority given to SIP projects must be, therefore, in balance with the above priorities.

Integrating Air Quality Considerations and the Transportation Planning Process: Experience in the Washington Area

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Any discussion of the relation between transportation and air quality planning on a metropolitan scale must necessarily begin with a brief explanation of the roles and responsibilities of key agencies and organizations. Accordingly, this paper starts with a summary description of those planning and implementing agencies in the National Capital Region that contribute to the integration of air quality considerations into transportation planning. This is followed by a review of the area's experience with the annual assessment of consistency of the region's transportation plans and programs to state implementation plans to achieve air quality. Several of the key issues that have generated controversy between transportation planners and air quality planners are identified and discussed. And, finally, this paper reports on the current organizational and planning approach being developed for the metropolitan Washington area to meet the requirements of the Clean Air Act Amendments of 1977.

AGENCY ROLES AND RESPONSIBILITIES

The areawide umbrella agency that has both transportation and air quality-related responsibilities on the metropolitan planning scale is the Metropolitan Washington Council of Governments (COG). COG was established in 1957 for the primary purpose of coordinating mutual efforts by the major governments in the Washington area against common interjurisdictional problems. COG is the region's only areawide, multipurpose organization, where local officials direct a comprehensive assessment of the problems and opportunities that confront the region and determine cooperative courses of action. An integral part of COG's program is the development of policies on the future form, structure, and quality of life in the metropolitan area. These policies are put forth as general guidelines for decision makers in agencies in the Washington area. The power to implement the policies lies in the hands of these governments and agencies.

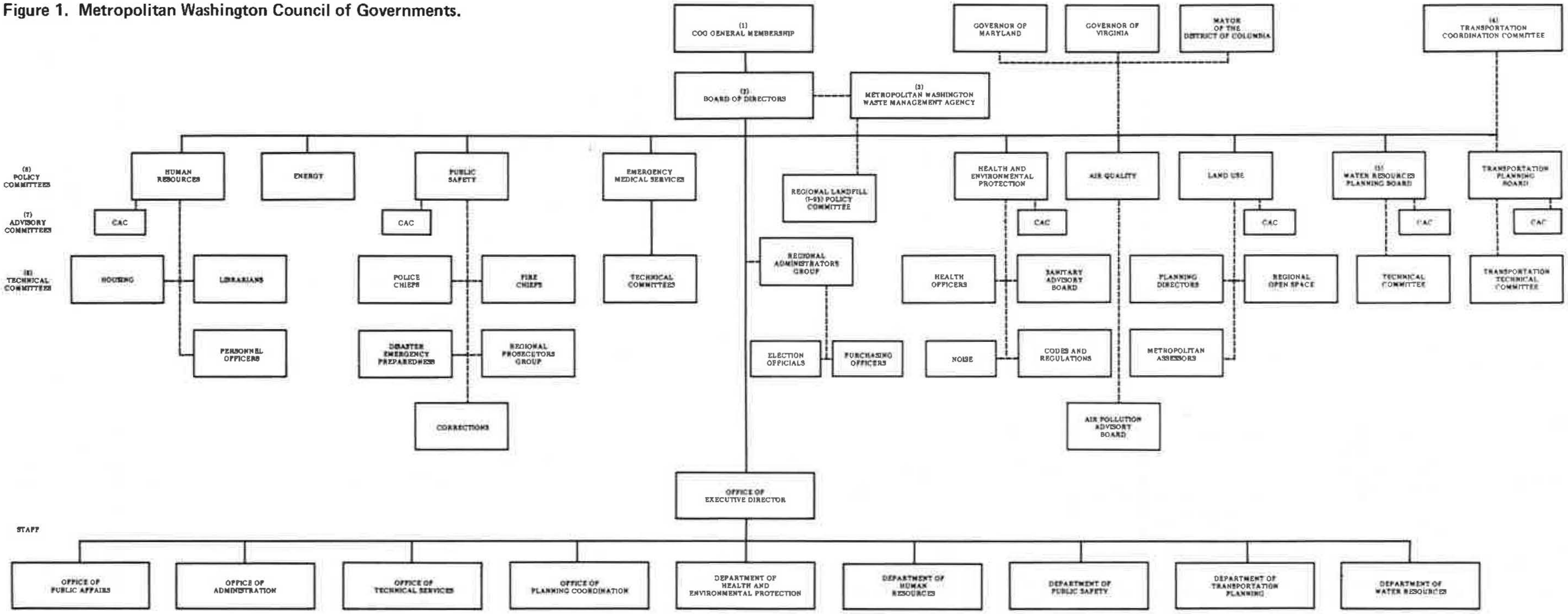
COG coordinates comprehensive planning, transportation planning, and transit planning and programming by the many regional, subregional, and local agencies in the Washington metropolitan area. COG has been designated as the metropolitan clearinghouse for the area and has the responsibility to review and comment on whether proposed federal-aid projects are consistent with areawide policies, goals, and objectives.

In a formal sense, COG is a nonprofit corporation, and membership in it is voluntary. It operates on a basis of consensus and does not have coercive authority. Figure 1, the COG organizational chart, indicates the broad spectrum of functional planning activities within COG's comprehensive planning umbrella.

The National Capital Region Transportation Planning Board (TPB), a member of the COG family, is responsible for conducting the continuing, comprehensive, and cooperative transportation planning process for the Washington metropolitan area in accordance with the requirements of the Federal-Aid Highway Act of 1962 and the Urban Mass Transportation Act of 1964, as amended. Its policy body is made up of local government officials, representatives of the state transportation agencies and the regional transit authority, and appropriate federal agencies. The governors of Maryland and Virginia and the mayor of the District of Columbia have designated the TPB as the metropolitan planning organization (MPO) for the Washington metropolitan area. The TPB also serves as the transportation planning arm of COG to ensure that transportation planning is integrated with comprehensive metropolitan planning and development and is responsive to the local political decision-making process.

The Air Quality Planning Committee (AQPC), another member of the COG family, was established by administrative agreement between the governors of Maryland and Virginia and the mayor of the District of Columbia to coordinate the interjurisdictional planning aspects of the air pollution control activities within the National Capital Interstate Air Quality Control Region. The AQPC is composed of local government officials and air pollution control agency officials in the three major jurisdictions. It plans for the preservation, protection, and improvement of air quality in the region and develops recommendations to ensure attainment and maintenance of air quality standards.

Figure 1. Metropolitan Washington Council of Governments.



(1) 213 MEMBERS CONSISTING OF THE MEMBERS OF THE GOVERNING BODIES OF THE 18 MAJOR LOCAL JURISDICTIONS, TOGETHER WITH ALL CONGRESSIONAL AND STATE LEGISLATORS OF THE METROPOLITAN WASHINGTON AREA.

(2) 23 MEMBERS. FOUR SELECTED FROM AND BY THE DISTRICT OF COLUMBIA, TWO EACH FROM FAIRFAX, MONTGOMERY AND PRINCE GEORGE'S COUNTIES, ONE FROM EACH OF THE REMAINING SUBURBAN JURISDICTIONS AND ONE MEMBER EACH FROM THE MARYLAND AND VIRGINIA LEGISLATURES.

(3) COMPOSED OF THE COG BOARD OF DIRECTORS, THE HEALTH AND ENVIRONMENTAL PROTECTION POLICY COMMITTEE, AND SUCH OTHER ELECTED OFFICIALS FROM THE WASHINGTON METROPOLITAN AREA AS MAY BE PROVIDED FOR IN THE BY-LAWS.

(4) ONE REPRESENTATIVE FROM EACH OF 12 LOCAL GOVERNMENTS AND THE DISTRICT OF COLUMBIA, VIRGINIA, AND MARYLAND HIGHWAY DEPARTMENTS.

(5) COMPOSED OF REPRESENTATIVES OF LOCAL GOVERNMENTS AND THE STATES OF MARYLAND, VIRGINIA AND THE DISTRICT OF COLUMBIA, ACTING AS A STATE THROUGH THE INTERSTATE COMMISSION ON THE POTOMAC RIVER BASIN, AND THE NORTHERN VIRGINIA PLANNING DISTRICT COMMISSION.

(6) GENERALLY COMPOSED OF LOCAL GOVERNING OFFICIALS AND REPRESENTATIVES OF THE STATE AND FEDERAL GOVERNMENTS AND SPECIAL PURPOSE AGENCIES, WHERE APPROPRIATE.

(7) COMPOSED OF CITIZENS REPRESENTING LOCAL JURISDICTIONS AND REPRESENTATIVES OF SPECIAL INTEREST GROUPS.

(8) COMPOSED OF SENIOR STAFF MEMBERS OF LOCAL GOVERNMENTS IN THE WASHINGTON AREA AND OTHER CONCERNED AGENCIES.

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A number of agencies responsible for implementation participate in the planning activities of COG, the TPB, and the AQPC. The following should be noted because of their role in implementing air quality-related transportation measures in the region.

The Washington Metropolitan Area Transit Authority (WMATA) was created by interstate compact in 1966 and is charged with the planning, development, financing, and operation of the rapid rail transit system for the Washington metropolitan area. Early in 1973, WMATA assumed ownership and operation of the area's four bus companies. The first 29 km (18 miles) of a planned 161-km (100-mile) rapid rail system is now in operation.

At the state level, the Maryland Department of Transportation, the Virginia Department of Highways and Transportation, and the D.C. Department of Transportation are responsible for the planning, design, and construction of the major highway systems in their respective jurisdictions and for transit planning as related to providing roadway access to rapid transit stations and facilities for preferential treatment of buses. The Maryland Department of Transportation also has responsibility for other modes of transportation and provides a substantial portion of the Maryland local governments' share of capital and operating costs of the Metrorail and Metrobus systems.

Finally, at the local level, the Arlington County (Virginia) Department of Transportation, the Montgomery County (Maryland) Department of Transportation, and the Prince George's County (Maryland) Department of Public Works and Transportation are responsible for the construction, operation, maintenance, and signalization of all county roads within their specific jurisdictions. Other responsibilities include traffic operations improvements, preferential transit treatment, and bikeway construction. The Montgomery County Department of Transportation maintains over 12 000 public parking spaces in four business districts, operates a fixed-route minibus system, and controls a general aviation airport.

ASSESSMENT OF CONSISTENCY

The annual assessment of consistency in the Washington metropolitan area generally begins with the preparation of a set of findings by the TPB technical committee and staff on the degree to which transportation decisions and actions during the previous year have contributed to the improvement of air quality in the region. These findings, together with supporting documentation, are then presented to the TPB for review and concurrence before the materials are transmitted to the cognizant air pollution control agencies in the region, the AQPC, and appropriate state and local agencies for review and comment. The comments received are then reviewed and analyzed by the technical committee and staff. Each of the points made by the cognizant air pollution control agencies is addressed and a report is prepared. The report includes a specific recommendation on consistency, as well as a number of additional recommendations responsive to the comments and suggestions of the cognizant air pollution control agencies and designed to further improve air quality in the year ahead. The report and recommendations are transmitted to the TPB for consideration and final action.

Since the federal requirements for an assessment of consistency were established several years ago, the TPB has been able to make a determination each year that the transportation planning process for the National Capital Region is in general compliance with the requirements of part 770 of title 23, Code of Federal Regulations.

In their most recent joint statement of certification of the transportation planning process for the Washington metropolitan area, the Federal Highway Administration (FHWA) and the Urban Mass Transportation Administration (UMTA) found the following with regard to the TPB's December 1976 assessment of consistency.

> Review of the latest air quality consistency determination indicates (a) positive response to our previous comments, (b) adequate coordination with the air pollution control agencies, (c) adequate support for the consistency determination, (d) a strong commitment to continue efforts to consider air quality in both the short-range and the long-range planning efforts, and (e) a strong commitment to evaluate and work toward implementation of additional transportation measures that will aid in improving air quality.

The impression that transportation and air quality planners are in complete accord needs to be corrected. In varying degrees, several of the cognizant air pollution control agencies have not agreed with the findings of the TPB, and a number of air quality-related transportation issues continue to divide transportation and air quality planners. Among the questions that are still being debated by transportation and air quality planners are

1. How should consistency be defined?
2. How much highway capacity should there be in a transportation plan?
3. How much should vehicle kilometers of travel be reduced?

DEFINITION OF CONSISTENCY

In the National Capital Region, air quality planners have viewed consistency in rather strict terms of whether or not transportation plans and programs will achieve ambient air quality standards for the region. They have also placed the burden of proof in achieving standards on TPB transportation plans and programs, regardless of whether actions beyond the control of the TPB [such as elimination of key transportation control measures by Congress and the U.S. Environmental Protection Agency (EPA) and delays in implementation of the federal motor vehicle emission control plan] have made achievement of standards increasingly difficult, if not impossible.

The TPB, on the other hand, has made its finding of consistency based on the degree of commitment and demonstrated effort by the responsible transportation agencies in the region to improve air quality within the prerogatives available to them. This approach recognizes that air quality standards cannot be achieved by transportation actions alone, and that consistency at this point in time can be measured most realistically in terms of whether or not transportation decisions and actions will contribute to the further improvement of air quality on a year-by-year basis.

Highway Capacity

As evidence of the continuing efforts and commitment of the region to improve air quality, the TPB may point to such recent actions as

1. Significant reductions in major highway elements of the long-range transportation plan (LRTP),
2. Major transfers of Interstate highway funds for use in construction of the area's Metrorail rapid transit network, and

3. Adoption of a heavily transit-oriented transportation improvement program.

The area's air pollution agencies generally recognized such progress in moving toward air quality goals, but they still have difficulty finding consistency because of transportation plans and programs that still contain highway improvements. Their positions vary from concern over indicated major highway facilities in the LRTP to minor improvements to a local arterial intersection or a traffic signal system in the short range transportation improvement program (SRTIP). These varying views and concerns involve two issues.

The first issue relates to the LRTP. The responsibility of the TPB is to identify long-range transportation demands at the regional scale, given currently accepted forecasts of population and employment growth, and the currently adopted mass transit system proposed for the region, including the Metrorail, Metrobus, commuter rail, and other transit improvements. Where technical analysis identifies future deficiencies in highway capacity to meet forecast vehicular travel growth, even given an extensive transit network, these deficiencies must be addressed in the LRTP. To ignore such deficiencies and not identify the highway improvements that would be required to meet the projected demand would result in an incomplete transportation planning process, inconsistent with federal requirements and unacceptable to federal agencies for certification purposes.

This does not necessarily mean that all major highway elements shown in the LRTP can or should be built. Rather, it indicates the future highway capacity that will be required unless significant changes in land use, transportation patterns, and regulatory policies occur in the interim period. It is essential to show needed highway improvements in the LRTP so that decision makers can plan ahead either to provide the necessary facilities or to take steps to reduce or eliminate the need for such facilities. The conflict arises when air quality agencies review the LRTP and declare it inconsistent because it contains some highway improvements, without considering the nature and requirements of the long-range transportation planning process, which over the past 10 years has resulted in a continuing reduction in major highway elements and distance and a continuing increase in major transit elements and distance.

The second issue relates to the SRTIP. In this case, some air quality planners appear to consider any increase in highway capacity, either directly or incidentally and no matter how minor or for what purpose, to be inconsistent with air quality goals. And yet, while some short-range highway improvements may serve automobile travel exclusively, the large majority of highway improvements are designed to remedy hazardous safety problems (such as high accident intersections and deteriorating structures) and to provide for improved bus and carpool movements and bus access to Metro stations. Elimination of all short-range highway improvements in the name of air quality would fail to satisfy certain critical transportation needs and may prove to be counterproductive. Rather, both air quality and transportation planners should evaluate short-range highway improvements (which in a number of cases are actually transit improvements using highway funds) in terms of their relative impacts and contributions in the areas of air quality, traffic safety, energy conservation, transit service, traffic congestion, and cost-effectiveness, so that decision makers can consider trade-offs in setting transportation investment priorities.

Vehicle Kilometers of Travel

In their comments, some air pollution control agencies have also pointed out that current transportation plans and programs do not reduce vehicular trips and distances traveled sufficiently (without indicating how much is sufficient). The issue here is the degree to which such reduction can be achieved by transportation measures and options alone, without an adverse impact on the region's economic health and vitality.

Commuter trip length is directly related to the distance between home and work. Unless the trip length can be reduced by rearrangements of land use, the distance between home and work for a given trip will remain the same. Further, since most of the future growth in population and employment will be in the outer suburbs (causing increases in intrasuburban travel not readily served by transit), distance traveled will increase in the region, even with Metro expected to absorb most of the future growth in radial travel demand to the core. Therefore, while a certain amount of reduction in distance traveled can be achieved by transportation system management measures, more attention must be given to spatial relationships in the growing suburban areas designed to reduce trip lengths and the number of trips required, if significant areawide reductions are to be achieved. Reduction in the distances traveled and the number of trips must be considered within this larger and longer range context, as well as in terms of the immediate impact on air quality.

A distinction between length of trips and the number of trips should be noted here. As the Federal Motor Vehicle Emission Control Plan is implemented, emissions from motor vehicles will become more a function of the numbers of trips made than trip length. The reason for this is that motor vehicle emission controls will reduce emissions significantly while a vehicle is in motion, but have little effect on the emissions resulting from cold start and hot soak phenomena at the beginning and end of a trip. Therefore, reductions in the number of trips will become more significant in improving air quality than reductions in length of trips. This suggests greater emphasis on land use arrangements that encourage walking, biking, or transit trips instead of automobile trips, and one-stop automobile trips instead of multistop automobile trips. It also suggests greater emphasis on strategies such as automobile and van pooling to reduce the number of single-occupant automobile trips required for commuting purposes.

IMPACT OF CLEAN AIR ACT AMENDMENTS OF 1977

The Clean Air Act Amendments of 1977 provide that, in areas that do not meet national ambient air quality standards, a revised implementation plan can be prepared, thus extending the deadline for attaining the national standards. The Washington metropolitan area is an area that does not meet standards. To ensure their participation and involvement, certain steps must be taken by the area's local governments no later than February 7, 1978.

First, the local governments may designate an organization of elected officials of local governments to prepare the revised plan. If they do not act by February 7, the governors shall make the designation. Second, the local governments, states, and regional agency in a nonattainment area must determine jointly which elements of a revised plan will be planned for, implemented, and enforced by local governments, states, or a regional agency.

Table 1. Possible assignments of state, local, and regional responsibilities.

Candidate Element Classifications	Planning	Implementation	Enforcement
Traffic operation improvement	Regional, local, state	State, local	State, local
Improve transit and high-occupancy vehicles treatment and service	Regional, local	Regional, local	State, local
Pedestrian and bicycle movement	Regional, local	State, local	State, local
Parking management	Regional, local	Local	Local
Vehicle inspection and maintenance	Regional, state	State	State
Transportation pricing	Regional, state	State, local	State, local
Control of emissions at source (mechanical control)	Regional	State, local	State, local

In the Washington metropolitan area, a local-state-regional partnership approach has been proposed. It builds on the experience and cooperative working relations developed under the general COG umbrella.

Under this approach, the TPB would have primary responsibility for planning and scheduling transportation control measures. The AQPC would have primary responsibility for measures to reduce nonmobile sources of air pollution. The primary responsibility of the Board of Directors (BOD) of COG will be to ensure that the planning efforts of TPB and AQPC can be integrated into a revised plan that will meet national standards. The goal of this joint cooperative effort is a comprehensive 5-year program of implementable measures designed to achieve air quality standards for the region by the end of 1982.

Two principles were followed in drafting the proposed organizational framework and planning process necessary to comply with the act.

1. The existing planning structure of COG (its committees of local and state government representatives) was used to avoid duplication of effort or the creation of a separate agency or planning process.

2. While building on the existing decision-making structure in COG, participation in the process would not diminish the special transportation planning authority in the TPB or the policy role of the AQPC.

The proposed general planning sequence and responsibilities for carrying out the necessary planning effort are given below.

Planning Sequence	Responsible Authority
Predict future growth patterns	BOD
Predict future transportation demand	TPB
Predict future air quality levels	AQPC
Review existing land use measures	BOD
Review existing transportation measures	TPB
Review existing nonmobile measures	AQPC
Identify potential of locally implemented land use measures	BOD
Identify potential transportation measures	TPB
Identify potential nonmobile measures	AQPC
Determine air quality benefits of all measures	AQPC
Determine feasibility of locally implemented land use measures	BOD
Determine feasibility of transportation measures	TPB
Determine feasibility of nonmobile sources	AQPC
Integrate the coordinated planning efforts of TPB and AQPC into a revised TCP meeting national standards	BOD

Table 1 identifies possible assignments of local, state, and regional responsibilities for various candidate element classifications.

Considerable negotiating efforts still lie before us, but we believe that the cooperative organizational principles proposed, including the involvement and active participation of all responsible local, state, and regional agencies in the planning process, will enable us to meet the requirements of the Clean Air Act Amendments of 1977 and to develop a realistic and implementable program of measures designed to achieve air quality standards for the region in a timely and acceptable manner.

Development of a Method to Relate 8-Hour Trip Generation to Emissions Characteristics

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The objective of this paper is to demonstrate the development and integration of an efficient method for computing 8-h periods of trip generation and their resulting carbon monoxide, nitrogen oxide, and hydrocarbon emissions, by employing current emissions-dispersion models in conjunction with a direct assignment algorithm and appropriate regression analysis. After appropriate determination of land use stimuli and functional highway class, volumes are forecast using the direct assignment approach and input into the emissions model computations. Subsequently, calibration of a regression-of-emissions versus trip-generation input yields the capability to forecast a series of emissions consequences versus land use.

Transportation planners are becoming increasingly concerned about the planning tools available for small to medium-sized cities (50 000 to 250 000 population). The analytic modeling and associated computer packages developed to date are only cost-effective for larger urban areas. Another issue that has compounded this problem is the Clean Air Act of 1970, which as amended forces air quality criteria into the transportation and land use planning process. Further, the current models for assessment of air quality are also more useful for larger urban areas.

In light of the above, the objective of this research endeavor is to demonstrate the development and integration of an efficient method for computing 8-h periods of trip generation and their resulting carbon monoxide (CO), nitrous oxide (NO_x), and hydrocarbon (HC) emissions by employing current emissions models (1) in conjunction with a direct assignment algorithm and appropriate regression analysis (2). After appropriate determination of land use stimuli and functional highway class, volumes are forecast using the direct assignment approach and input into the emissions model computations. Subsequently, calibration of a regression-of-emissions versus trip-generation input is made, which yields the capability of forecasting a series of emissions consequences of specific land use patterns and highway network components.

Concern in the early 1960s about planning tools for small to medium-sized urban areas indicated development of a gap between needs and capabilities. Computer packages, such as the urban transportation plan (UTP) program package, were only cost-effective for larger urban areas that have large areawide networks and transportation systems. More recent activity, such as the incorporation of air quality criteria (3) in the planning process have aggravated this gap through the use of assessment models directed to larger urban areas.

The direct assignment technique was first developed by Schneider (4) in the early 1960s to mitigate many of the above disadvantages as well as to fulfill needs for detailed local information. The capability was sought to relate specific land use or development impacts to adjoining street segment volumes, thus yielding the capability to analyze specific network links or modifications.

For the application of the direct assignment technique, certain critical parameters must be defined or quantified. (SI units are not given for the variables of this model inasmuch as its operation requires that the variables be in U.S. customary units.) Trip end density refers to a measure of the specific area attractiveness, expressed in terms of trip ends per acre. Roadway spacing refers to the mean distance between various parallel links of functionally equivalent roadway segments, such as expressway, arterial, and local. Finally, a value for the mean trip length must be developed to reflect travel behavior in the region under study. The output of the direct assignment is the 24-h average daily traffic (ADT) for the specific link in question (5).

Direct assignment can be viewed as a generalized form of a gravity model, which has been typically expressed as

$$T_{ij} = V_i F_{ij} V_j / I_j \tag{1}$$

where

T_{ij} = trips between points i and j,
V_i = trip origins at i,
F_{ij} = separation function between i and j,
V_j = trip destinations at j, and
I_j = accessibility function.

The approach of direct assignment is to substitute for the term V_j some measure of land development at j, the notation R_j. Now the above equation becomes

$$T_{ij} = V_i F_{ij} R_j / I_j \tag{2}$$

where

R_j = measure of land development at j (6).

For the purposes of direct assignment, a trip is defined as that portion (complete or partial) of the travel trajectory lying on the minimum cost path. This path can be typically represented by an exponential decay function with input parameters, such as travel time and travel cost. As seen from the above equation, an increase in trip volumes will result from increases in accessibility and land development (7).

Generally, for any given link in a network, direct assignment of traffic volumes is a four-step procedure. Initially, domain boundaries for the specific link in question are defined, as well as the associated minimum path trees. The domain boundary represents the set of indifference points that can be reached equally well by traveling the link either northbound or southbound.

The north prime domain (n′) is a subset of points of the north domain for which the minimum path of northbound necessitates the use of the link under study. By a similar definition, the south prime domain (s′) is presented.

Next, the minimum path trees are also defined for other links crossing the domain boundary. The minimum path trees for the link in question are then partitioned into two sets. One set consists of minimum path trees that are not part of the minimum path trees for any competing link and are designated as the prime domains. The other is the entire nonpartitioned set of minimum path trees.

Finally, the traffic volume on the link under study is calculated from the equation

$$Q = (I_n I_s' + I_s I_n')/(I_n + I_s) \tag{3}$$

where

Q = traffic volume,
I_n = north domain integral,
I_s = south domain integral,
I_n' = north prime domain integral, and
I_s' = south prime domain integral.

These domain integrals have the following interpretation. For each of the respective domain regions, I is defined as the accessibility of a point that generates trip density (V) modified by the appropriate land development (R). Notationally,

$$I_i = \sum_j R_j F_{ij} \tag{4}$$

where

I_i = domain integral for point i,
R_j = measure of land development at point j, and
F_{ij} = separation function between i and j.

In practice, such prime domain-minimum time paths and the associated travel costs are used in conjunction with trip end density, trip length, and measures of roadway spacing to generate a book of direct assignment tables (8). Previous analysis and applications (9, 10) indicated a reasonable fit of predicted to actual link volumes. Limitations do exist for this assignment technique. Direct assignment is not formulated to consider the travel demand process for the individual tripmaker. However, the technique has proved reliable in the estimation of traffic volumes under the previously described study design and parameters.

After some period of study, the Kansas Air Pollution Package (KAPP) (11) was chosen as suitable for the uses anticipated in this project. KAPP is an integrated package of an emissions model and a diffusion model. Although the emissions model is generically the same as the SAPOLLUT model (12) (i.e., based on average speed), it posesses several advantages. Of primary importance, it is oriented toward current emission estimates and uses actual roadway count information. It is simple to modify vehicle age distributions in the model for both trucks and automobiles to be more specific to a particular local area. KAPP is a comprehensive package, well documented, containing excellent report and graphics capabilities. Finally, it has an efficient input format, which allows ease of estimation of emissions on arbitrary roadway segments. This latter characteristic renders it especially attractive for site-specific studies, where the analyst is continually varying certain parameters of the site and observing the results.

OVERVIEW OF MODELING APPROACH

The modeling process developed in this research study uses available land use and roadway information inputs for an arbitrarily compact study area and attempts to translate these into meaningful estimates of traffic volumes and emissions. The theoretical foundation of this process includes empirical trip generation information and direct traffic assignment computational entities. The end result has several significant advantages over existing traffic and emissions estimating procedures: (a) the process requires data that can be obtained easily and inexpensively for a small area, and (b) the overhead of running an emissions model for an entire network to observe the results in a small area is not required. This latter result is important from the point of view of both the land use developer and the local public agency charged with making zoning decisions that affect air quality. By employing such a modeling approach, the developer is not required to make costly, detailed site plans in order to estimate the air quality impact, only to discover that the development would violate air quality standards.

Submodels

The first submodel uses land use and roadway information to predict roadway traffic volume estimates for a given geographic area. It will be referred to as the Stage I model. The first input to the model is land use information, which takes the form of the number of acres of specific types of land in the geographic area of interest. For the Peoria case study sites, the land use acreages by ten categories for the transportation analysis zones (TAZ) were used.

The next set of inputs are the roadway network characteristics. These include average spacing (in miles) between local streets, arterial streets, and expressways. The input information is used in a group of regression equations to predict the output of the Stage I model. The output is predicted 24-h roadway volume stratified by functional class of roadway (local, arterial, or expressway). The direct assignment process is incorporated in this model via the regression equations. Direct assignment is used to provide the predicted volumes, by functional class, to be used as dependent variables in the calibration process.

The Stage II model makes the next logical step in the modeling process, using the same land use and roadway spacing inputs employed in the Stage I model. It is used to predict emissions of CO, NO_x, and HC for small geographic areas. The Stage II model results in a series of regression equations; however, the equations now predict total emissions of CO, NO_x, and HC for the geographic area under consideration. An important component of the calibration of the Stage II model is the emissions estimation process used to derive dependent variables for the Stage II model calibration procedure. The process has several inputs. The first set is the predicted roadway volumes by functional class output from the Stage I model direct assignment process for a particular geographic area's roadway links. The other set of inputs is average speed information on each link in the geographic area. This information was obtained from the Federal Highway Administration (FHWA) link data cards supplied by Illinois Department of Transportation. Additional link information such as link distance and node numbers are used as appropriate identification characteristics of the links under study.

All of the above information is used by the KAPP emission model to predict emissions of CO, NO_x, and HC for a particular geographic area. The Stage I model is used to predict roadway volumes, and the Stage II model is used to predict area emissions given such volumes. Both use the same land use and roadway spacing information and yield valuable information on land use and roadway network behavior and land use-mobile source emissions.

Case Study City

Peoria is a medium-sized city in west-central Illinois with a metropolitan area population of 127 000. Peoria has just completed an urban transportation planning study in conjunction with the Illinois Department of Transportation. Recently Peoria has been the site of an air pollution monitoring program by the Illinois Environmental Protection Agency (13).

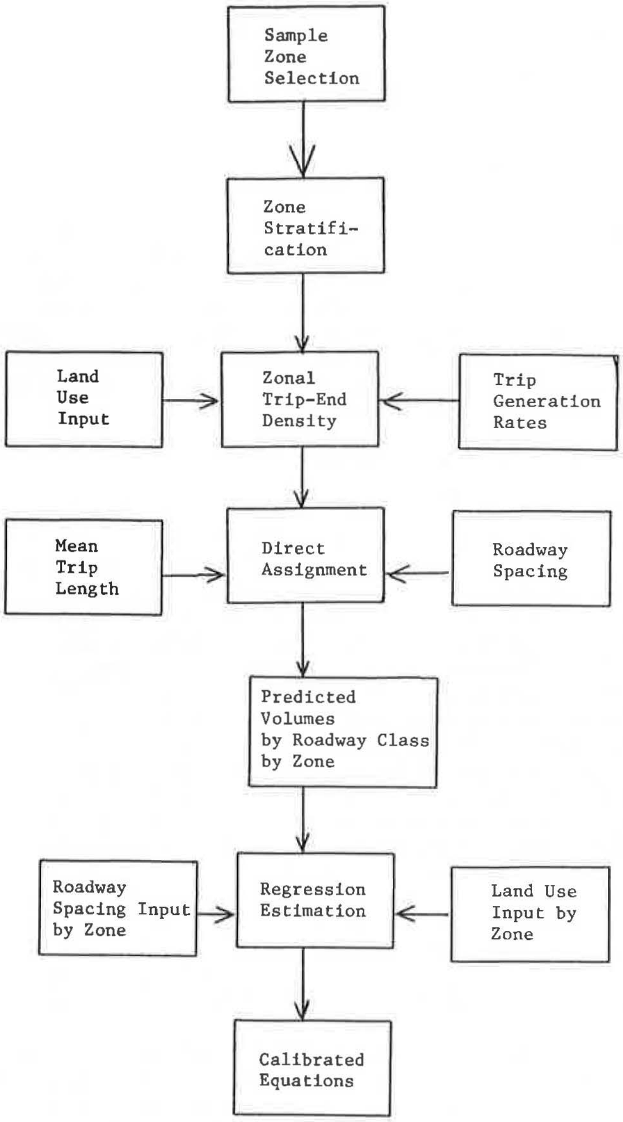
Peoria has seen pressures in recent years for outward urban growth similar to that in other cities within the 50 000 to 250 000 population size. Concurrent with this outward migration, a freeway system is emerging within the urban area. Finally, the socioeconomic breakdown of the population of the Peoria area is similar in nature to that of other small to medium-sized cities of Illinois, thus allowing for comparison with other areas within the state.

STAGE I MODEL CALIBRATION PROCEDURE

The calibration procedure for the Stage I model was composed of several steps, as indicated in Figure 1. The first task involved the selection of a representative sample of traffic analysis zones to be used as observations. A sample of 30 zones was selected randomly and included several from the Peoria central business district (CBD), some from Peoria city, Peoria County, and some from Tazewell County, including East Peoria. The next step in the procedure was to stratify the selected zones. Stratification was done on the basis of zone sites (in acres) because the smaller, more urban zones would likely have different network behavior than the larger suburban and semirural zones. This line of reasoning was proven to be appropriate: Results indicated that the statistical fit with two stratifications was roughly twice as good as when all zones are in the same sample. The size limit for the zone was set at 50 acres; 16 zones fell in the less than 50-acre class and 14 zones fell in the over 50-acre class.

The next major step in the process was to estimate end density for vehicle trips for the zones in the sample. The land use and site-specific trip generation rates derived from selected Illinois small to medium-sized cities were adjusted slightly for the Peoria area and were used with the various land-use acreages in each zone to estimate the vehicle trip ends generated. These estimated vehicle trip ends were then divided by the total acreage in each zone to yield the vehicle trip end density for each zone.

Figure 1. Stage I model calibration.



The above end densitities for vehicle trips were then used to estimate roadway volumes via the direct assignment technique. The other parameters needed for each zone were the average spacing between local streets, arterial streets, and expressways, and the mean trip length.

Using the Peoria 1970 network, individual roadway links were assigned to each of the zones. The mean trip length of 6 miles was used for the direct assignment process (4, p. 74). Given the three spacing parameters, the trip end density, and the mean trip length for each zone, a direct assignment was carried out for each zone, which yielded estimates of daily local, arterial, and expressway volumes. In general, the direct assignment volumes tended to be quite close for arterials, somewhat low for local streets, and somewhat high for expressways compared to the indicated daily volumes on the link records.

The predicted volumes for each functional class in each zone were then used in a multivariate linear regression procedure. The volumes were treated as dependent variables, and the acres of land by type and the roadway spacing by class were treated as independent variables. Hence, one regression model was run for each functional class for each of the two-zone size stratifications, resulting in a total of six regressions. A summary of the regression statistics for the six models is shown below.

Dependent Variable	F-Ratio	R^2
Local street volume		
Small zones (A)	15.86	0.977
Large zones (B)	8.38	0.978
Arterial street volume		
Small zones (C)	9.78	0.964
Large zones (D)	6.22	0.971
Expressway volume		
Small zones (E)	7.75	0.955
Large zones (F)	20.61	0.991

The variables for each model were the same, and the coefficients for each, the intercept term, and the standard errors of estimate are depicted in Table 1. The percentage of total variance explained by the models is very high, 95.5 to 99.1, but the confidence intervals for several of the parameter coefficients include zero. One possible explanation for this might be the relatively large number of variables in the models. It can be shown that the percentage of variance explained increases, in general, as more variables are added. Further analysis indicated that satisfactory fits could be obtained with about half as many variables.

Table 1. Variable coefficients and standard errors for Stage I model.

	Coefficients[a]						Standard Error					
Variable	A	B	C	D	E	F	A	B	C	D	E	F
Intercept	1388	208	10 399	2 345	455 507	117 306	497	378	5 880	2892	208 339	38 531
Automobile parking	-555	-95	-4 381	-298	-128 842	-4 919	253	20	2 996	156	106 171	2 084
Residential	-55	-3	-404	-30	-13 200	-652	25	2	300	17	10 617	226
Institutional	8	-4	-828	1	-13 521	328	286	10	3 386	78	119 957	1 047
Office	583	38	6 424	194	172 601	15 154	212	41	2 513	311	89 019	4 138
Commercial	976	145	9 649	1 059	264 693	23 999	206	63	2 435	479	86 280	6 386
Warehouse	-54	-74	1 447	-306	21 232	-27 252	557	105	6 593	805	233 568	10 725
Industrial	-7292	-17	-75 884	-78	-2 013 873	3 408	3236	62	38 278	471	1 356 142	6 278
Transportation-utility	-58	-9	-567	-91	-11 072	-1 223	41	4	489	29	17 328	383
Open	-280	2	-3 187	6	-91 783	67	187	0.36	2 210	3	78 292	37
Recreational	-69	-6	-826	-6	-27 423	-719	112	12	1 321	92	46 789	1 220
Arterial spacing	-1507	1588	-10 520	13 124	-852 057	22 762	1365	945	16 151	7224	572 207	96 253

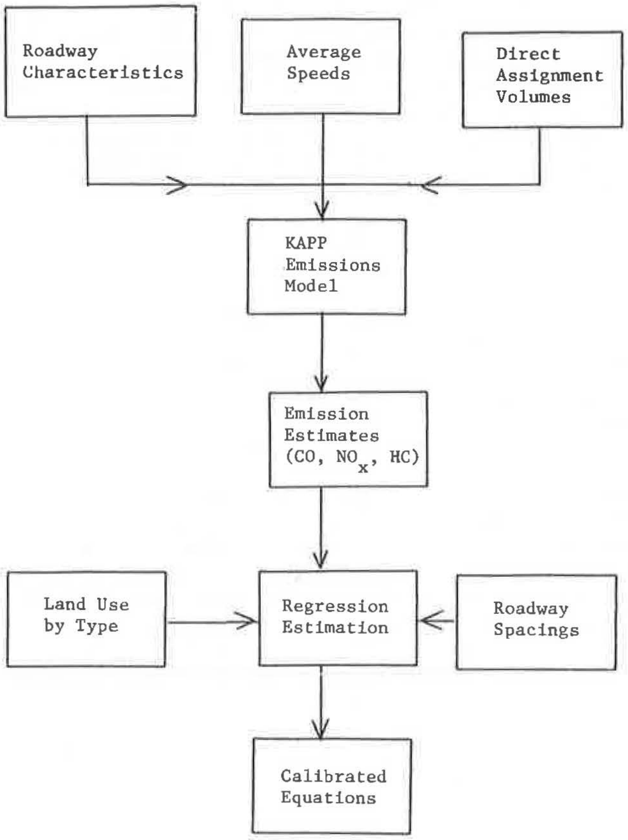
[a] Dependent variables are identified in text table 1.

STAGE II MODEL CALIBRATION PROCEDURE

The calibration procedure used for the Stage II model was quite simple in comparison to that for the Stage I model. The procedure is depicted in Figure 2, using the same sample set of zones and the same stratification from the Stage I model. The appropriate link distances and link average speeds for those links within each of the 30 zones were used from the Peoria 1970 network. The volumes used for the emissions estimation were those derived from the direct assignment process.

At this point, the KAPP emissions model was employed to yield estimates of the emissions of CO, NO_x, and HC. These emission estimates were made using 1976 as the calendar year, no correction for cold start operation, and a vehicle mix compiled from registration data for the Peoria area.

Figure 2. Stage II model calibration procedure.



The emissions estimates were the dependent variables and the roadway spacings and land use by type for each zone were the independent variables when a regression model was run for each pollutant. The land use information and the roadway spacing information were the same as those used by the Stage I model calibration procedure. The regression statistics are displayed below.

Dependent Variable	F-Ratio	R^2
CO		
Small zones (A)	8.88	0.96
Large zones (B)	0.53	0.74
NO_x		
Small zones (C)	8.14	0.95
Large zones (D)	0.46	0.71
HC		
Small zones (E)	8.96	0.96
Large zones (F)	0.52	0.74

The variable coefficients and standard errors are shown in Table 2. In general, the percent of variance explained is high, ranging from 71 to 96. As with the Stage I model, the standard errors on the estimates of the variable coefficients are somewhat high. Additional analysis on this data indicated that models with fewer land use variables could produce R^2's in the vicinity of 0.70, an acceptable level.

SELECTED SITE ANALYSIS

This section illustrates the use of the Stage I and Stage II models on four selected sites in the Peoria area. The sites include one in the Peoria CBD, one elsewhere in the city of Peoria, one in Peoria County, and one in Tazewell County. In each case, the land use and roadway spacing inputs will be presented as well as the volume estimates from the Stage I model and emission estimates from the Stage II model. In addition, the hourly and 8-h maximum emission estimates will be presented. All results are shown in Table 3.

The first area to be examined is in the Peoria CBD and corresponds to traffic analysis zone 3 of the Peoria Area Transportation Study (PATS). It is bounded by Washington, Main, Adams, and Fulton streets. The land is predominantly used in this zone for commercial and office space. The daily local street volume estimated (2382 vehicles) was somewhat low compared to actual counts, but the arterial volume (21 667 vehicles/d) was within 5 percent of actual counts. The Stage II model estimated 55.03 kg of CO, 4.52 kg of NO_x, and 5.01 kg of HC.

The second area considered for analysis was one selected elsewhere in the city of Peoria. It corresponds to traffic analysis zone 63 and is located on the south side of Peoria in the vicinity of Lincoln and Jefferson

Table 2. Variable coefficients and standard errors for Stage II model.

	Coefficients[a]						Standard Error					
Variable	A	B	C	D	E	F	A	B	C	D	E	F
Intercept	-28.43	175	-3.77	23	2.7	17.3	94	502	7.8	59	8.4	48.2
Automobile parking	4.23	-3.64	-0.97	-0.9	0.16	-0.41	48	27	3.97	3.2	4.3	2.6
Residential	-2.43	1.32	-0.21	0.07	-0.22	0.11	4.8	2.95	0.39	0.34	0.43	0.28
Institutional	-16.76	1.27	-1.60	-0.38	-1.52	0.04	54	13	4.49	1.61	4.88	1.31
Office	-0.13	-21	0.07	-1.9	-0.04	-1.93	40	54	3.33	6.3	3.62	5.2
Commercial	10.6	45	2.03	0.75	1.11	3.67	39	83	3.23	9.8	3.51	8
Warehouse	7.61	-23	2.25	3.2	0.54	-1.39	105	139	8.74	16.5	9.51	13.4
Industrial	-1450.0	-3.2	-122	0.46	-132	-0.19	614	81.9	50	9.6	55	7.9
Transportation-utility	-16	2.8	-1.52	0.36	-1.52	0.27	7.8	5	0.64	0.59	0.70	0.48
Open	61	-0.06	4.37	0	5.51	0	35	0.49	2.93	0.05	3.18	0.04
Recreational	59	-3.3	4.31	-0.77	5.36	-0.37	21	15.9	1.75	1.88	1.90	1.52
Arterial spacing	569	-72	51	-11	52.29	-7.37	259	1256	21	148	23.29	120

[a] Dependent variables are identified in text table 2.

Table 3. Example site analysis.

Item	Zone 3	Zone 63	Zone 198	Zone 242
Land use, acres				
Automobile parking	0.8	0.0	0.0	8.0
Residential	0.0	36.8	57.4	176.0
Institutional	0.1	6.2	0.0	10.0
Office	0.1	0.0	0.0	7.0
Commercial	1.5	4.2	0.0	3.0
Warehouse	0.0	2.1	2.0	4.0
Industrial	0.0	0.0	8.5	22.0
Transportation-utility	0.0	0.0	65.3	159
Open	0.3	1.0	1161.2	2222.0
Recreational	0.0	0.0	70.1	87.1
Total	2.8	50.2	1364.6	2698
Roadway spacing, miles				
Local	0.1	0.1	0.5	0.5
Arterial	0.2	0.4	1.0	0.6
Stage I predicted volumes, vehicles/d				
Local	2 382	528	650	1535
Arterial	21 667	5050	12 869	1954
State II predicted emissions/d, kg				
CO	55.03	155.33	20.63	85.12
NO_x	4.52	13.33	2.28	8.08
HC	5.01	14.20	1.94	7.86
8-h maximum CO, kg	30.82	86.98	11.54	47.66

avenues. Table 3 shows that land use mix for the zone is predominately residential in nature. The Stage I model estimates of roadway volumes are 528 vehicles/d on local streets and 5050 vehicles/d for arterials. Again, as with zone 3, the local street volumes are somewhat low and the predicted arterial volumes are within 5 percent of the observed. The Stage II model estimated 155.33 kg of CO, 13.33 kg of NO_x, and 14.20 kg of HC.

A third geographic area used for analysis purposes was located in eastern Peoria County. It corresponded to zone 198 and is located between IL-8 and the town of Norwood. The area can be characterized as predominantly open space with some residential, some recreational, and a small amount of industrial land. As shown in Table 3, the Stage I model estimated daily volumes of 650 vehicles for local streets and 12 869 vehicles for arterials. The local street volume predicted exceeds the observed by about 400 vehicles/d. There were no arterial roads in this zone. The low volumes are offset by the roadway links, which tend to be rather long in a zone of this size and geographic character. The Stage II model predicted 20.63 kg of CO, 2.28 kg of NO_x, and 1.94 kg of HC.

The final example zone analyzed was located in Tazewell County and corresponds to zone 242. It is located on either side of IL-116, northeast of the McClugage Bridge in extreme north Tazewell County. Like the previous area, it is dominated by open space and residential acreage. As shown, the Stage I model predicted daily volumes for local streets at 1535 vehicles and for arterials at 1954 vehicles. No local streets in the zone were coded for the network. The observed arterial volumes were significantly higher than the predicted. This may be because the major arterial through the area is a major state route and hence carries traffic not destined for the zone itself. The Stage II model predicted emissions of 85.12 kg of CO, 8.08 kg of NO_x, and 7.86 kg of HC.

NETWORK SENSITIVITY

The volume and emission results of the Stage I and Stage II models are daily estimates for typical weekday operation. Using the hourly and 8-h maximum travel distribution information developed, emission estimates can be developed for any given hour of the day or for an 8-h maximum period. Examples of the 8-h maximum CO emissions for the four test sites are also shown in Table 3.

An appropriate issue in dealing with the results of the above models is their sensitivity to land use and network changes. The capability obviously exists to change the land use mix in an area to correspond to some proposed development. Consider zone 198 again: If a 5-acre shopping facility and additional 20 acres of residential land were planned for development, the Stage I model would indicate that local street volume would go from 650 vehicles to 1350 vehicles/d and daily arterial volumes would go from 12 869 vehicles to 17 564 vehicles/d. The Stage II model would indicate an increase of CO from 20.63 to 123.0 kg, NO_x from 2.28 to 4.61 kg, and HC from 1.94 kg to 10.19 kg. Thus, use of the equations and their coefficients yields a simple and straightforward procedure for estimating the emissions impacts of land use changes. The travel distributions discussed earlier may then be used to compute new hourly and 8-h maximum emissions estimates.

CONCLUSIONS

It is important to categorically summarize the major research achievements emanating from the work developed in this study.

1. The development and calibration of a simple regression equation format to directly forecast mobile source emissions from a land use and its adjacent supply of highway travel facilities. Such equations, given that they are logical and meaningful, represent a major breakthrough in the mobile source emissions and air quality state of the art.
2. Development, calibration, and employment of a functional battery of models for transportation demand forecasting, and emissions computation in a small to medium-sized urban area. These models are simple and direct, can be operated manually or by computer, and make use of simple and available land use inventory and traffic count data from the urban area.

Some significant users of the above research results include:

1. The urban or regional planner who must contemplate travel and air quality shifts resulting from modifications in land use or travel facilities; and
2. The land use developer confronted with meeting air quality, zoning, parking, and traffic standards, when modifying land uses at an assembled site for capital-intensive or profit-oriented reasons. By specifying the proposed land use development, its gross acreage, net square footage of use, and adjacent highway facilities, the resulting traffic and emissions may be forecast and modified with respect to standards, without initially resorting to intensive and costly preliminary engineering or site planning and architectural analysis.

In any research endeavor, the initial effort yields shortcomings in data collection for the study design and reveals opportunities for improvement in subsequent research and modeling thrusts. The following shortcomings were noted during the conduct of this research:

1. As in any regression-oriented research, concern should be registered about the sample size. Although the city size was appropriate to small and medium-sized urban area modeling, the UTP zonation resulted in a reasonably small random sample (30 zones). The im-

pact of this on the statistical validity of representation of the sample, except in judging it to exist as a heuristically representative sample for a community of such size, is simply not known.

2. Related to the above, the calibration is specific to Peoria. Its true transferability to other communities of the same size seems logical but is not guaranteed to be statistically justifiable without larger sampling of zones in other cities of a like size and character, comprising a statistical and descriptively appropriate sample of the universe of cities of this size and character in the United States.

3. An induced and ever-present problem in urban transportation planning is the zonal size and its effect on variance. The zones in Peoria vary widely in size, as typical of all UTP conventional modeling efforts. The problems of zonal variance have been well noted in the literature and will not be repeated here (15). Suffice it to say, the variance and the representation of zonal land use and zonal variety of functional classes of highways is overlaid on the statistical representation problems alluded to in 1 and 2 above.

FURTHER RESEARCH

In light of the above achievements, potential users, and shortcomings of the present research, several needs and opportunities for future research emerge, including:

1. Generalization of the model by employment of a larger random sample dealing with zones from a bigger statistical universe, possibly all U.S. or Midwestern communities of the same size range, yielding a set of statistically generalized and transferable regression equations.
2. An appropriate and significant extension of the present effort through the development of a complete regional land use simulation model that randomly developed land use plats or subregions and regenerated the entire land use plan according to a series of alternative growth and environmental policies and recorded the traffic and emissions consequences. To the extent possible, transfer and impact functions for other consequences (noise, regional value added, and change in tax base) could be developed and calibrated, and a comprehensive public works-environmental consequences taxonomy model could be pursued.

In summary, the research effort has constructively synthesized direct traffic assignment forecasting methods with emissions computation capabilities and demonstrated an efficient approach to calculate emissions consequences of land use-highway travel supply combinations. In so doing it has yielded a significant achievement in the mobile source emissions state of the art and revealed opportunities for further advancements in subsequent research endeavors.

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