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ROADWAY -- A NUMERICAL MODEL FOR PREDICTING AIR POLLUTANTS NEAR HIGHWAYS

User's Guide

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC

ROADWAY -- A NUMERICAL MODEL FOR PREDICTING AIR POLLUTANTS NEAR HIGHWAYS

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by

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NOTICE

AFFILIATION

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PREFACE

One area of research within the Meteorology and Assessment Division is development, evaluation, validation, and application of models for air quality simulation, photochemistry, and meteorology. The models must be able to describe air quality and atmospheric processes affecting the transport and diffusion of airborne pollutants on scales ranging from local to global. Within the Division, the Environmental Operations Branch adapts and evaluates new and existing meteorological dispersion models and statistical technique models, tailors effective models for recurring user application, and makes these models available through the User's Network for Applied Modeling of Air Pollution (UNAMAP) system of EPA.

ROADWAY is a numerical model for predicting air pollution levels near highways. It solves a conservation of species equation via finite-difference approximations. Temperature at two heights and wind velocity upwind of the highway are required inputs; surface layer similarity theory is used to produce wind and turbulence profiles. A unique aspect of ROADWAY is the treatment of vehicle wake effects which are superimposed on the wind and turbulence fields. Chemical reactions due to exhaust emissions near the roadway are simulated by a 2-step mechanism that yields concentrations of NO, NO_2, and O_3 in the very near field.

Although attempts are made to thoroughly check computer programs with a wide variety of input data, errors are occasionally found. Revisions may be obtained as they are issued by completing and returning the form on the last page of this guide.

The first four sections of this document are directed to managers and project directors who wish to evaluate the applicability of the model to their needs. Sections 5, 6, 7, and 11 are directed to engineers, meteorologists, numerical analysts, and other scientists who are required to become familiar with the details of the model. Finally, Sections 8 through 11 are directed to persons responsible for implementing and executing the program.

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Technical questions regarding use of the model should be directed to (919) 541-4551. Users within the Federal Government may call FTS 629-4551. Copies of the user's guide are available from the National Technical Information Service (NTIS), Springfield, VA 22161.

The magnetic tape containing FORTRAN source code for ROADWAY can be found (along with other diffusion models) in UNAMAP Version 6 and up which is available from Computer Products, NTIS, Springfield, VA 22161 (phone number: (703) 487-4763).

ABSTRACT

ROADWAY is a finite-difference model which solves a conservation of species equation to predict pollutant concentrations within two hundred meters of a highway. It uses surface layer similarity theory to predict wind and eddy diffusion profiles from temperature at two heights and wind velocity upwind of the highway. A unique feature of the model is its use of vehicle wake theory, which was originally developed by Eskridge and Hunt (1979), and was modified by Eskridge and Thompson (1982); and Eskridge and Rao (1983, 1985). It is assumed that vehicle wakes affect the wind and turbulence fields in a linear manner with wake intensity a function of vehicle speed, downwind distance, and distance from the wake center. The user has the option of considering NO, NO_2, and O_3 chemical reactions near the road. Output from the model consists of x-z fields of wind components, eddy diffusion coefficients, and concentration of pollutant species.

CONTENTS

CONTENTS (continued)

FIGURES

TABLES

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. Brian Eder and Mr. William Petersen for helpful comments regarding aspects of the work presented here. Special mention is made to Mr. Thomas Chico who optimized the source code. Most of this text was excerpted from technical publications dealing with ROADWAY over the past few years.

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EXECUTIVE SUMMARY

ROADWAY is a numerical model for predicting air pollution levels near highways. It solves a conservation of species equation via finite-difference approximations. Temperature at two heights and wind velocity upwind of the highway are required. With these inputs surface layer similarity theory is used to produce wind and turbulence profiles. A unique aspect of ROADWAY is its treatment of vehicle wakes which are superimposed linearly on the wind and turbulence fields. The vehicle wake intensity is a function of vehicle speed, downwind distance, and distance from the wake center. Additionally, the user has the option of considering NO, NO_2, and O_3 chemistry; reactions of these pollutants are calculated by a 2-step mechanism applicable to the very near field. Output from the model consists of fields in the x-z plane for wind components, eddy diffusion coefficients, and concentrations of four pollutant species.

To estimate concentrations for any simulated hour, information on meteorology, highway configuration, and emissions are required. The meteorological information needed for the computation includes representative roughness length, temperature at two heights upwind of the highway, and hourly average wind speed and direction at the level of the upper temperature sensor. If the chemistry option is exercised, two photochemical reaction rate constants, background for each species, and conversion factors (gm/sec to ppm) are also required. The following highway configuration data are needed for execution of the model:

- number of traffic lanes,
- width of each lane (m),
- width of the traffic median (m),

- angle between highway and a line running north-south (degrees),
- traffic volume (veh/hr),
- average vehicle speed (km/hr), and
- average vehicle dimensions (m).

Air quality and emission data necessary for model execution are background pollutant concentrations and vehicle emission rates. No sampling grid or receptor information is required as these are internally generated.

Since ROADWAY is a numerical model it has none of the limitations generally associated with Gaussian algorithms. That is,

- it is a multilayer model which considers vertical variation of both wind and diffusivity,
- it can treat calm or light wind conditions, and
- it can simulate chemical reactions of the emitted pollutant species.

Also, the model can include up to ten traffic lanes and has features to reduce execution costs (at the expense of accuracy) and to provide intermediate output. ROADWAY was developed independent of tracer data, and has been demonstrated to perform as well as other highway models currently available.

ROADWAY has several limitations. A major restriction of the model is the requirement that the vehicle speed be much greater than the wind speed. This requirement, however, should be met in most instances of significant pollutant impacts. More importantly, the model is valid for all vehicle speeds when wind speeds are light. Another limitation is that ROADWAY does not consider wind meander which becomes important when the mean wind is parallel to the highway. Also, because its use is restricted to the very near field (within 200 m of the roadway), other algorithms would be better suited for calculating impacts at longer distances. Finally, since ROADWAY algorithms are

SECTION 1

INTRODUCTION

The problem of automobile pollution has been of interest since 1969 when the National Environmental Policy Act was promulgated. The Act requires that construction of new highways which are partially paid for by federal funds include an environmental impact statement as part of the plans. Various approaches including Gaussian solutions (Zimmerman and Thompson, 1975) and numeric solutions of conservation of species equations (Danard, 1972) have been used to predict concentrations near highways. A theory to predict vehicle wake effects did not exist, however, and earlier models either ignored the vehicle wake effects on the velocity and turbulence fields or parameterized them in a simple manner (such as by enhancing dispersion over the highway).

Eskridge et al. (1979b) developed a finite-difference model for calculating pollutant concentrations on and near a highway that incorporates the vehicle wake theory formulated by Eskridge and Hunt (1979) from a perturbation analysis of the equations of motion. The major restriction of the model is the requirement that the vehicle speed be much greater than the wind speed. Vehicle wake theory was evaluated and modified in wind tunnel experiments by Eskridge and Thompson (1982) and Eskridge and Rao (1983, 1986). The results of these wind tunnel investigations are included in the version of ROADWAY described here. Because certain pollutants emitted on the road are reactive, a simplified chemical mechanism was added to the model. Chemical reactions involving nitric oxide (NO), nitrogen dioxide (NO_2), and ozone (O_3) are simulated by a 2-step mechanism.

Recently, Rao et al. (1986) evaluated ROADWAY and two other highway models, HIWAY-2 and CALINE3, using statistical techniques suggested by Fox (1981), Willmott (1982), extreme value statistics (Tabony, 1983), and the "bootstrap" method (Diaconis and Efron, 1983). Tracer data from the General Motors (GM) Sulfate Dispersion Experiment were used for the evaluation. The results indicate that all three models perform well but HIWAY-2 and ROADWAY fit the data better than CALINE3. It should be noted that unlike HIWAY-2 and CALINE3, the ROADWAY model was developed independent of the GM data set.

This document is directed toward three different readers: managers, air pollution meteorologists, and computer specialists. The first four sections are aimed at managers and project directors who wish to evaluate the applicability of the model to their needs. Sections 5, 6, 7, and 11 are directed to meteorologists or engineers who must become familiar with details of the model. Finally, Sections 8 through 11 are directed toward persons responsible for implementing and executing the program, and, if necessary, making modifications to the code. A listing of the FORTRAN source statements are included in Appendix A; Appendix B gives a reprint of an article on the performance of ROADWAY against observed data and the two other highway models noted earlier.

SECTION 2

DATA-REQUIREMENTS CHECKLIST

To estimate concentrations for any simulated hour, data for program control, as well as information on meteorology, highway configuration, and emissions are required. These are mentioned briefly here; more detail on proper formatting for data entry is given in Section 9.

The user must indicate whether the following features are to be employed:

- chemistry option,
- antidiffusion calculation option, and
- intermediate print option.

The meteorological information needed for the computations are:

- roughness length (m),
- temperature at two heights upwind of the highway (K), and
- hourly average wind speed (m/sec) and direction (degrees).

The following highway configuration data are required:

- number of traffic lanes,
- width of each lane (m),
- width of the traffic median (m),
- angle between highway and a line running north-south (degrees),
- traffic volume,
- average vehicle speed (km/hr), and
- average vehicle dimensions (m).

The user must supply the following air quality and emission data for each hour of simulation:

- Background pollutant concentrations (ppm),
- Vehicle emission rates (g/km•veh), and
- Factor to convert grams per second (gm/sec) to parts per million (ppm) for the pollutant.

If the user exercises the chemistry option, then background concentrations, vehicle emission rates, and conversion factors must be provided for nitrogen oxide (NO), carbon monoxide (CO), and nitrogen dioxide (NO_2). Also, the background ozone (O_3) must be given.

No sampling grid or receptor information is required since both are internally generated by the model. The concentration output is in the form of x-z fields which define a plane perpendicular to the highway.

SECTION 3

FEATURES AND LIMITATIONS

The diffusion equation derived from a statement of the conservation of mass or species, forms the basis for the ROADWAY computational system. This equation is one of three partial differential equations used to describe distributed parameter systems otherwise known as fields.

The conservation of species equation (i.e., a diffusion equation), is used to predict pollutant concentration fields near highways. The finite-difference method used in ROADWAY represents the time-space continuum by a set of discretely spaced points; the grid produced by these points is not evenly spaced upon the field in ROADWAY since higher resolution is needed near the road and lesser away from it. An algebraic equation approximating the partial differential equation is derived for each grid point. The solution is found by solving these equations for all points in the grid after applying boundary conditions and initial values to the field. Since ROADWAY is a numerical model it has none of the limitations of Gaussian solutions to the diffusion equation. That is,

- ROADWAY is a multilayer model which considers vertical variation of both wind and diffusivity,
- it treats calm or light wind conditions, and
- optionally computes chemical reactions of source pollutant species.

As mentioned previously, ROADWAY requires a reduced meteorological input data set. Realistic wind and turbulence profiles can be calculated using surface layer similarity theory as evidenced by a verification study using the GM data set

(Eskridge and Binkowski, 1979). The model was developed on theoretical grounds and using wind tunnel experiments and is independent of tracer studies. It, nevertheless, performs as well as the most accurate highway models today. Up to ten traffic lanes can be simulated. The model can provide intermediate output and, at the expense of accuracy, has features to reduce execution costs.

Since the algorithms of ROADWAY are solved by a computer, the calculations are subject to truncation and roundoff errors. In the context of numerical analysis, truncation errors occur in approximating infinite series by a finite number of terms. Roundoff errors, on the other hand, are machine-dependent and occur because computations are done on the precision of a computer which introduces errors by the dropping off of digits. Another source of error is that related to computational instability. In solving the conservation of species equation, both the time and space variables must be discretized by means of finite-difference expansions. A small error made at one time step of the calculation can result in a larger error at a later time resulting in unbounded error growth. A segment of the ROADWAY code tests conditions to ensure that calculations remain stable.

A model limitation is that the vehicle speed must be much greater than the ambient wind speed. Considering usual freeway speeds and meteorological scenarios where significant pollutant impacts would occur, this may not be a limitation. More importantly, the model is valid for all vehicle speeds when winds are light which is when Gaussian approaches breakdown. ROADWAY does not consider wind meander; this becomes important when the mean wind is nearly parallel to the highway. The use of ROADWAY is restricted to the very near field -- within two hundred meters of the roadway, beyond two hundred meters meteorological processes that are not accounted for in the model become important.

Another limitation is costs related to computer execution. Being a numerical model, ROADWAY is relatively expensive to run when compared to Gaussian-based models. Execution time using the chemistry option is on the order of 10 CPU minutes on a DEC VAX-11/780. ROADWAY implementation on a personal computer is entirely possible and execution costs in this environment would be much less.

Due to its applicability in only the near field and because of execution expense, ROADWAY is recommended for use in conjunction with a Gaussian model such as HIWAY-2 (Petersen, 1980; Rao and Keenan, 1980).

SECTION 4

BASIS FOR ROADWAY

This section gives a brief narrative highlighting important aspects of the modeling approach. A detailed technical description of the various algorithms that accomplish the simulation is presented in Section 5.

NUMERICAL APPROACH

Three fundamental partial differential equations serve as the mathematical model for virtually all problems of applied physics. One of these is the conservation of mass or diffusion equation which serves as the basis of the ROADWAY computational system. A statement of the conservation of mass, this equation is generically given as,

$$\frac{\partial P}{\partial t} = \nabla \cdot K \nabla P \qquad (1)$$

where P is a scalar field and K is determined by the parameters of the system. Where the medium is itself in motion, the equation becomes

$$\frac{\partial P}{\partial t} = -V \cdot \nabla P + \nabla \cdot K \nabla P \qquad (2)$$

which, in its modified form, is used to predict pollutant concentrations near a highway. In the Eulerian (or fixed) coordinate system, the equation is,

$$\partial C/\partial t = \underbrace{-\nabla \cdot VC}_{\text{advection term}} + \underbrace{\nabla \cdot K \nabla C}_{\text{diffusion term}} + \underbrace{S,}_{\text{source/sink term}} \qquad (3)$$

where C represents concentration of a given pollutant species, V is the wind vector, and K the three-dimensional eddy diffusivity. Eq. 3 is, therefore, a statement of the conservation of species.

The finite-difference method used in ROADWAY represents the time-space continuum by a set of discretely spaced points. The grid produced by these points is not evenly spaced upon the field since higher resolution is needed near the road and lesser away from it. An algebraic equation approximating the partial differential equation is derived for each grid point; the solution is found by solving all these equations for all points in the grid after applying boundary conditions and initial values to the field. Four grid points define a box, and the pollutant mass within each box depends upon the advection of pollutant into and out of the box (advection term), the diffusion of pollutant mass through the sides of the box (diffusion term), and any sources or sinks of effluent within the box (source/sink term). In ROADWAY, vehicle exhaust is a source of effluent, while chemical reactions act as both source and sink for certain pollutant species.

Automobile exaust gases contain nitrogen dioxide which in the presence of sunlight undergoes a chemical change forming ozone and nitrous oxide. Simultaneously, reverse reactions take place tending to convert the NO back to NO_2. The rate at which the NO_2, NO, and O_3 constituents form and dissipate are approximated by the three partial differential equations. Therefore, to simulate the system, the transport and diffusion of the three constituents has to be represented by three coupled, simultaneous diffusion equations.

In the numerical treatment of systems of partial differential equations, four unavoidable sources of error are encountered. These are modeling errors, measurement errors, truncation errors, and roundoff errors. Of these, the last two concern the numerical analyst/meteorologist. Truncation errors are due to the finite representation of what are otherwise infinite series. Roundoff errors occur because calculations are made with the available precision of a computer whose internal representation of numeric data fields cannot accommodate all the digits of a calculation. Somewhat related to these is still another source of error which is known as computational instability. In solving the ROADWAY conservation of species equation, both the time and space variables must be discretized by means of finite-difference expansions. Unless the time interval d is sufficiently small compared to the net spacing h and z, computational instability can result (i.e., a small error at time t can propagate with each successive calculation so that at future times unbounded error growth occurs). Other ROADWAY errors relate to assumptions of initial and boundary conditions and to uncertainties in the input parameters.

SIMILARITY THEORY

The ROADWAY computational system uses the theory of surface layer similarity to produce wind and turbulence profiles from temperature at two levels and wind observed just upwind of the highway. From the initial assumption of a horizontally homogeneous atmosphere, similarity theory predicts the wind and turbulence profiles from the friction velocity and Monin-Obukhov length. These profiles comprise the basic-state atmosphere upon which the vehicle wake effects are added. The reader is referred to Busch (1973) for a review of surface layer similarity theory.

VEHICLE WAKE THEORY

Early attempts to predict pollutant concentration adjacent to highways via line source algorithms yielded unsatisfactory results because traffic-induced turbulence was not considered or was poorly represented. A unique aspect of ROADWAY is its treatment of vehicle wake effects. The theory was originally developed by Eskridge and Hunt (1979) and modified by Eskridge and Thompson (1982) and Eskridge and Rao (1983, 1986).

Vehicle wake theory predicts that turbulent mixing and hence pollutant concentration near the highway are dependent on vehicle speeds. Vehicle wake turbulence is greatest over the highway and decreases rapidly with increasing downwind distance and increasing height above the highway. The theory finds that these effects are more important during stable atmospheric conditions than during neutral and unstable conditions.

SECTION 5

TECHNICAL DESCRIPTION

In the prior section a brief description of the algorithm and method was given to acquaint the reader with generic aspects of the model. Presented here is the mathematical formulation of the physical processes taking place near the road and their simulation by the algorithms of ROADWAY. Equations are shown in their final form for brevity, but references are given for those readers interested in details of the derivations.

CONSERVATION OF SPECIES EQUATION

The conservation of species equation, a modified form of the diffusion equation, is expressed as follows

$$\partial C/\partial t + \nabla \cdot CV = \nabla \cdot K \nabla C + E + R, \qquad (4)$$

where ∇ is the divergence operator in x and z coordinates, E is an emission source term, K is the eddy diffusion coefficient, C is a chemical species, and R is a corresponding set of chemical reactions.

One of the main assumptions made in the model is that a reference atmosphere describable by surface layer similarity theory exists and that upon this reference atmosphere the perturbations due to the vehicles can be added. I.e.,

$$K_x = K_x^S(z) + K_x^W(x,z)$$

and (5)

$$K_z = K_z^S(z) + K_z^W(x,z),$$

where K_i^S and K_i^W are eddy diffusion coefficients from similarity and wake theories, respectively. Likewise, the wake velocity deficit is added to the wind field described by similarity theory to yield the total wind field.

The equation of continuity for an incompressible fluid, $\nabla \cdot \underset{\sim}{V} = 0$, is used to yield w, the vertical velocity, which is non zero along the road in the presence of vehicle wakes. Because there is no time dependence in this equation, the numeric calculation is stable.

THE BOUNDARY CONDITIONS

The problem of imposing boundary conditions is always difficult in atmospheric modeling, especially when the scale of the problem is small. In this model, it is assumed that the gradient at the surface is zero, i.e.,

$$\partial C/\partial z = 0 \qquad \text{at } z = 0, \tag{6}$$

which implies no losses at the surface. At the side boundaries the following conditions are imposed:

$$\partial C/\partial x = 0 \qquad \text{at the outflow boundary}$$

and (7)

$$C = \text{background} \qquad \text{at the inflow boundary.}$$

At the top boundary it is assumed that the concentration is at background levels, i.e.,

$$C = \text{background} \qquad \text{at } z = z_{max}. \tag{8}$$

These boundary conditions are not perfect physical constraints as they are imposed primarily for mathematical reasons. It has been found in numerical experiments that the model results are more sensitive to the height of the modeling region than to any other boundary condition. Therefore, when winds are light or nearly parallel to the roadway, the height of the integration region is raised from 20 to 70 m.

THE GRID

The finite-differencing scheme used by the model represents the time/space continuum by a set of discretely spaced points. The grid produced by these points is not evenly spaced upon the field in ROADWAY since higher resolution is needed near the road and lesser farther away. The numerical scheme of Steven Zalesak (described in the Appendix of Eskridge et al., 1979) allows this variable grid spacing in the horizontal and vertical directions. The grid also varies according to the wind speed and direction and the number of highway lanes. Table 1 summarizes how the grid is set; (one should note the time assumed to reach steady-state conditions and that u is the component of the wind perpendicular to the road).

TABLE 1. ALGORITHM USED TO SET GRID DIMENSIONS AND THE STEADY-STATE TIME PERIOD

Horizontal scale	
Road-wind angle:	Dimensions:
$> 10^\circ$	scale begins 20 m upwind of first lane; scale ends 30 m downwind of last lane
$\leq 10^\circ$	scale begins 25 m upwind of first lane; scale ends 25 m downwind of last lane
Vertical scale	
u (m/sec):	Dimensions:
$u < 0.1$	scale begins at 1 m; scale ends at 70 m
$0.1 \leq u < 0.5$	scale begins at 1 m; scale ends at 50 m
$u \geq 0.5$	scale begins at 1 m; scale ends at 20 m
Steady-state time period	
u (m/sec):	Time to reach steady-state conditions:
$u < 0.1$	900 sec
$0.1 \leq u < 0.5$	600 sec
$u \geq 0.5$	300 sec

An algebraic equation approximating the partial differential equation is derived for each grid point. The solution is found by solving all these equations for all points in the grid after applying boundary conditions and initial values to the field.

THE NUMERICAL SCHEME

Eq. 4 can be written in operator form as

$$\partial C/\partial t + B_1 C + B_2 C + B_3 C + B_4 C = E + R \tag{9}$$

where B_1, B_2, B_3, and B_4 are linear operators representing $\partial u(\ )/\partial x$, $\partial w(\ )/\partial x$, $-(\partial/\partial x)K_x\partial(\ )/\partial x$, and $-(\partial/\partial z)K_z\partial(\ )/\partial z$, respectively. Eq. 9 can be approximated by

$$(C_{ik}^{n+1} - C_{ik}^{n})/\Delta t + \sum_{m=1}^{4} L_m(C_{ik}) = E_{ik} + R_{ik}, \tag{10}$$

where L_m $(m = 1,\ldots,4)$ are approximations of B_m using $x = i\Delta x$, $z = k\Delta z - 0.5z$, and $t = n\Delta t$. Eq. 10 is solved by a fractional step method (Marchuk, 1975). The procedure is as follows:

$$C^1 = C^n + \Delta t L_1(C^n), \tag{11}$$

$$C^2 = C^1 + \Delta t L_2(C^1), \tag{12}$$

$$C^3 = C^2 + \Delta t L_3(C^2), \tag{13}$$

$$C^4 = C^3 + \Delta t L_4(C^3), \text{ and} \tag{14}$$

$$C^{n+1} = C^4 + \Delta t(E_{ik} + R_{ik}). \tag{15}$$

If $C^1,\ldots,C^4$ are eliminated, the system reduces to an equation of the form

$$C^{n+1} = C^n + \Delta t\sum_m L_m C^n + \Delta t(E_{ik}+R_{ik}) + (\Delta t)^2(\ldots) + \text{higher order terms}. \tag{16}$$

The operators L_3 and L_4 are approximations centered in space, while the operators L_1 and L_2, which solve the advection terms, are based on the flux-corrected algorithm of Zalesak which is an upstream algorithm that ensures nonnegative values for the concentration at every grid point. As shown by Eskridge et al. (1979b), this scheme reduces numerical diffusion and is stable for

$$\Delta t \le 0.5 \Delta x / u_{max}. \tag{17}$$

THE BASIC-STATE ATMOSPHERE

The basic-state for upwind atmospheric conditions are determined by surface layer similarity theory which requires the specification of the vertical temperature gradient and the wind velocity. From this information, vertical profiles of u, v, K_x, and K_z are generated. Binkowski (1979) gives details on the theory.

The wind profiles used in the model are obtained from similarity theory in the following manner. Since the Obukhov length L is very difficult to measure directly, the bulk Richardson number is used as a stability parameter

$$R_b = \frac{gh\Delta\theta}{\theta_h U_h^2}, \tag{18}$$

where g is the acceleration due to gravity, h the height of the wind observation, U_h the wind speed at height h, θ_h the potential temperature at h, and $\Delta\theta$ the difference in potential temperature between two tower points. The temperature difference is taken over the height increment $(h-z_1)$, where the height z_1 of the lower instrument is assumed to be small enough relative to h so that $\Delta\theta$ is representative of a temperature difference over the entire distance h. The Obukhov length L may be expressed as

$$L = \frac{hG(h)}{kF^2(h)R_b}, \tag{19}$$

where

$$F(h) = \frac{1}{k}\left[\ln\left(\frac{h}{z_0}\right) - P\left(\frac{h}{L}\right)\right], \tag{20}$$

$$G(h) = \frac{1}{k}\left[\ln\left(\frac{h}{z_1}\right) + Q\left(\frac{h}{L}\right)\right], \tag{21}$$

$$P(h/L) = \ln\{[(X_0^2 + 1)(X_0 + 1)^2/[(X^2 + 1)(X + 1)^2]\} + 2[\tan^{-1}X - \tan^{-1}X_0], \tag{22}$$

where

$$X = (1-16h/L)^{\frac{1}{4}}, \quad X_0 = (1-16z_0/L)^{\frac{1}{4}} \tag{23}$$

for $L < 0$ (unstable),

$$P(h/L) = 5(h-z_0)/L \quad \text{for} \quad L > 0 \text{ (stable)}, \tag{24}$$

$$Q(h/L) = 2\ln[(Y_1 + 1)/(Y + 1)], \tag{25}$$

$$Y = X^2, \; Y_1 = (1-16z_1/L)^{\frac{1}{2}} \text{ for } L < 0 \text{ (unstable)},$$

$$Q(h/L) = 5(h-z_1)/L \quad \text{for } L > 0 \text{ (stable)}. \tag{26}$$

Given a value of R_b, Eq. (19) is solved by an iterative process to return a value of L. The present method has an error in reproducing a given L of at most 0.08% in the range $-4 \leq z/L \leq 4$. The number of iterations can be increased to improve accuracy since only three iterations are used in the unstable case and five iterations in the stable case. In the following discussion of the similarity theory [Eqs. (27) -(44)], the wind speed u is oriented along the direction of the wind, whereas in the rest of this paper u is the component of the wind along the x axis.

The friction velocity u_*, the scaling temperature T_*, and the extrapolated temperature T_0 at z_0 are then obtained as follows:

$$u_* = U_h/F(h), \tag{27}$$

$$T_* = \Delta\theta/G(h), \tag{28}$$

$$T_0 = \theta_h - \Delta\theta - T_* G_0, \tag{29}$$

where

$$G_0 = \frac{1}{k}[\ln(z_1/z_0) + Q(z_1/L)], \tag{30}$$

$$Q\left(\frac{z_1}{L}\right) = 2\ \ln[(Y_0 + 1)/(Y_1 + 1)],$$

$$Y_0 = X_0^{\frac{1}{2}} \quad \text{for } L < 0, \tag{31}$$

$$Q\left(\frac{z_1}{L}\right) = 5(z_1 - z_0)/L \quad \text{for} \quad L > 0. \tag{32}$$

Once U_*, T_*, and T_0 are obtained, the profiles of u and T are available from

$$u = u_* F(z), \tag{33}$$

$$T = T_0 + T_* G(z), \tag{34}$$

where z replaces h, and z_0 replaces z_1 everywhere in Eqs. (20)-(26).

The eddy diffusivity for vertical turbulent transfer of a passive scalar is written

$$K_z \doteq c_1 \sigma_w \lambda, \tag{35}$$

where λ is a length scale and c_1 a constant determined as follows. For steady, neutral flow in the surface layer,

$$K_z = kzu_*. \tag{36}$$

It follows from (35) and (36) that

$$c_1 = \frac{kzu_*}{\sigma_w \lambda}. \tag{37}$$

and under neutral conditions

$$\sigma_w / u_* = 1.28, \quad z\lambda^{-1} = 0.4,$$

hence $c_1 = 0.125$. For simplicity, this neutral value will be used in all the following calculations. The following approximation is used for the surface layer

$$\frac{\sigma_w}{u_*} = \left(\frac{\phi_m - z/L}{3kf_m}\right)^{\frac{1}{3}}, \tag{38}$$

where $\phi_m = (1 - 16z/L)^{-\frac{1}{4}}$ for unstable cases, and $\phi_m = 1 + 5z/L$ for stable cases. The length scale λ in the surface layer is obtained from

$$\lambda = zf_m^{-1}, \tag{39}$$

where f_m, the nondimensional frequency at which the maximum power occurs in the w spectrum, is given by the empirical expression

$$f_m = \begin{cases} 0.4[0.4 + 0.6\exp(4z/L)], & z/L < 0 \\ 0.4[1.0 + 3.39z/L - 0.25(z/L)^2], & 0 \le z/L \le 2.0 \\ 0.04[6.78 + 2.39(z/L - 2.0)], & z/L > 2 \end{cases} \tag{40}$$

which is based on the results of Kaimal (1973).

Estimating K_x^s is much more difficult and is important only when the winds have a large component parallel to the roadway. It is assumed in this model that

$$K_x^s = \begin{cases} |\sigma_u \cos\theta + \sigma_v \sin\theta|_{z=0.5\Delta z}\lambda, & z/L \ge 0 \\ |\sigma_u \cos\theta + \sigma_v \sin\theta|_{z=0.5\Delta z}\lambda, & z/L < 0 \end{cases} \tag{41}$$

where θ is the wind direction and where σ_u and σ_v are given by

$$\frac{\sigma_u}{u_*} = \left(\frac{2.0\phi_m + R_1}{R_2}\right)^{\frac{1}{2}}, \quad \frac{\sigma_v}{u_*} = \left(\frac{R_1}{R_2}\right)^{\frac{1}{2}}, \tag{42}$$

where

$$R_1 = (3.2f_m + 1.2)(\sigma_w/u_*)^3 + 1.4z/L, \tag{43}$$

$$R_2 = 3.2f_m\sigma_w/u_*. \tag{44}$$

The above formulation does not include the cross correlation terms.

VEHICLE WAKE THEORY

The vehicle wake theory was developed by Eskridge and Hunt (1979) and modifications were made based upon wind tunnel experiments by Eskridge and Thompson (1982) and Eskridge and Rao (1983, 1986). All known constants in the wake theory are now based upon wind tunnel measurements. A brief description of those studies is given next.

Single Vehicle Wake

The wake velocity deficit of a single vehicle is given by

$$u_D = QA(\bar{s})^{-0.75} f(\bar{n}/l(s), \bar{z}/l(s)), \quad (45)$$

where

$$\bar{s} = s/h; \quad \bar{z} = z/(\gamma Ah); \quad \bar{n} = n/(\lambda\gamma Aw_d);$$

h is the height of the vehicle; Q is the wind speed relative to the vehicle; A is the strength of the wake determined by the overturning moment acting on the vehicle; γ and λ are constants with experimentally-determined (wind tunnel) values of 0.95 and 1.14, respectively; s is the coordinate along the centerline of the wake; n is the coordinate in the horizontal plane perpendicular to s; z is the vertical coordinate; l(s) is the vertical scale length of the wake; and w_d is the width of the vehicle. A and l(s) are given by

$$A^4 = C_d(32\pi\sqrt{e}\lambda\gamma^3)^{-1} \quad (46)$$

and

$$l(s) = \gamma Ah(\bar{s})^{1/4}, \quad (47)$$

where C_d is the drag coefficient and the other variables are given above. Figure 1 shows the coordinate system used in the model.

The function f in Eq. 45 is the solution to a partial differential equation which does not have a closed form solution (Eskridge and Thompson, 1982). However, the equation is separable as follows,

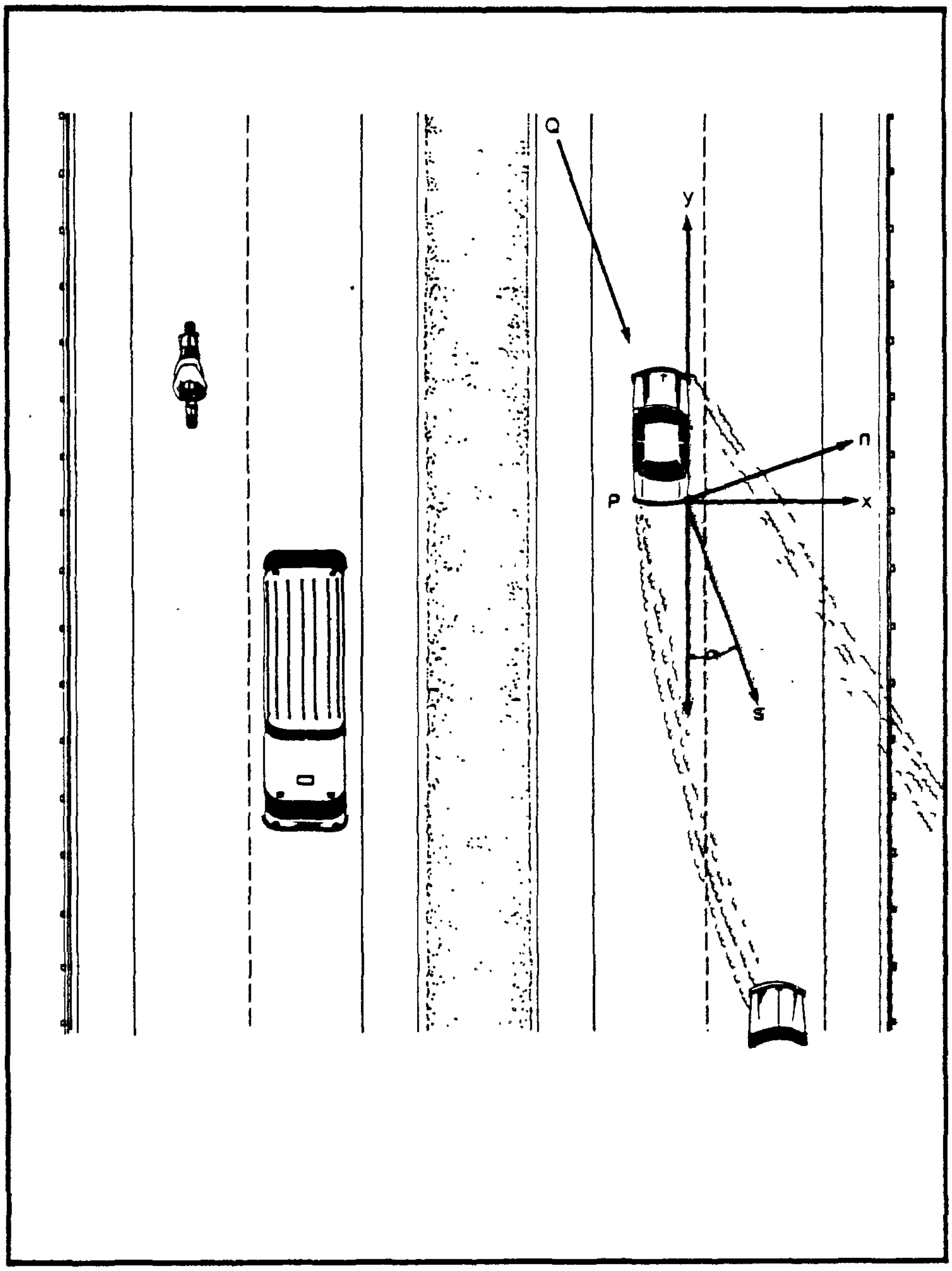


Figure 1. Coordinate system used in the model; n,s,z pertain to the vehicle wake; x,y,z are fixed coordinates in the usual cartesian sense.

$$f(\bar{n}/l(s),\bar{z}/l(s)) = Y(\bar{n}/l(s))T(\bar{z}/l(s)), \quad (48)$$

where

$$Y(\bar{n}/l(s)) = C_1 \exp(-\bar{n}^2/(8 \cdot l^2(s)).$$

$T(\bar{z}/l(s)$ was found by fitting a polynomial to wind tunnel measurements of velocity deficit given by

$$T(\bar{z}/l(s)) \equiv T(\zeta) = b_0 + b_1\zeta + \cdots + b_6\zeta^5, \quad (49)$$

where the coefficients $b_0,\ldots,b_6$ are listed in Table 2.

The turbulent kinetic energy terms are given by

$$(\overline{u'^2},\overline{v'^2},\overline{w'^2}) = (a_1,a_2,a_3)A^2Q^2\bar{s}^{-1.2}F_c(\chi,\omega) \quad (50)$$

where

$$\chi = n/(w_d\bar{s}^{0.4}), \quad \omega = z/(h\bar{s}^{0.4}),$$

and u and v are oriented in the s and n directions, respectively. The constants a_1, a_2, and a_3 were evaluated from wind tunnel data and were found to be 0.048, 0.040, and 0.030, respectively. The function F_c was determined by a least-squares orthogonal polynomial fit to wind tunnel data and is given by

$$F_c(\chi,\omega) = \sum_{n=0}^{4} \sum_{m=0}^{2} \psi_{2m,n}\omega^n\chi^{2m}, \quad (51)$$

and subject to the restriction that $F_c > 0.0$. The constants in Eq. 51 are listed on the right side of Table 2.

TABLE 2. CONSTANTS FOR THE POLYNOMIAL FITS IN EQS. 47 AND 49

Equation 47		Equation 49	
Coeff.	Value	Coeff.	Value
b_0	0.0179349	ψ_{00}	0.3511237×10^{-1}
b_1	2.5765870	ψ_{01}	0.1255308×10^{2}
b_2	-2.3062584	ψ_{02}	-0.4796241×10^{2}
b_3	0.8951468	ψ_{03}	0.6732523×10^{2}
b_4	-0.1758604	ψ_{04}	-0.3572466×10^{2}
b_5	0.0169970	ψ_{20}	-0.1890581
b_6	-0.0006404	ψ_{21}	-0.9345507×10^{1}
		ψ_{22}	-0.1821427×10^{3}
		ψ_{23}	0.5617911×10^{3}
		ψ_{24}	-0.3995373×10^{3}
		ψ_{40}	0.2649465
		ψ_{41}	-0.9434068×10^{2}
		ψ_{42}	0.1034830×10^{4}
		ψ_{43}	-0.2348153×10^{4}
		ψ_{44}	0.1510437×10^{4}

The observed wind velocity fluctuation at some fixed point near a roadway are due to three distinct causes. Velocity fluctuations are produced by vehicle wake turbulence as described by Eq. 50 and they are also due to ambient turbulence. Fluctuations also occur because of the time variation in the wind velocity as the vehicle wake passes a fixed point. This wake-passing effect is clearly not turbulence, but is an artifact of the fact that the data are taken in the Eulerian rather than the Lagrangian frame of reference.

Let the superscripts p and w and the subscript ∞ represent the wake-passing effect, the wake turbulence, and the ambient turbulence, respectively. The total velocity variance is assumed, as a first approximation, to be determined by adding the components, so that

$$\overline{u'^2} = \overline{u'^2}^p + \overline{u'^2}^w + \overline{u'^2_\infty}, \tag{52}$$

with similar expressions for $\overline{v'^2}$ and $\overline{w'^2}$. Eq. 52 assumes there are no interactions between the various scales of turbulence. The total velocity variance energy is defined by

$$\sigma^2 = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2, \tag{53}$$

with similar definitions for the ambient, wake, and wake-passing velocity variances. It should be noted that while the wake-passing turbulence can be very large, it is nondiffusive, and one is interested in it only as a feature of the vehicle wake theory and in the analysis of roadway data. During the normal execution of the ROADWAY model, the wake-passing effects are not calculated.

Multi-vehicle Velocity and Turbulence Fields

The equations describing multi-vehicle wind velocity, turbulence, and wake-passing effect are presented below. The derivations for these equations are given in Eskridge and Rao (1983).

The horizontal wind velocity components are computed by

$$\overline{u(\underset{\sim}{x}_0,t)} = \overline{U_\infty(z_0,t)} - 1/TV_h \sum_{j=1}^{N} \int_{-TV_h/2}^{TV_h/2} U_{D_j}(\underset{\sim}{x}_0, y/V_h) \sin\alpha \, dy$$

and (54)

$$\overline{v(\underset{\sim}{x}_0,t)} = \overline{V_\infty(z_0,t)} - 1/TV_h \sum_{j=1}^{N} \int_{-TV_h/2}^{TV_h/2} U_{D_j}(\underset{\sim}{x}_0, y/V_h) \cos\alpha \, dy$$

where V_h is the average vehicle speed, $\underset{\sim}{x}_0 = (x_0, y_0, z_0)$, u_{D_j} is given by Eq. 45, N is the number of vehicles passing the point x_0 during the time interval $(-T/2, T/2)$, α is the angle between the relative wind Q and the highway, and $U_\infty(z,t)$ and $V_\infty(z,t)$ are upwind ambient conditions.

The turbulent kinetic energy component along the x-axis is given by

$$\overline{u'^2(\underset{\sim}{x_0},t)} = 1/TV_h \sum_{j=1}^{N} \int_{-TV_h/2}^{TV_h/2} \overline{u'^2_w(\underset{\sim}{x_0},y/V_h)}\ dy, \qquad (55)$$

where $\overline{u'^2_w}$ is defined by Eq. 50 and similar expressions are found for $\overline{v'^2}$ and $\overline{w'^2}$.

The velocity variance due to wake-passing is given by

$$\overline{u'^2(\underset{\sim}{x_0},t)} = 1/TV_h \sum_{j=1}^{N} \int_{-TV_h/2}^{TV_h/2} [U_j(\underset{\sim}{x_0},y/V_h)\sin\alpha - \overline{u(\underset{\sim}{x_0},t)}]^2\ dy$$

and (56)

$$\overline{v'^2(\underset{\sim}{x_0},t)} = 1/TV_h \sum_{j=1}^{N} \int_{-TV_h/2}^{TV_h/2} [U_j(\underset{\sim}{x_0},y/V_h)\cos\alpha - \overline{v(\underset{\sim}{x_0},t)}]^2\ dy,$$

where $U_j = |U_\infty, V_\infty| - u_{D_j}$. Eqs. 54, 55, and 56 are integrated using Simpson's method.

CHEMICAL REACTIONS

An automobile exhaust emits nitrogen dioxide (NO_2) as a function of time. With sunlight, the NO_2 undergoes a chemical change forming ozone (O_3) and nitrous oxide (NO). Simultaneously, reverse reactions take place tending to convert the NO back to NO_2. The basic reactions are:

$$\begin{aligned}
NO_2 + h\nu &\xrightarrow{k_1} NO + O \\
O &\xrightarrow{k_2} O_3 \\
NO + O_3 &\xrightarrow{k_3} NO_2 \\
NO + XO &\xrightarrow{k_4} NO_2 + X \\
O_3 + X &\xrightarrow{k_5} XO
\end{aligned} \qquad (57)$$

Where XO represent organic radical reactants. The rate at which the NO_2, NO, and O_3 constituents form and dissipate is expressed by three partial differential equations

$$\frac{\partial(NO_2)}{\partial t} = -k_1(NO_2) + k_3(O_3)(NO) + k_4(NO)(XO)$$

$$\frac{\partial(NO)}{\partial t} = k_1(NO_2) - k_3(O_3)(NO) - k_4(NO)(XO) \qquad (58)$$

$$\frac{\partial O_3}{\partial t} = k_2(O) - k_3(O_3)(NO) - k_5(O_3)(X)$$

Where k_1, k_2, k_3, k_4, and k_5 are chemical reaction rate constants. These equations show that the rate of change of NO_2, for example, at any point depends upon its own concentration and those of NO, O_3, and the organic radicals. (Note that the O_3 and M concentrations have been absorbed in the k_2 rate constant). Therefore, to simulate the system, the diffusion of the three principal constituents must be represented by three coupled, simultaneous diffusion equations with mass transfer.

ROADWAY assumes that the physical processes of interest occur within approximately 200 m of the highway. For this length scale and reasonable crosswind velocities, the length of time the vehicle emissions are close to the road limits the applicable chemistry. Because of this, it is assumed that the following reactions are the only important ones near the highway:

$$NO + O_3 \xrightarrow{k_1} NO_2 \qquad (59)$$

and

$$NO_2 \xrightarrow{k_2} NO + O_3. \qquad (60)$$

k_1 and k_2 are chemical reaction rate constants with values of 22.0 $ppm^{-1}min^{-1}$ and 0.46 min^{-1}. The value for k_2 is a mid-day value; k_2 varies diurnally (Note that O_2 concentration has been absorbed in the k_2 rate constant). These reactions lead to the following conservation of species equations:

$$\partial A/\partial t + \nabla \cdot AV = \nabla \cdot K \nabla A + E_A - k_1 DA + k_2 C, \quad (61)$$

$$\partial C/\partial t + \nabla \cdot CV = \nabla \cdot K \nabla C + E_C + k_1 DA - k_2 C, \quad (62)$$

and

$$\partial D/\partial t + \nabla \cdot DV = \nabla \cdot K \nabla D + E_D - k_1 DA + k_2 C, \quad (63)$$

where A, C, and D represent the concentration of NO, NO_2, and O_3, respectively; vehicle emissions are in units of g/km·veh.

SECTION 6

EXAMPLE PROBLEM

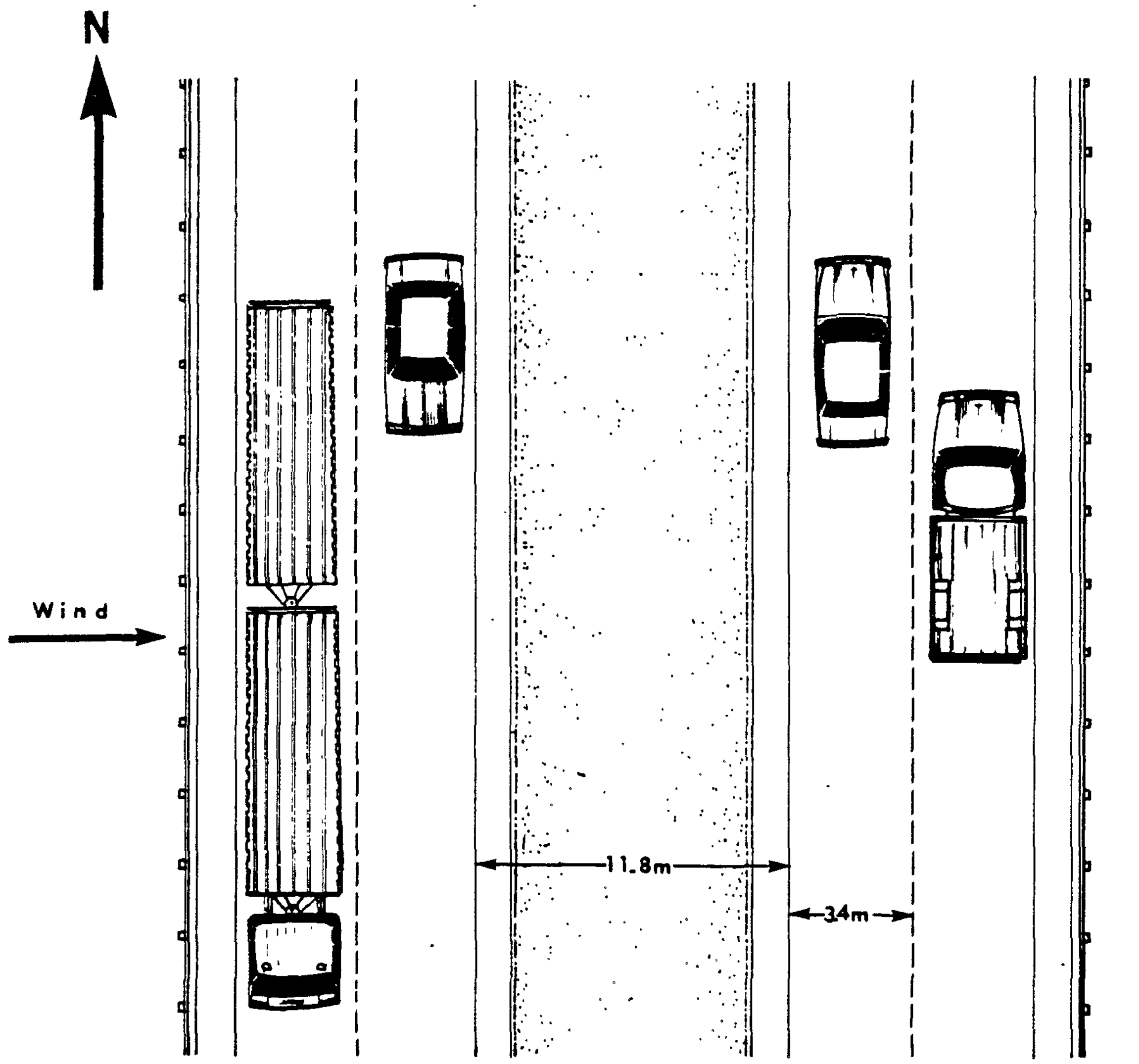
This section presents a hypothetical problem to illustrate the use of ROADWAY and the type of information provided by the model. Details concerning input and output for this example are given in Section 11 after the reader has become familiar with the preparation of model inputs.

The geometry of the example problem is depicted in Figure 2 which also includes the required highway information. The area upwind of the highway can be described as flat with medium to long grass with a representative roughness length of 0.5 m. The pertinent meteorological and air quality measurements just upwind of the highway are as follows:

- 274.22 K at a height of 1.22 meters,
- 274.33 K at a height of 4.24 meters,
- due westerly winds at 0.94 m/sec (measured at the same height as the upper temperature instrument), and
- background NO, NO_2, O_3, and CO concentrations of 0.052 ppm, 0.25 ppm, 0.10 ppm, and 40.0 ppm respectively.

All measurements represent hourly averages.

The horizontal wind fields are shown in Figure 3. The vertical velocity field, also provided by ROADWAY, is not shown. The u field is fairly uniform except for the expected increase of speed with height. The v field shows, as expected, that the southbound lanes contribute a southerly component to the wind (negative sign); while the northbound lanes result in a northerly component (positive sign). It should be noted that the traffic influence decreases with height and distance downwind of the



Highway Data

Volume (veh/hr)	1366	1366	1366	1366
Speed (km/hr)	80	80	80	80
NO (g/km veh)	2.7	2.7	2.7	2.7
CO (g/km veh)	90	90	90	90
NO_2 (g/km veh)	3.0	3.0	3.0	3.0

Figure 2. Geometry of the example problem.

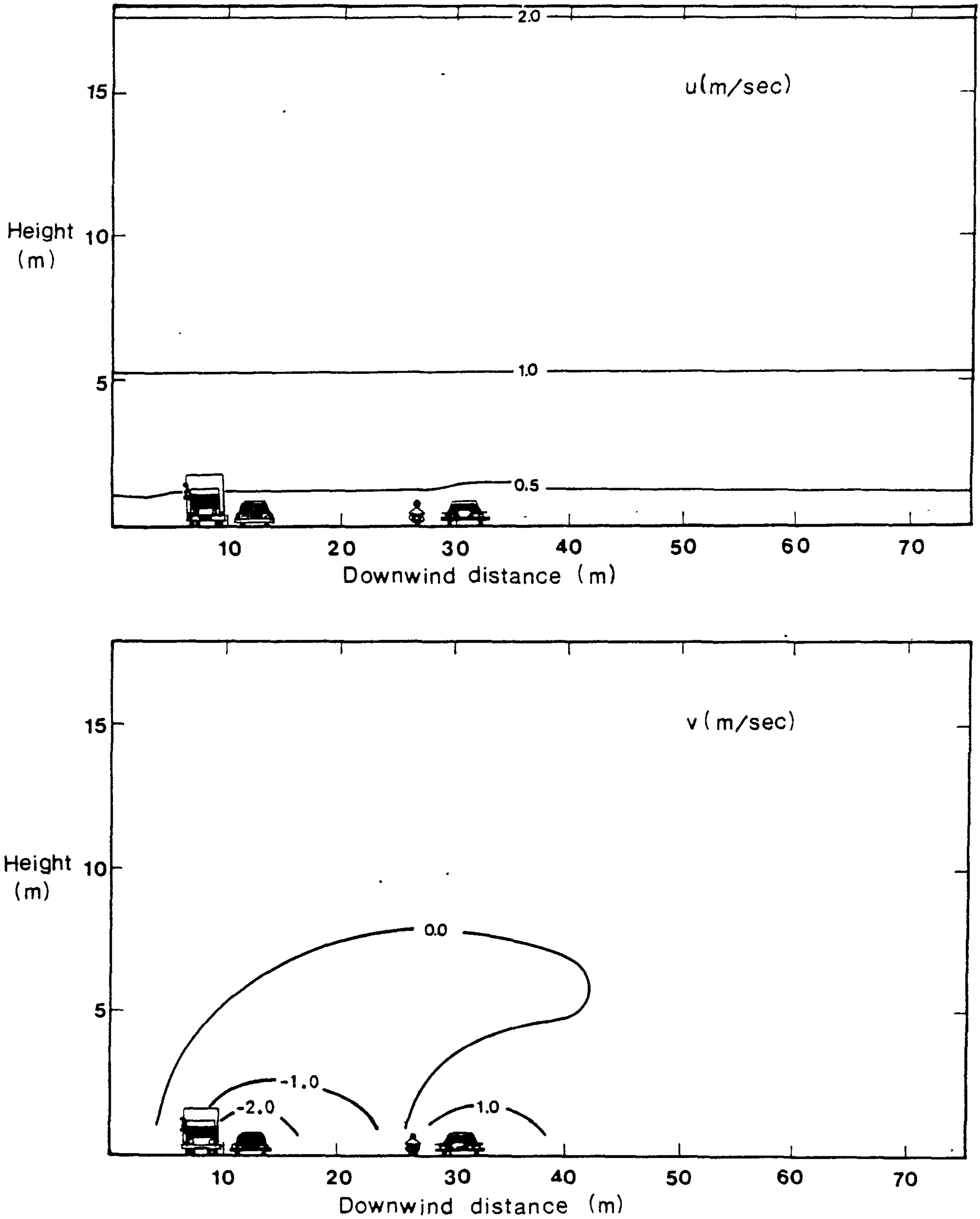


Figure 3. u and v wind fields for the example problem.

highway.

The diffusivity fields are given in Figure 4. Vehicle wakes associated with the traffic contribute significantly to both the K_x and K_z fields. The wake turbulence decreases with height and distance downwind of the highway.

The pollutant fields are provided in Figure 5. Because the chemistry option was exercised, the four concentration fields are given on output. Concentrations of the pollutants except O_3 are highest in the vicinity of the traffic lanes and decrease with a skewed pattern in the downwind direction. The O_3 concentrations, on the other hand, are lowest near the highway since chemical reactions are such that vehicle emissions combine to act as sinks for O_3 decreasing upward to the background value given by the user in the input stream.

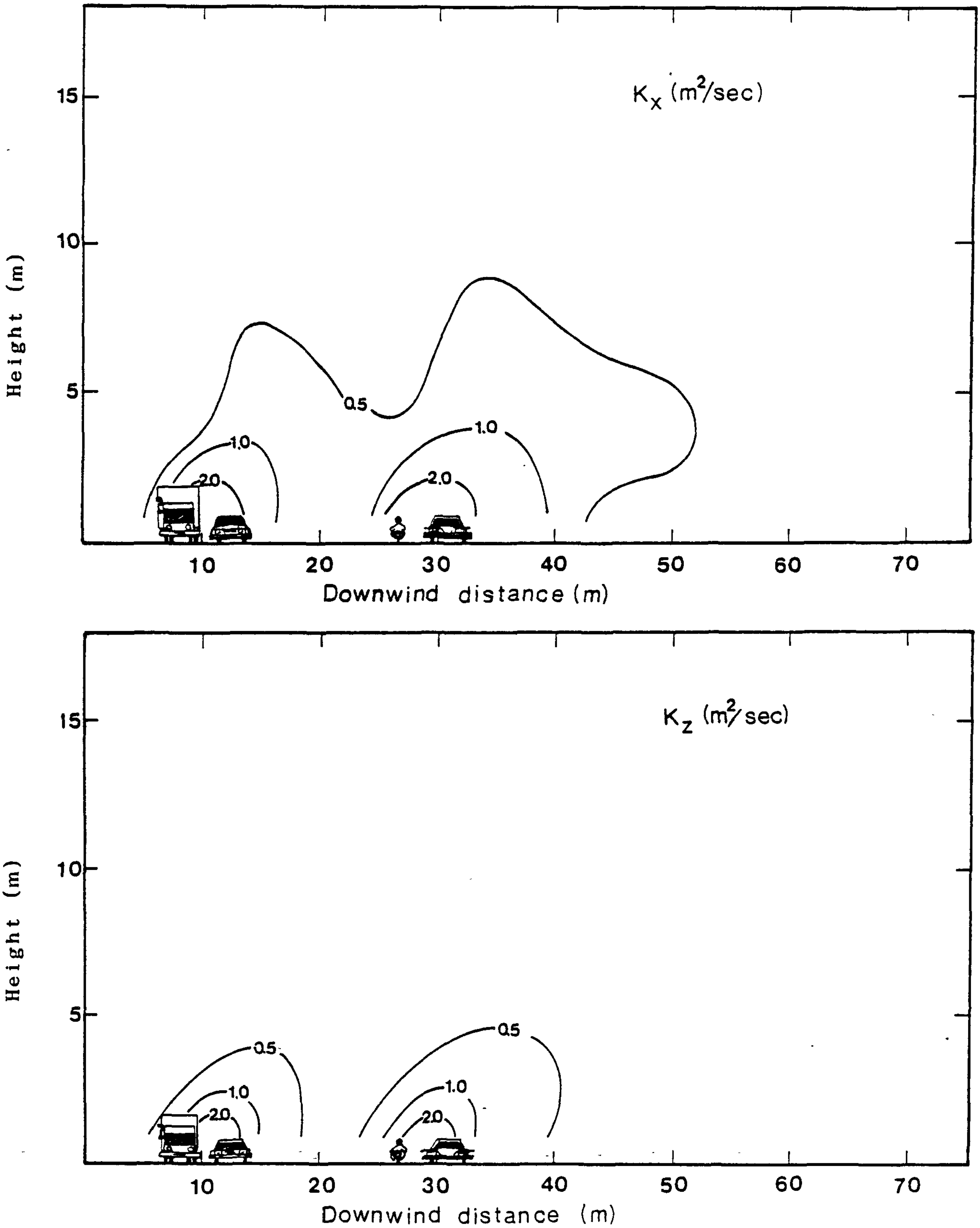


Figure 4. Turbulence fields for the example problem.

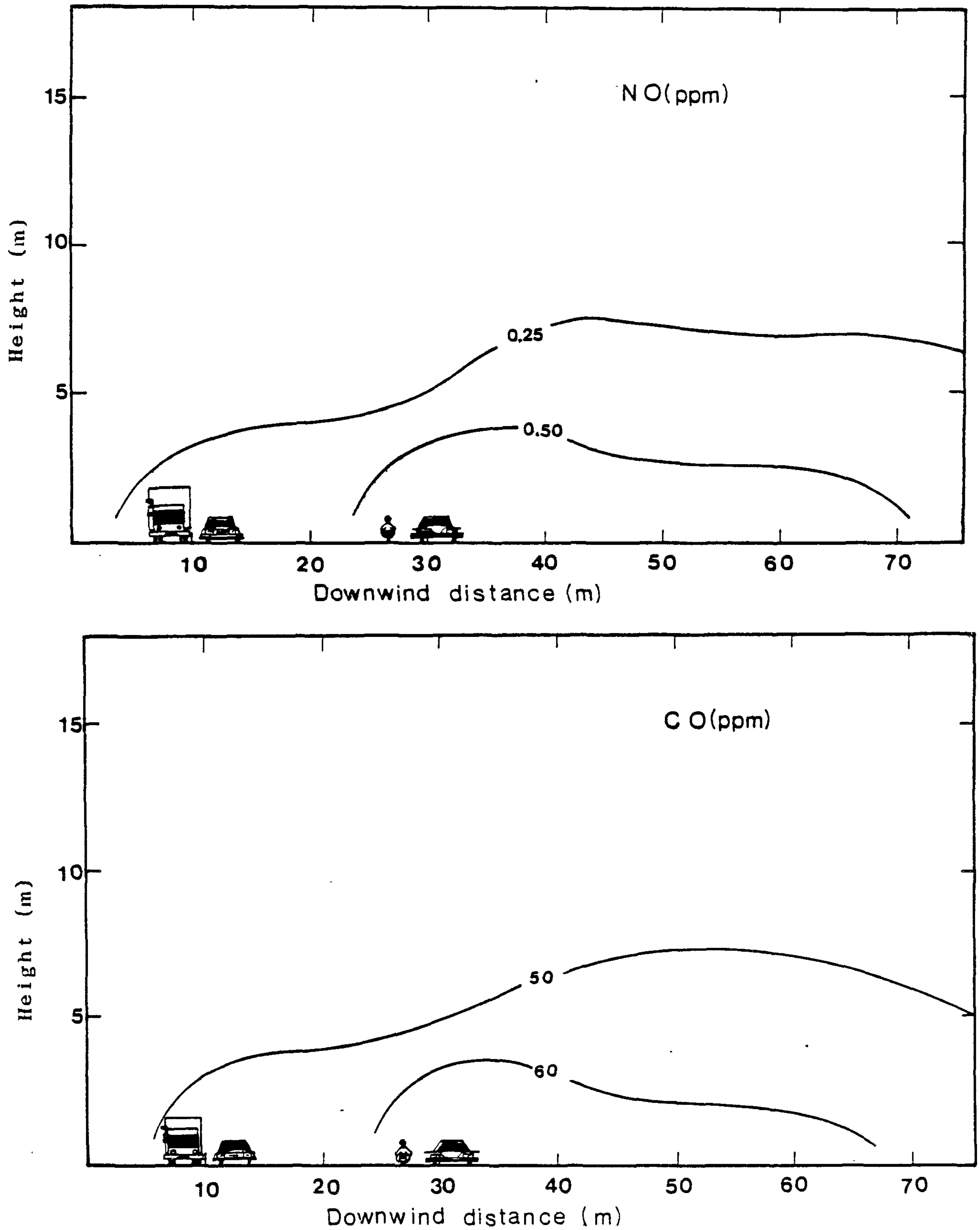
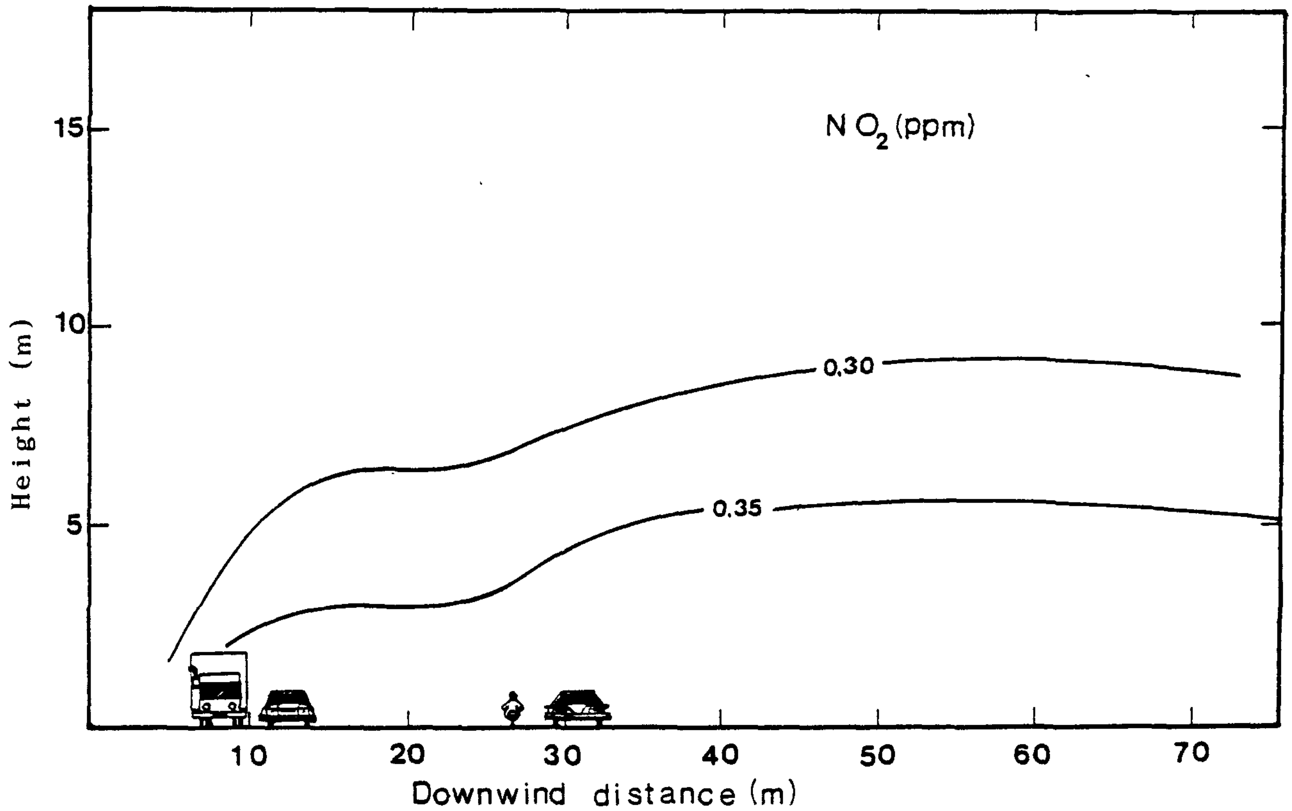


Figure 5. Pollutant concentration field for the example problem.



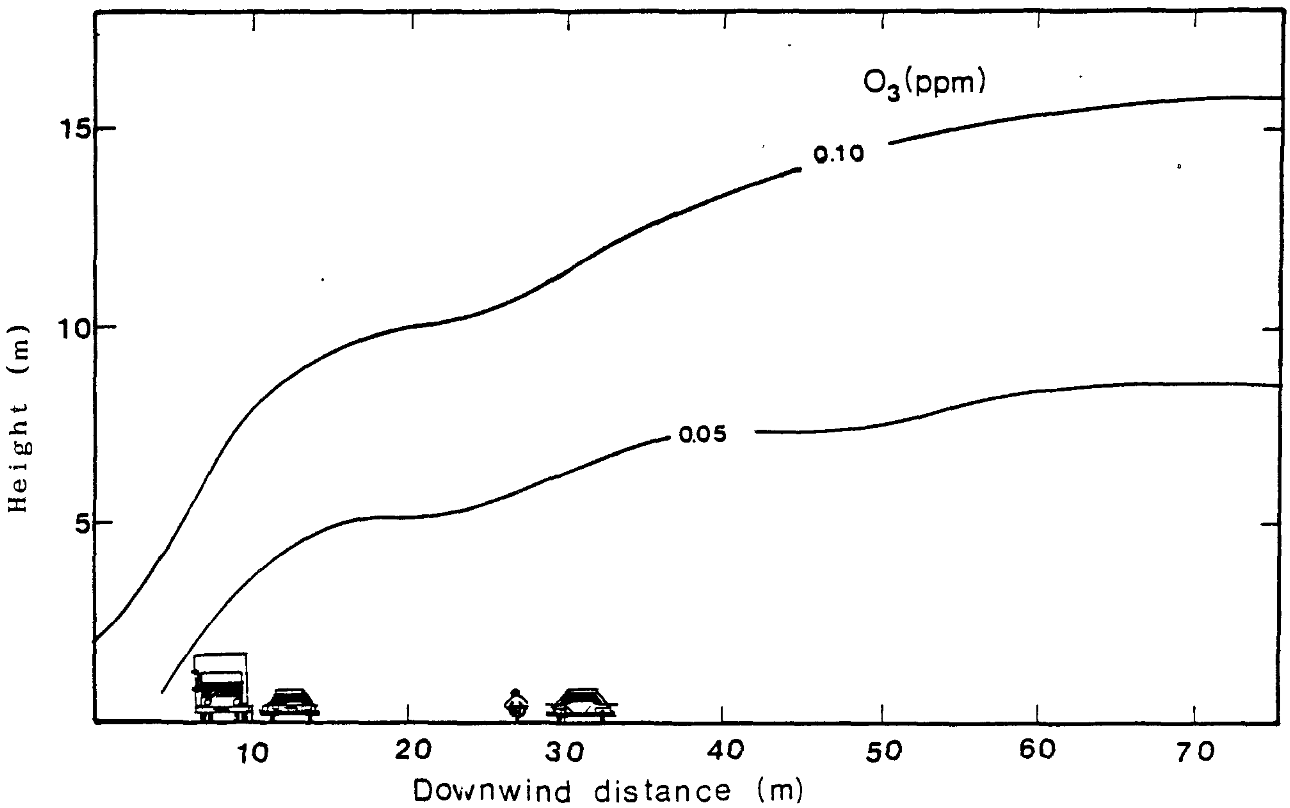


Figure 5. continued

SECTION 7

MODEL EVALUATION

BACKGROUND

Rao et al. (1980) evaluated four Gaussian models (GM, HIWAY, AIRPOL-4, and CALINE2) and three numerical models (DANARD, MROAD 2, and ROADS) using tracer data from the General Motors Sulfate Dispersion Experiment (Cadle et al., 1976). In general, the numerical models as a group performed rather poorly compared to the Gaussian models. Although the GM model (Chock, 1978) performed best, it had a tendency to underpredict. For this reason, it was found inappropriate for decision-making where worst-case results are desirable to ensure compliance with the standards. For regulatory applications, it was concluded that the HIWAY model (Zimmerman and Thompson, 1975) was the most useful since it had the highest percentage of overprediction in most of the statistical tests considered.

Based on recent studies that quantified traffic-induced turbulence and its influence on pollutant dispersion in the near field, Rao and Keenan (1980) modified the Pasquill-Gifford diffusion curves used by HIWAY. They also added an aerodynamic drag factor to handle dispersion under near-calm conditions. With these refinements, model performance was improved significantly giving results comparable to those of GM. Although predictions are significantly improved in the new HIWAY model (renamed HIWAY-2), a slight tendency to overpredict still remains. This makes HIWAY-2 appropriate for screening regulatory applications.

Recently, Rao et al. (1985) have evaluated ROADWAY along with HIWAY-2 and CALINE3 using statistical techniques suggested by Fox

(1981) and Willmott (1982), extreme value statistics (Tabony, 1983), and the "bootstrap" method (Diaconis and Efron, 1983). CALINE3 is based on the Gaussian equation and employs a mixing zone concept to characterize diffusion over the road. Some of the results of the evaluation are discussed here. A reprint of the journal article describing the study is given in Appendix B. This study used the SF_6 data taken in the GM Sulfate Dispersion experiment for the model evaluations.

EVALUATION RESULTS

The paired statistical test parameters are given in Table 3. HIWAY-2, ROADWAY, and CALINE3 explain respectively 70-, 65-, and 29-percent of the variance. The slopes of the regression lines are close to 1.0 and the intercepts are small for all three models. The index of agreement is a measure of the degree to which model predictions are free from error. It shows that the performance of ROADWAY and HIWAY-2 is similar and that both predict considerably better than CALINE3. The mean difference and mean fractional error, which are measures of overall model bias, indicate that both ROADWAY and HIWAY-2 overpredict, while CALINE3 has a slight tendency toward underprediction. One of the better overall measures of model performance is the root mean square error (RMSE). As shown in Table 3, the RMSE values for the three models indicate that HIWAY-2 performs slightly better than ROADWAY and both are considerably better than CALINE3. It should be noted also that most of the error associated with the three models is not systematic (i.e., MSE_S approach zero). This indicates that the models are performing as well as possible without major algorithm modification. Figure 6 illustrates the relative performance of the three models relating them to observed data.

TABLE 3. COMPARISON OF MODEL RESULTS USING THE GM DATA SET

Statistic	Observed	HIWAY-2	CALINE3	ROADWAY
N	594	594	594	594
range	0.01-4.92	0.01-4.68	0.09-17.97	0.02-5.29
mean	0.96	1.07	0.96	1.20
s	0.74	0.77	1.31	0.92
r^2		0.70	0.29	0.65
slope, b		0.87	0.96	1.00
intercept, a		0.23	0.04	0.25
D		0.91	0.64	0.86
$\bar{d}$		0.11	0.00	0.25
MFE		-0.12	0.04	-0.21
RMSE		0.44	1.11	0.60
MSE_u		0.18	1.22	0.29
MSE_s		0.02	0.00	0.06
MSE		0.20	1.22	0.35

N = sample size
s = standard deviation
r^2 = correlation coefficient squared
D = index of agreement
$\bar{d}$ = mean difference
MFE = mean fractional error
RMSE = root mean square error
MSE = mean square error
MSE_u = unsystematic MSE
MSE_s = systematic MSE

For the following equations, P = predicted, M = measured, and $\hat{P}_i = a + bM_i$.

$$d = (1/N)\sum_1^N (P_i - M_i) = (1/N)\sum_1^N d_i = \bar{P} - \bar{M}$$

$$D = 1 - \left[\sum_1^N (P_i - M_i)^2 / \sum_1^N (|P_i'| + |M_i'|)^2\right],$$

$$MFE = (\sqrt{2}/N)\sum_1^N (M_i - P_i)/\sqrt{(M_i + P_i)}$$

$$RMSE = \left[(1/N)\sum_1^N d_i^2\right]^{1/2}$$

$$MSE_u = (1/N)\sum_1^N (P_i - \hat{P}_i)^2$$

$$MSE_s = (1/N)\sum_1^N (\hat{P}_i - M_i)^2$$

$$MSE = RMSE^2$$

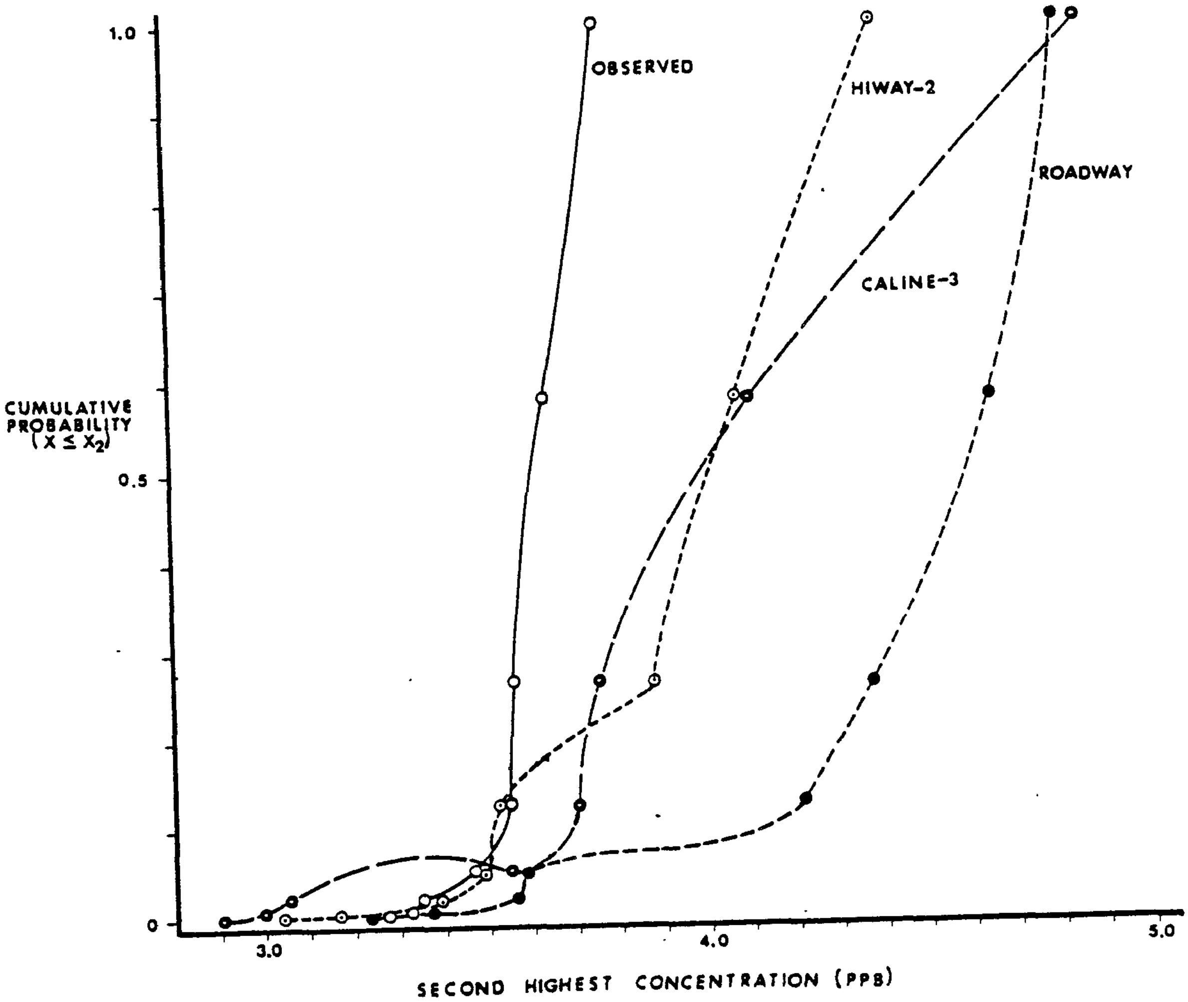


Figure 6. Comparative performance of highway models.

SECTION 8

COMPUTER ASPECTS OF THE MODEL

This section discusses ROADWAY from a system design and programming perspective to give the reader a general view of the computational system. The overall structure of the program, a brief description of each subprogram, and the general processing flow are given next.

STRUCTURE OF ROADWAY

ROADWAY consists of a main routine, 19 subroutines, and 8 functions as shown in Figure 7. All input data are read and screened in subroutine READER. Output is provided by several subroutines: ECHO prints the input data; the downwind grid points and traffic lane locations are output in subroutine CENTER; the velocity, turbulence, and concentration fields are all printed by subroutine GRAPH. A brief description of the main program, subroutines, and functions follows.

PROGRAM MODULES

Main -- The mainline program begins with introductory comments including the program abstract, authorship, program structure, and input/output units. After these introductory comments, the program performs the following tasks by subroutine call: read and echo input data, initialize arrays, determine ambient atmospheric conditions using similarity theory, initialize x-z grid system, compute and add vehicle wake effects to the turbulence fields, advect and diffuse the pollutants, and write the results.

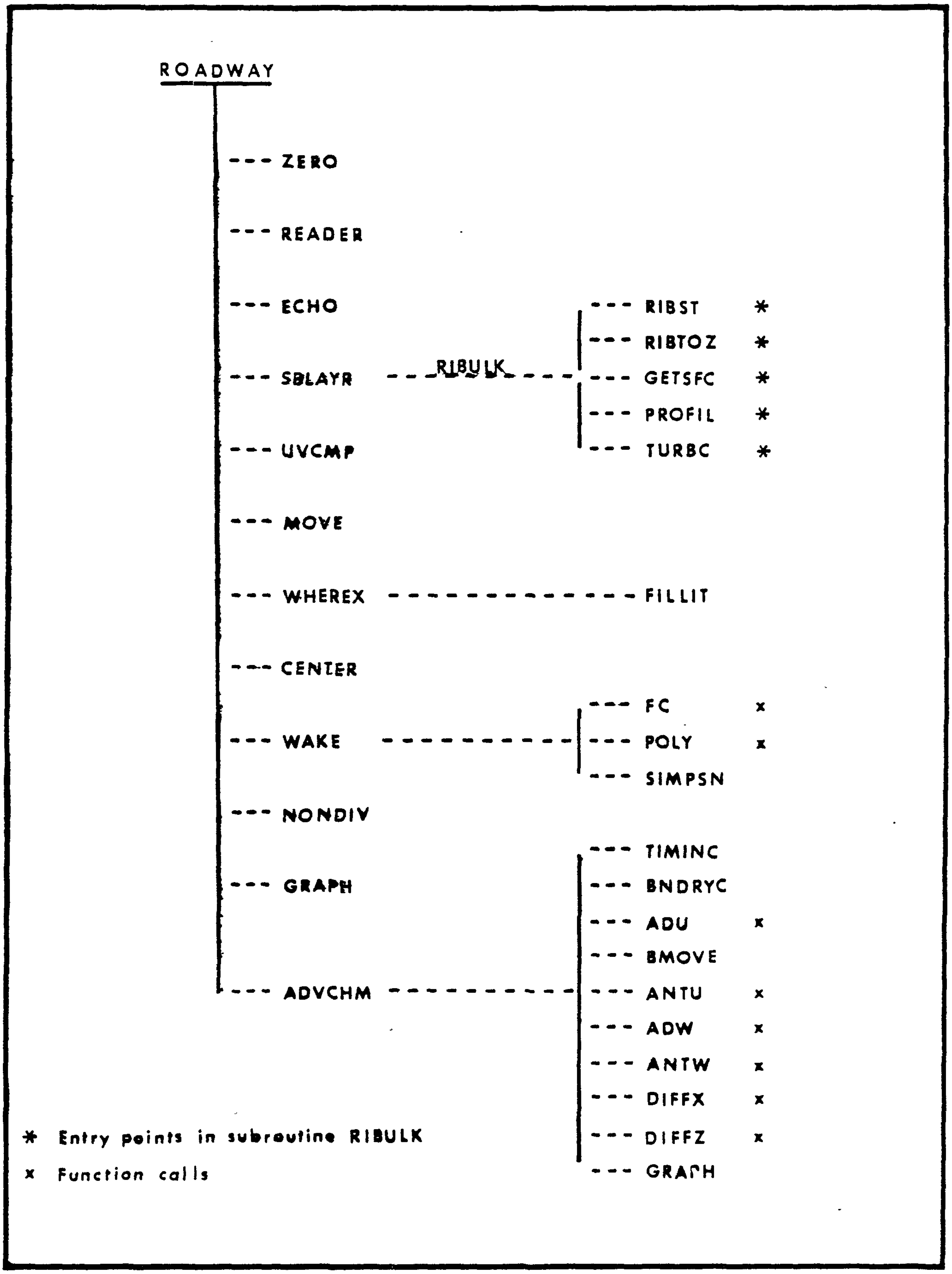


Figure 7. Structure of ROADWAY computational system.

While error messages are printed from pertinent code segments, control of program execution including program termination occurs exclusively in the main routine.

READER -- This module is called by the main routine and reads all input data from FORTRAN unit 5. The data is screened to detect gross errors. If an error is detected, then a nonzero value is assigned to variable IERR, an error message is printed, and control is returned to the main routine. Input data is shared with the main and subroutines via labeled common INCOM.

ECHO -- Called by the main program, this subroutine echoes the input data. The data is passed to this module by labeled common (INCOM).

ZERO -- Subroutine called by the main program to perform initialization of arrays.

SBLAYR -- This module is called by the main routine and is the driver for the surface layer model which uses similarity theory to obtain surface boundary layer parameters. It calculates the velocity profiles, turbulence profiles, and the eddy diffusion coefficients.

UVCMP -- Called by the main program, this subroutine converts wind velocity into its u and v components.

MOVE -- Module called by the main routine to initialize the grid in the x direction.

WHEREX -- This subroutine is called by the main program to calculate the number and spacing of grid points in the x direction. It also builds the arrays containing emissions at each lane location.

CENTER -- This module determines the center of each traffic lane. The x direction grid points and traffic lane locations are written here. This subroutine is called by the main program.

WAKE -- Calculates the changes in the wind and turbulence fields due to the vehicle wakes. It can also calculate the wake passing effect (Eskridge and Rao, 1983); these calculations are not normally done, however. WAKE is called by the main routine.

NONDIV -- Subroutine NONDIV is called by the main program to find the vertical velocity using the inflow and outflow in the x direction from the u field and the vertical inflow through the bottom of the box around each grid point. The vertical velocity at a grid point is a linear interpolation of the vertical velocity at the bottom and top boundaries of the box.

ADVCHM -- Called by the main routine, this module controls the advective, diffusion, and chemical calculations by calling pertinent subroutines and functions.

RIBULK -- Entry points in this subroutine are called by SBLAYR to calculate surface quantities such as u_* and T_* using similarity theory. Entry points RIBST, RIBTOZ, GETSFC, PROFIL, and TURBC are accessed by subroutine SBLAYR.

FILLIT -- Called by module WHEREX, it builds grid points in the x direction using the specified indices and increment.

FC -- This function is called by subroutine WAKE to perform a 2-dimensional fit to wind tunnel data of the turbulent kinetic energy terms in the y-z plane (Eskridge and Thompson, 1982).

POLY -- Called by subroutine WAKE, this function calculates the vertical variation of wake velocity deficit using a curve fit to wind tunnel data in subroutine FC.

SIMPSN -- This module performs a numerical integration using Simpson's method. It is called by subroutine WAKE.

TIMINC -- This subroutine is called by module ADVCHM and finds the maximum allowable time step for advection and diffusion to eliminate computational instability. It also calculates a stable chemical reaction time step.

BNDRYC -- Subroutine called by module ADVCHM to set the boundary conditions for a pollutant during the marching process.

ADU -- This function is called by subroutine ADVCHM to determine transport in the x direction by an upstream flux corrected-method.

BMOVE -- Called by module ADVCHM, this subroutine initializes an array passed in the argument list.

ANTU -- This function performs the antidiffusion or flux delimiter calculation in the x direction and is called by subroutine ADVCHM.

ADW -- This function is called by subroutine ADVCHM to obtain transport in the z direction using an upstream flux corrected method. This function is called by subroutine ADVCHM.

ANTW -- This function performs the antidiffusion or flux delimiter calculation in the z direction and is called by subroutine ADVCHM.

DIFFX -- Function called by module ADVCHM to calculate diffusion in the x direction by centered-in-space differences making allowances for the unequal spacing of the grid.

DIFFZ -- Function called by module ADVCHM to calculate diffusion in the z direction by differences centered-in-space making allowances for unequal spacing.

GRAPH -- This subroutine prints velocity, diffusivity, and pollutant concentration fields. It is called by both the main program and subroutine ADVCHM.

Figure 8 presents a flow diagram of ROADWAY showing its major loops and the relationships of the subroutines and functions to each other.

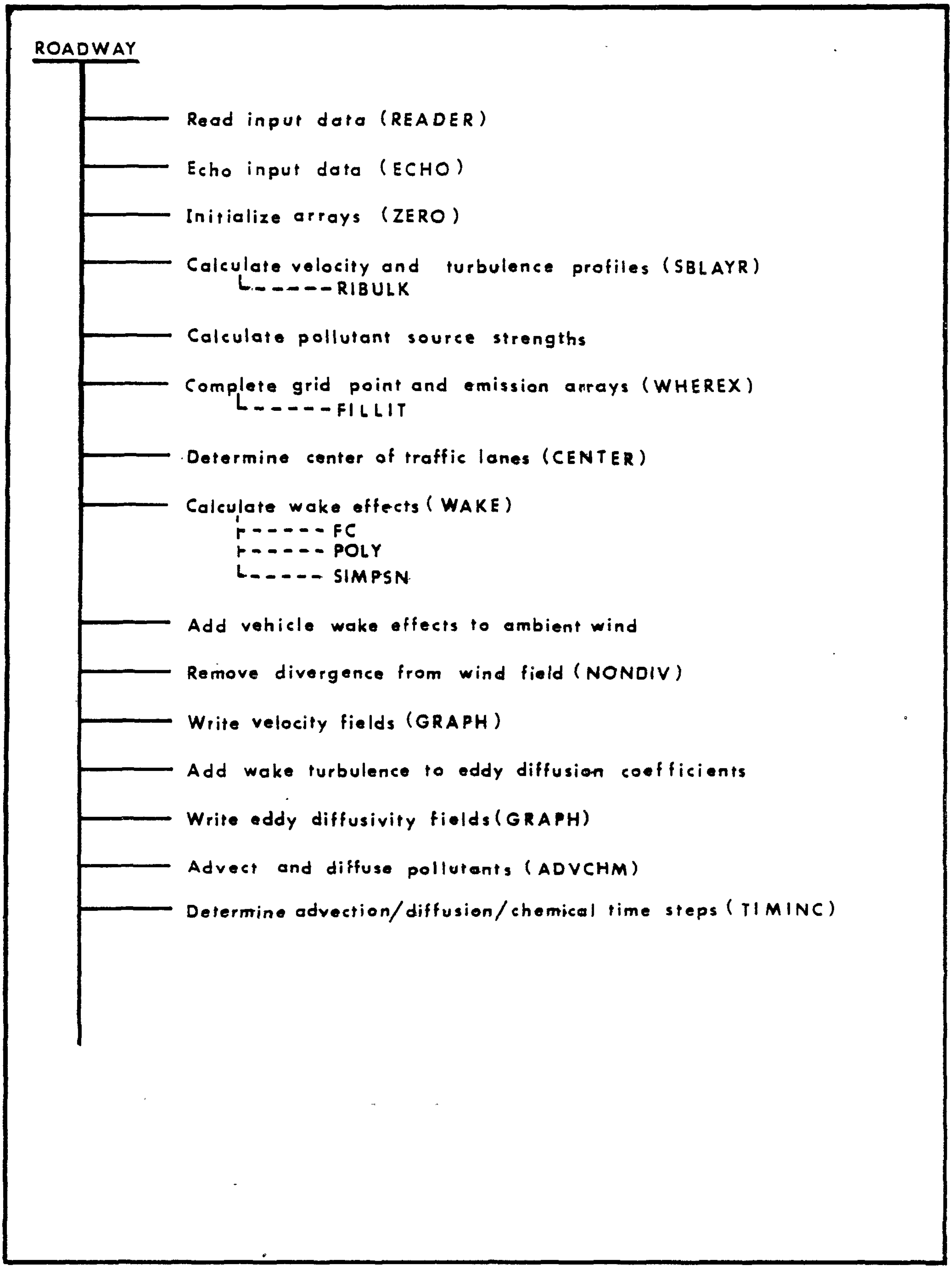


Figure 8. ROADWAY flow diagram.

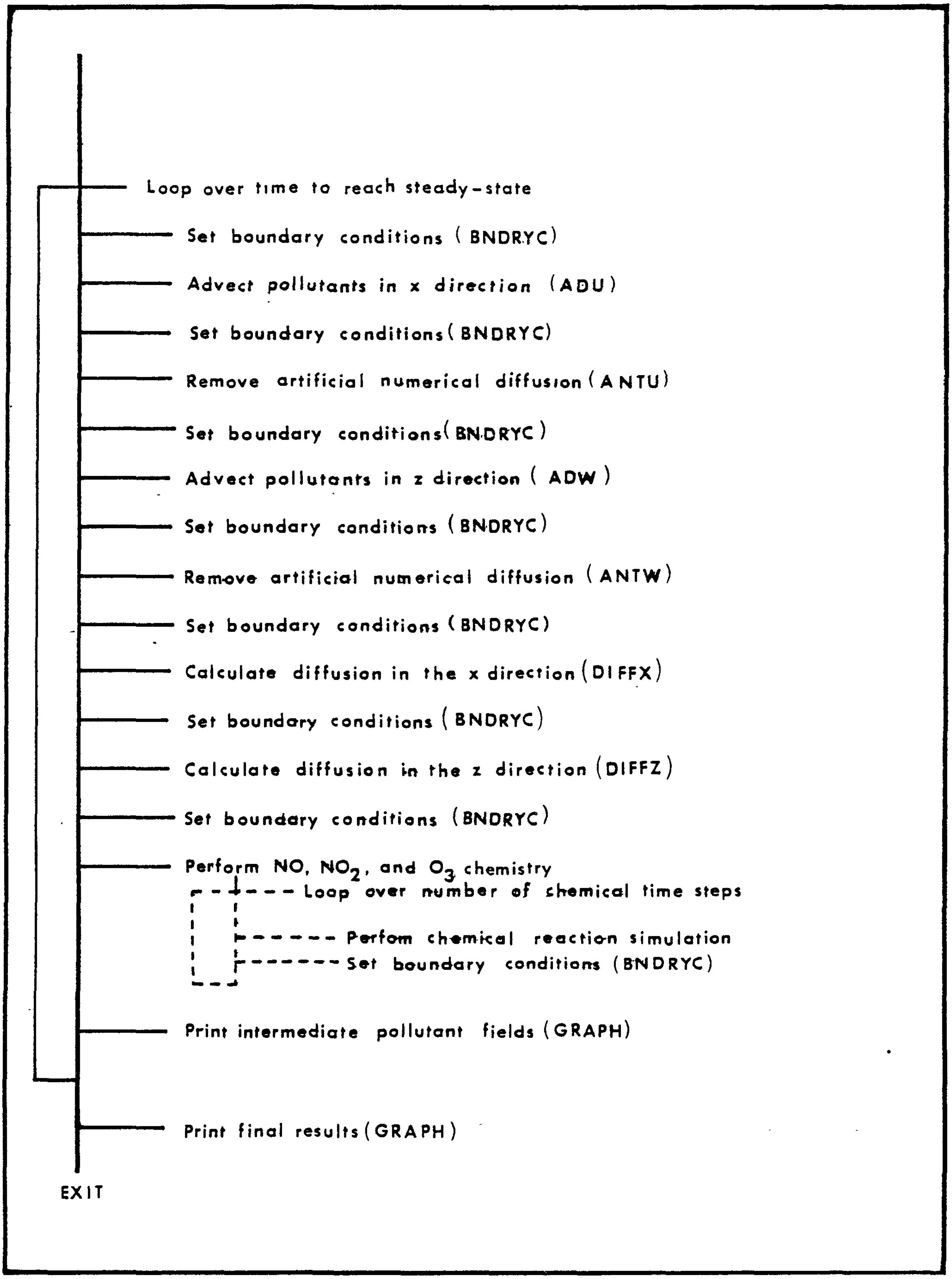


Figure 8. (continued).

SECTION 9

INPUT DATA PREPARATION

RECORD INPUT SEQUENCE

There are 11 record types read by ROADWAY; 8 of these are free format input. While the free format is simple to use, care should be taken to ensure that variables are given values in the correct order. Each variable should be separated by a comma and should conform to the variable name type (i.e., integer or real). One of the record types is optional, depending on the options exercised on record type 4. A brief description of each input parameter is given in Table 4 where correct units are also displayed. Under the "Format" column in Table 4, FF represents free format.

TABLE 4. RECORD INPUT SEQUENCE FOR ROADWAY

Record type & Variable	Column	Format	Variable description	Units
Record type 1				
HEAD1	1-80	20A4	80-character title	---
Record type 2				
HEAD2	1-80	20A4	80-character title	---
Record type 3				
HEAD3	1-80	20A4	80-character title	---
Record type 4				
Z0	---	FF	Surface roughness	m
Z1	---	FF	Height of lower temperature instrument	m

(continued)

TABLE 4 (continued)

Record type & Variable	Column	Format	Variable description	Units
Z2	---	FF	Height of upper temperature and anemometer	m
ICHEM	---	FF	Chemistry option 0, include NO, CO, NO_2, and O_3 chemistry 1, do not include chemistry	---
IANTI	---	FF	Antidiffusion calculation option 0, do antidiffusion calculation 1, skip antidiffusion calculation	---
INTPR	---	FF	Intermediate print option 0, print fields of meteorological variables and intermediate concentration fields 1, print only final concentration fields	---
Becord type 5				
T1	---	FF	Temperature at height Z1	K
T2	---	FF	Temperature at height Z2	K
WSPD	---	FF	Hourly average wind speed	m/sec
WDIR	---	FF	Hourly average wind direction	deg
RDANGL	---	FF	Angle between road and line running north-south. Counterclockwise is positive, clockwise is negative and always less than 90°.	deg

(continued)

TABLE 4 (continued)

Record type & Variable	Column	Format	Variable description	Units
Record type 6 -- Background concentrations *				
BACKGA	---	FF	Background concentration of NO	ppm
BACKGB	---	FF	Background concentration of CO	ppm
BACKGC	---	FF	Background concentration of NO_2	ppm
BACKGD	---	FF	Background concentration of O_3	ppm
Record type 7 -- Highway information				
NLANE	---	FF	Number of traffic lanes. Maximum of 10; minimum of 4. Must be in increments of 2.	---
WIDL	---	FF	Width of one lane	m
MEDN	---	FF	Width of traffic median	m
Record type 8 -- Traffic information				
NVEH	---	FF	Number of vehicles per southbound lane in an hour.	veh•hr
NVEH1	---	FF	Number of vehicles per northbound lane in an hour.	veh•hr
VSPD	---	FF	Average vehicle speed in southbound lanes	km/hr
VSPD1	---	FF	Average vehicle speed in northbound lanes	km/hr
VWID	---	FF	Average width of vehicles	m
VHGH	---	FF	Average height of vehicles	m
Record type 9 -- Emission information †				
EMA	---	FF	NO emission rate for southbound lanes	g/km/veh
EMB	---	FF	CO emission rate for southbound lanes	g/km/veh

TABLE 4 (continued)

Record type & Variable	Column	Format	Variable description	Units
EMC	---	FF	NO_2 emission rate for southbound lanes	g/km/veh
EMA1	---	FF	NO emission rate for northbound lanes	g/km/veh
EMB1	---	FF	CO emission rate for northbound lanes	g/km/veh
EMC1	---	FF	NO_2 emission rate for northbound lanes	g/km/veh
Record type 10 -- Conversion factors **				
CNA	---	FF	Conversion from g/sec to ppm for NO	---
CNB	---	FF	Conversion from g/sec to ppm for CO	---
CNC	---	FF	Conversion from g/sec to ppm for NO_2	---
CND	---	FF	Conversion from g/sec to ppm for O_3	---
Record type 11 -- Reaction rates (read only if ICHEM = 0)				
K1	---	FF	Reaction rate for $NO + O_3 \longrightarrow NO_2 + O_2$	$ppm^{-1}min^{-1}$
K2	---	FF	Reaction rate for $NO_2 + O_2 \longrightarrow NO + O_3$	min^{-1}

FF = free format

* If ICHEM = 1, then BACKGA is the background concentration of the pollutant and BACKGB, BACKGC, and BACKGD are omitted.

† If ICHEM = 1, then EMA and EMA1 are the pollutant emission rates of the southbound and northbound lanes, respectively, and EMB, EMC, EMB1, and EMC1 are omitted.

** If ICHEM = 1, then CNA is the conversion factor for the pollutant and CNB, CNC, and CND are omitted.

INTRICACIES OF THE DATA

Most of the input data listed are straightforward. However, there are some input variables which require clarification to be sure that values are assigned properly.

Record Type 4

The roughness length, Z_0, must represent the surface characteristics immediately upwind of the highway. Roughness lengths for model input are listed below.

TABLE 5. ROUGHNESS LENGTHS FOR VARIOUS SURFACE TYPES

Land-use type	Roughness Z_0 (cm)	Source
cropland and pasture	20	from Sheih et al. (1979)
cropland, woodland, and grazing land	30	from Sheih et al. (1979)
irrigated crops	5	from Sheih et al. (1979)
grazed forest and woodland	90	from Sheih et al. (1979)
ungrazed forest and woodland	100	from Sheih et al. (1979)
subhumid grassland and semiarid grazing land	10	from Sheih et al. (1979)
open woodland grazed	20	from Sheih et al. (1979)
desert shrubland	30	from Sheih et al. (1979)
swamp	20	from Sheih et al. (1979)
marshland	50	from Sheih et al. (1979)
metropolitan city	100	from Sheih et al. (1979)
lake or ocean	~0.01	from Sheih et al. (1979)

From Sheih et al. (1979)

If the chemistry option is exercised (i.e., ICHEM = 0), then chemical reactions of NO, NO_2, and O_3 near the road are simulated. For exercising this option, the user must provide the following additional information:

- Background concentrations of NO, CO, NO_2, and O_3;
- NO, CO, and NO_2 emission rates for northbound and southbound vehicles;

- Conversion factors (g/sec^3 to ppm) for NO, CO, NO_2, and O_3; and
- Chemical reaction rates for

  $NO + O_3 \longrightarrow NO_2 + O_2$ and

  $NO_2 + O_2 \longrightarrow NO + O_3$.

The upwind differencing scheme for advection tends to diffuse the concentration field artificially. By exercising the antidiffusion option (i.e., IANTI = 0), most of the numerical dispersion is removed. Although execution time is increased, it is recommended that this option be used.

The user may see the concentration fields evolve before reaching steady-state conditions by using the intermediate print option (i.e., INTPR = 0). The velocity and diffusivity fields are also provided when this option is exercised. If the user chooses not to implement the intermediate print option (i.e., INTPR = 1), then ROADWAY simply echoes the input data and prints the steady-state concentration fields.

Record Type 5

RDANGL is the angle between the highway and a line running north-south. The angle is always less then 90°. Examples of several highway configurations and their appropriate values of RDANGL are given in Figure 9.

Record Type 6

If the chemistry option is exercised (i.e., ICHEM = 0), then the background concentrations of NO, CO, NO_2, and O_3 must also be given. When the chemistry option is not considered (i.e., ICHEM = 1), then only the background concentration of the pollutant being simulated is required.

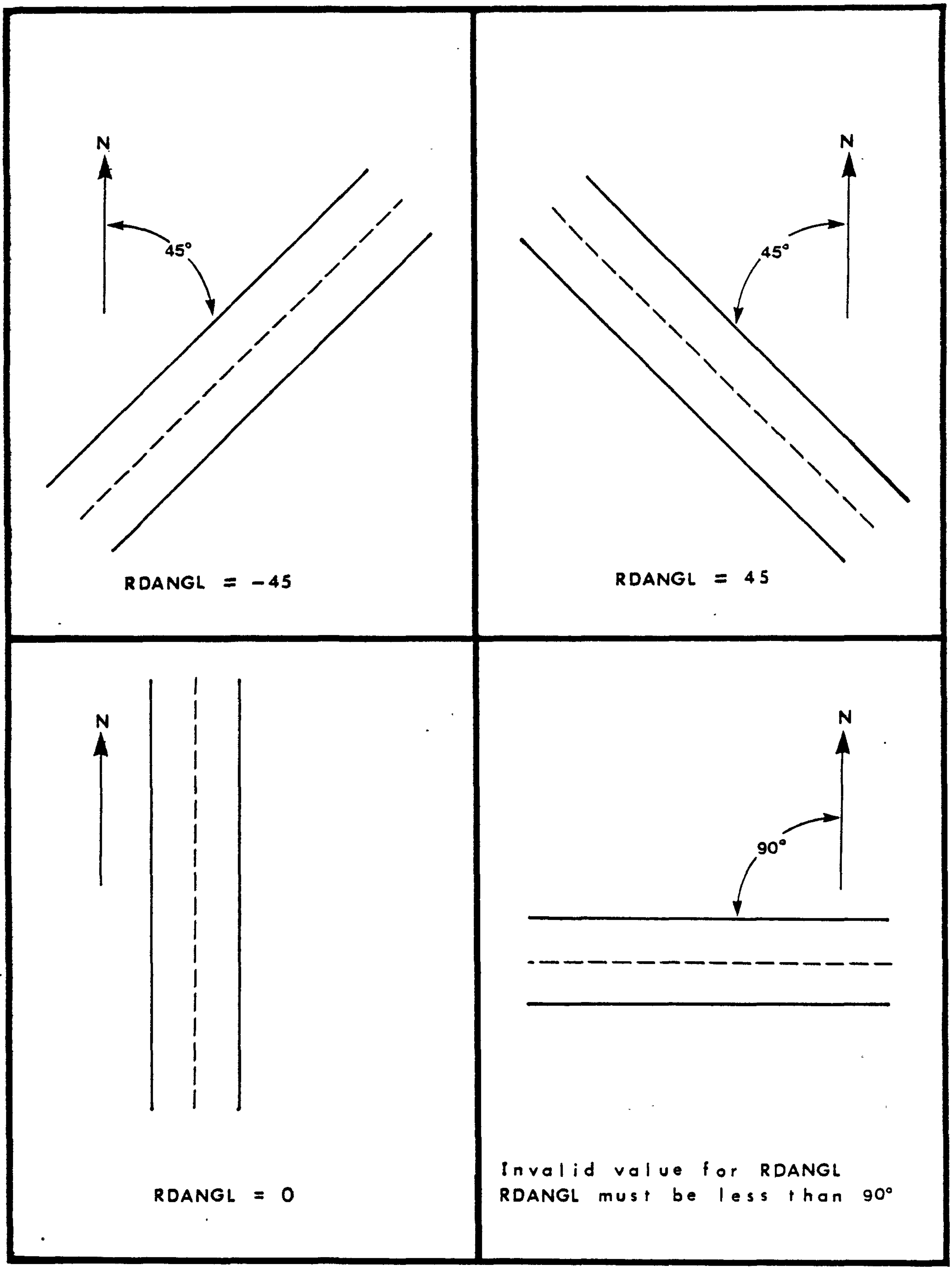


Figure 9. Examples of several highway configurations and their appropriate values of RDANGL.

Record Type 7

MEDN, the width of the traffic median, should be treated as a real number not as an integer; the value provided for the median width should contain a decimal point.

Record Type 8

Northbound refers to lanes with a northerly component to the traffic flow; southbound refers to lanes with a southerly component to the traffic flow. While traffic volume and traffic speed can differ between northbound and southbound lanes, NVEH and VSPD apply to all northbound lanes and NVEH1 and VSPD1 apply to all southbound lanes.

Values of VWID and VHGH for an intermediate size American automobile are 1.8 m and 1.4 m, respectively.

Record Type 9

If the chemistry option is exercised (i.e., ICHEM = 0), then vehicle emission rates for NO, CO, and NO_2 for both north- and southbound lanes must be given by the user. When the chemistry option is not considered (i.e., ICHEM = 1), only the north- and southbound emission rates for the pollutant being simulated are required. Any inert pollutant can be simulated by placing the emission rate in EM.

Record Type 10

The multipliers to convert emision rate in grams per second to parts per million for each pollutant species can be obtained from

$$\text{Conversion factor} = 83144\ T/M \cdot P \qquad (64)$$

where T is the ambient air temperature (K), M is the molecular weight of the pollutant species, and P is the atmospheric pressure (mb). The factor 83144 is the universal gas constant in appropriate units. If the chemistry option is requested (i.e., ICHEM = 0), then the conversion factors for NO, CO, NO_2, and O_3 must be provided on the input stream. At a temperature of 25°C and sea level pressure of 1013.25 mb, these conversion factors are 815.24, 873.45, 531.74, and 509.69 for NO, CO, NO_2, and O_3, respectively. When the chemistry option is not used (i.e., ICHEM = 1), only the conversion factor for the pollutant under consideration is required.

Record Type 11

When the chemistry option is requested (i.e., ICHEM = 0), the chemical reaction rates k_1, k_2 for the chemical mechanism

$$NO + O_3 \xrightarrow{k_1} NO_2 + O_2$$
$$NO_2 + O_2 + h\nu \xrightarrow{k_2} NO + O_3$$

need to be provided. These reactions are assumed to be the only ones of importance near the roadway. Seinfeld (1975) gives the values 22.0/($ppm^{-1}min^{-1}$) and 0.46/min as applicable to k_1 and k_2, respectively.

SECTION 10

EXECUTION AND INTERPRETATION OF THE MODEL

ROADWAY produces an error-free compile on UNIVAC EXEC 8, IBM MVS, and DEC VAX/VMS computers with comparable output results. A sample job stream is shown below.

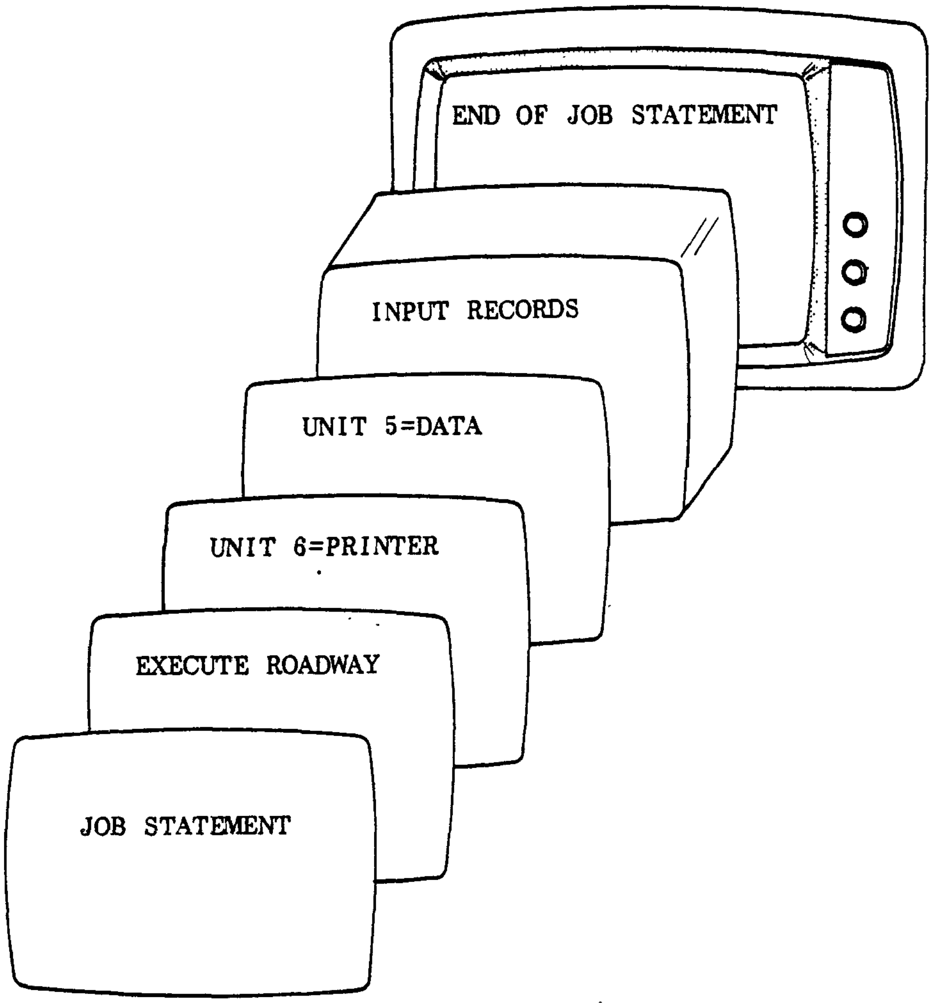


Figure 10. Sample job stream for ROADWAY.

Job control language (JCL) for model execution on a UNIVAC EXEC 8 system would have the following form:

```
@RUN,R/R JOB-ID,ETC
@ASG,A MODELS*LOAD.
@XQT MODELS*LOAD.ROADWAY
(input records shown in Table 6)
@FIN
```

On an IBM system under OS or MVS, the JCL would look as follows,

```
//JOBID      JOB   (PROJ,ACCT,OTHER),CLASS=A,TIME=1
//XTROADWY   EXEC  PGM=ROADWAY,TIME=(,10)
//STEPLIB    DD    DSN=USER.MODELS.LOAD,DISP=SHR
//FT06F001   DD    SYSOUT=A
//FT05F001   DD    *
(control information and model input data)
/*
//
```

ROADWAY VERIFICATION RUN

Sample test data (unit 5) for model verification are given in Table 6; Figure 11 shows the resulting model output for the sample test. Proper execution of the program can be verified by comparing results with those given in the figure. Using identical inputs, any machine should produce output numbers within 3% of those shown here. If this is not the case, either the version of the code is different or the data was not properly entered.

TABLE 6. INPUT DATA FOR THE SAMPLE TEST

Record	Record type
ROADWAY VERIFICATION RUN	1
INERT POLLUTANT SIMULATION	2
INTERMEDIATE PRINT OPTION EXERCISED	3
0.05,1.22,4.24, 1,0,0	4
284.38,284.49,0.94,270.,0.0	5
40.0	6
4,3.4,11.8	7
1366.,1366.,80.0,80.0,1.8,1.4	8
90.0,90.0	9
873.36	10

```
                    * * * ROADWAY (VERSION 86010) * * *

TITLE:  ROADWAY VERIFICATION RUN
        INERT POLLUTANT SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED


O P T I O N S

    CHEMISTRY OPTION (ICHEM) ............................        1
    ANTIDIFFUSION CALCULATION OPTION (IANTI) ............        0
    INTERMEDIATE PRINT OPTION (INTPR) ...................        0

M E T E O R O L O G Y

    SURFACE ROUGHNESS (Z0) ..............................   0.0500 M
    HEIGHT OF TEMPERATURE INSTRUMENTS
       LOWER (Z1) .......................................     1.22 M
       UPPER (Z2) .......................................     4.24 M
    TEMPERATURE AT HEIGHT:
       Z1 (T1) ..........................................   284.38 K
       Z2 (T2) ..........................................   284.49 K
    WIND SPEED (WSPD) ...................................     0.94 M/SEC
    WIND DIRECTION (WDIR) ...............................   270.00 DEG

H I G H W A Y   I N F O R M A T I O N

    NUMBER OF TRAFFIC LANES (NLANE) .....................        4
    WIDTH OF EACH LANE (WIDL) ...........................     3.40 M
    WIDTH OF MEDIAN (MEDN) ..............................    11.80 M
    ANGLE BETWEEN ROAD AND LINE RUNNING N-S (RDANGL) ....     0.00 DEG
    TRAFFIC VOLUME
       SOUTHBOUND LANES (NVEH) ..........................    1366. VEH/HR
       NORTHBOUND LANES (NVEH1) .........................    1366. VEH/HR
    AVERAGE VEHICLE SPEED
       SOUTHBOUND LANES (VSPD) ..........................    80.00 KM/HR
       NORTHBOUND LANES (VSPD1) .........................    80.00 KM/HR
    AVERAGE DIMENSIONS OF VEHICLES
       WIDTH (VWID) .....................................     1.80 M
       HEIGHT (VHGH) ....................................     1.40 M

E M I S S I O N   I N F O R M A T I O N

    BACKGROUND CONCENTRATION (BACKGA) ...................  40.0000 PPM
    EMISSION RATES:
       SOUTHBOUND LANES (EMA) ...........................  90.0000 G/KM/VEH
       NORTHBOUND LANES (EMA1) ..........................  90.0000 G/KM/VEH
    CONVERSION FACTOR FOR G/SEC TO PPM (CNA) ............ 873.3600


                      **************************
                      * Input information and  *
                      * model parameters are   *
                      * listed here            *
                      **************************
```

Figure 11. Printed output for the verification run.

TITLE: ROADWAY VERIFICATION RUN
INERT POLLUTANT SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

GRID POINTS IN X DIRECTION FROM
LEFT TO RIGHT ACROSS ROADWAY
(METERS)

20.0
35.0
45.0
48.4 *
51.8 *
55.2
59.4
63.6
67.0 *
70.4 *
73.8
83.8
98.8
118.8
143.8
173.8

* INDICATES LOCATION OF TRAFFIC LANE CENTER.

THE FOLLOWING GRAPHICAL OUTPUT IS A CROSS SECTION ACROSS THE HIGHWAY IN THE X-Z PLANE. IN EACH FIELD, THE BOTTOM LINE IS AT Z = 1 METER, WITH HEIGHT INCREASING TOWARD THE TOP OF THE PAGE. SUCCEEDING LINES REPRESENT Z = 2, 4.5, 10.5, 20, 50, AND 70 METERS. THE SPACING ACROSS THE ROAD IS DETERMINED BY STARTING AT THE BOTTOM LEFT POINT, WHICH CORRESPONDS TO THE FIRST VALUE OF THE X GRID PRINTED EARLIER, WITH INCREASING VALUES TO THE RIGHT. THE LAST SET OF CONCENTRATION FIELDS REPRESENT THE STEADY-STATE VALUES AND THE AVERAGES FOR THE 30 MINUTE PERIOD. THESE STEADY-STATE FIELDS OCCUR AT 300, 600, OR 900 SECONDS.

Figure 11. (continued)

TITLE: ROADWAY VERIFICATION RUN
INERT POLLUTANT SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

U FIELD (M/SEC)

4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18
2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14
1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.93	0.93	0.93
0.65	0.65	0.65	0.64	0.62	0.62	0.63	0.64	0.63	0.61	0.61	0.63	0.63	0.64	0.64	0.64
0.49	0.49	0.49	0.45	0.42	0.44	0.45	0.46	0.43	0.40	0.42	0.44	0.46	0.47	0.47	0.47
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

V FIELD (M/SEC)

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02
0.00	0.00	0.00	0.00	-0.11	-0.28	-0.27	-0.27	-0.28	-0.17	-0.01	0.01	0.04	0.03	0.02	0.01
0.00	0.00	0.00	-0.52	-1.32	-1.37	-0.99	-0.82	-0.22	0.65	0.75	0.26	0.12	0.07	0.04	0.03
0.00	0.00	0.00	-1.63	-2.98	-2.28	-1.58	-1.25	0.55	2.02	1.42	0.49	0.21	0.11	0.06	0.03
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

W FIELD (M/SEC)

0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.02	0.01	-0.01	-0.01	0.01	0.02	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

The input wind direction and speed and the assumption of non-divergence are used to generate these wind components

Figure 11. (continued)

TITLE: ROADWAY VERIFICATION RUN
INERT POLLUTANT SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

KX FIELD (M**2/SEC)

0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.27	0.28	0.29	0.30	0.32	0.30	0.29	0.28
0.25	0.25	0.25	0.25	0.45	0.63	0.53	0.44	0.40	0.57	0.73	0.49	0.36	0.31	0.29	0.28
0.25	0.25	0.25	0.91	1.49	1.06	0.57	0.44	1.05	1.60	1.14	0.47	0.34	0.29	0.27	0.26
0.25	0.25	0.25	2.24	2.80	0.99	0.49	0.38	2.33	2.87	1.05	0.39	0.30	0.27	0.26	0.26
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

KZ FIELD (M**2/SEC)

0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10
0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.10	0.11	0.11	0.13	0.15	0.13	0.11	0.10
0.05	0.05	0.05	0.05	0.25	0.43	0.34	0.25	0.20	0.37	0.53	0.29	0.17	0.12	0.09	0.08
0.03	0.03	0.03	0.57	1.04	0.69	0.30	0.19	0.69	1.13	0.76	0.21	0.11	0.07	0.05	0.05
0.02	0.02	0.02	0.83	1.06	0.32	0.12	0.07	0.86	1.09	0.34	0.08	0.04	0.03	0.03	0.02
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

Diffusivity fields computed in subroutine SBLAYR are given here

Figure 11. (continued)

TITLE: ROADWAY VERIFICATION RUN
INERT POLLUTANT SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

POLLUTANT CONCENTRATIONS (PPM) AT TIME 150.597061 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.03	40.04	40.04
40.00	40.00	40.00	40.00	40.01	40.06	40.16	40.21	40.33	40.35	40.91	41.05	41.89	42.53	42.57	42.57
40.00	40.00	39.98	40.22	44.04	46.39	47.45	47.42	49.03	54.08	56.44	56.31	56.30	53.95	50.46	50.46
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.67	68.60	65.43	61.08	61.12	55.03	49.61	49.61
40.00	40.00	44.23	59.24	61.97	59.49	57.37	59.53	70.58	71.95	67.89	62.57	62.59	54.89	48.62	48.62
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

POLLUTANT CONCENTRATIONS (PPM) AT TIME 300.751068 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.01	40.03	40.05	40.05
40.00	40.00	40.00	40.00	40.00	40.07	40.15	40.24	40.29	40.44	40.65	41.38	41.67	42.51	42.90	42.90
40.00	40.00	39.98	40.22	44.03	46.39	47.44	47.48	48.90	54.34	56.60	56.44	56.33	54.63	53.70	53.70
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.74	68.82	65.79	61.28	60.01	57.49	56.14	56.14
40.00	40.00	44.23	59.24	61.97	59.49	57.38	59.55	70.68	72.16	68.29	62.74	61.14	58.34	56.81	56.81
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

POLLUTANT CONCENTRATIONS (PPM) AT TIME 450.905060 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.01	40.03	40.05	40.05
40.00	40.00	40.00	40.00	40.00	40.07	40.15	40.24	40.29	40.44	40.65	41.38	41.67	42.51	42.90	42.90
40.00	40.00	39.98	40.22	44.03	46.39	47.44	47.48	48.91	54.33	56.59	56.45	56.33	54.64	53.79	53.79
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.73	68.80	65.77	61.35	59.99	57.49	56.37	56.37
40.00	40.00	44.23	59.24	61.97	59.49	57.38	59.55	70.68	72.15	68.26	62.83	61.10	58.33	57.13	57.13
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

Pollutant concentrations are listed at each of four program steps

Figure 11. (continued)

```
TITLE:   ROADWAY VERIFICATION RUN
         INERT POLLUTANT SIMULATION
         INTERMEDIATE PRINT OPTION EXERCISED

POLLUTANT CONCENTRATIONS (PPM)                                                  AT TIME  600.173218 SEC

 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00

 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.00 40.01 40.01 40.03 40.05 40.05

 40.00 40.00 40.00 40.00 40.00 40.07 40.15 40.24 40.29 40.44 40.65 41.38 41.67 42.51 42.90 42.90

 40.00 40.00 39.98 40.22 44.03 46.39 47.44 47.48 48.91 54.33 56.59 56.45 56.33 54.64 53.79 53.79

 40.00 40.00 40.16 54.25 58.56 56.53 54.99 55.27 65.73 68.80 65.77 61.35 59.99 57.49 56.38 56.38

 40.00 40.00 44.23 59.24 61.97 59.49 57.38 59.55 70.68 72.15 68.26 62.83 61.10 58.33 57.13 57.13
-----------------------------------------------------------------------------------------------------
  20.0  35.0  45.0  48.4  51.8  55.2  59.4  63.6  67.0  70.4  73.8  83.8  98.8 118.8 143.8 173.8
                    ----  ----                    ----  ----

*** NORMAL TERMINATION.
```

This message is printed at the end to inform the user that no anomalies occurred during program execution

Figure 11. (continued)

EXAMPLE PROBLEM

In Section 6, a problem was discussed to illustrate model application to a four-lane highway; the chemistry option was used and most other options were exercised. Using model output, scalar fields of wind, diffusivity, and concentration were displayed. In this section, the same problem is considered but in more detail; intricacies of the input data are discussed and the output listing is displayed with annotations for ease of interpretation.

The unit 5 input stream is tabulated below. Unlike input for other models, no records are repeated (excepting title); record types 4 through 11 are unique and must be ordered as given.

TABLE 7. INPUT DATA FOR THE EXAMPLE PROBLEM

Record	Record type
EXAMPLE PROBLEM	1
NOX - O3 SIMULATION	2
INTERMEDIATE PRINT OPTION IMPLEMENTED	3
0.05,1.22,4.24,0,0,0	4
284.38,284.49,0.94,270.0,0.0	5
0.052,40.0,0.25,0.1	6
4,3.4,11.8	7
1366.,1366.,80.0,80.0,1.8,1.4	8
2.7,90.0,0.3,2.7,90.0,0.3	9
813.01,873.36,531.91,509.68	10
22.0,0.46	11

As noted in record 4, both the chemistry and intermediate print options are exercised: ICHEM and INTPR are set to zero. By using the chemistry option, the following applies:

- Background concentrations of NO, CO, NO_2, and O_3 are needed and should be provided in record type 6;

- NO, CO, and NO_2 emission rates for northbound and southbound vehicles are needed as in record type 9;
- Conversion factors (g/sec to ppm) for NO, CO, NO_2, and O_3 have to be supplied as in record type 10; and
- Optional record type 11 should be present and contain appropriate chemical reaction rates.

Output for the problem is given in Figure 12. The printed output consists of five parts: input data, grid information, wind velocity fields, diffusivity fields, and concentration fields. The velocity and diffusivity fields are printed optionally, depending on the value of INTPR as noted in Table 4. If the intermediate print option is not exercised (i.e., INTPR = 1), then only the steady-state concentration fields are printed. Because the intermediate print option was used, all the available output is printed.

```
                    * * * ROADWAY (VERSION 86010) * * *

TITLE:  EXAMPLE PROBLEM
        NOX-O3 SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED

 O P T I O N S

    CHEMISTRY OPTION (ICHEM) ..............................         0
    ANTIDIFFUSION CALCULATION OPTION (IANTI) ..............         0
    INTERMEDIATE PRINT OPTION (INTPR) .....................         0

 M E T E O R O L O G Y

    SURFACE ROUGHNESS (Z0) ................................    0.0500 M
    HEIGHT OF TEMPERATURE INSTRUMENTS
       LOWER (Z1) .........................................      1.22 M
       UPPER (Z2) .........................................      4.24 M
    TEMPERATURE AT HEIGHT:
       Z1 (T1) ............................................    284.38 K
       Z2 (T2) ............................................    284.49 K
    WIND SPEED (WSPD) .....................................      0.94 M/SEC
    WIND DIRECTION (WDIR) .................................    270.00 DEG

 H I G H W A Y   I N F O R M A T I O N

    NUMBER OF TRAFFIC LANES (NLANE) .......................         4
    WIDTH OF EACH LANE (WIDL) .............................      3.40 M
    WIDTH OF MEDIAN (MEDN) ................................     11.80 M
    ANGLE BETWEEN ROAD AND LINE RUNNING N-S (RDANGL) ......      0.00 DEG
    TRAFFIC VOLUME
       SOUTHBOUND LANES (NVEH) ............................     1366.  VEH/HR
       NORTHBOUND LANES (NVEH1) ...........................     1366.  VEH/HR
    AVERAGE VEHICLE SPEED
       SOUTHBOUND LANES (VSPD) ............................     80.00 KM/HR
       NORTHBOUND LANES (VSPD1) ...........................     80.00 KM/HR
    AVERAGE DIMENSIONS OF VEHICLES
       WIDTH (VWID) .......................................      1.80 M
       HEIGHT (VHGH) ......................................      1.40 M

TITLE:  EXAMPLE PROBLEM
        NOX-O3 SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED

E M I S S I O N   I N F O R M A T I O N

   BACKGROUND CONCENTRATIONS:
      NO  (BACKGA) .....................................     0.0520 PPM
      CO  (BACKGB) .....................................    40.0000 PPM
      NO2 (BACKGC) .....................................     0.2500 PPM
      O3  (BACKGD) .....................................     0.1000 PPM
   EMISSION RATES FOR THE SOUTHBOUND LANES:
      NO  (EMA) ........................................     2.7000 G/KM/VEH
      CO  (EMB) ........................................    90.0000 G/KM/VEH
      NO2 (EMC) ........................................     0.3000 G/KM/VEH
   EMISSION RATES FOR THE NORTHBOUND LANES:
      NO  (EMA1) .......................................     2.7000 G/KM/VEH
      CO  (EMB1) .......................................    90.0000 G/KM/VEH
      NO2 (EMC1) .......................................     0.3000 G/KM/VEH
   CONVERSION FACTORS (G/SEC TO PPM) FOR:
      NO  (CNA) ........................................   813.0100
      CO  (CNB) ........................................   873.3600
      NO2 (CNC) ........................................   531.9100
      O3  (CND) ........................................   509.6800
   CHEMICAL REACTION RATES FOR THE FOLLOWING:
      NO  + O3 ---> NO2 + O2 ...........................    22.0000 1/(PPM MIN)
      NO2 + O2 ---> NO  + O3 ...........................     0.4600 1/MIN
```

Figure 12. Printed output for the example problem.

```
TITLE:  EXAMPLE PROBLEM
        NOX-O3 SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED
```

```
GRID POINTS IN X DIRECTION FROM
 LEFT TO RIGHT ACROSS ROADWAY
          (METERS)

            20.0
            35.0
            45.0
            48.4 *
            51.8 *
            55.2
            59.4
            63.6
            67.0 *
            70.4 *
            73.8
            83.8
            98.8
           118.8
           143.8
           173.8

*  INDICATES LOCATION OF TRAFFIC LANE CENTER.
```

```
******************************************************************************
*                                                                            *
*  THE FOLLOWING GRAPHICAL OUTPUT IS A CROSS SECTION ACROSS THE HIGHWAY IN THE *
*  X-Z PLANE.  IN EACH FIELD, THE BOTTOM LINE IS AT Z = 1 METER, WITH HEIGHT  *
*  INCREASING TOWARD THE TOP OF THE PAGE.  SUCCEEDING LINES REPRESENT Z = 2,  *
*  4.5, 10.5, 20, 50, AND 70 METERS.  THE SPACING ACROSS THE ROAD IS DETERMINED *
*  BY STARTING AT THE BOTTOM LEFT POINT, WHICH CORRESPONDS TO THE FIRST VALUE  *
*  OF THE X GRID PRINTED EARLIER, WITH INCREASING VALUES TO THE RIGHT.  THE    *
*  LAST SET OF CONCENTRATION FIELDS REPRESENT THE STEADY-STATE VALUES AND THE  *
*  AVERAGES FOR THE 30 MINUTE PERIOD.  THESE STEADY-STATE FIELDS OCCUR AT 300, *
*  600, OR 900 SECONDS.                                                        *
*                                                                            *
******************************************************************************
```

Figure 12. (continued)

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

U FIELD (M/SEC)

4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18
2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14
1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.93	0.93	0.93
0.65	0.65	0.65	0.64	0.62	0.62	0.63	0.64	0.63	0.61	0.61	0.63	0.63	0.64	0.64	0.64
0.49	0.49	0.49	0.45	0.42	0.44	0.45	0.46	0.43	0.40	0.42	0.44	0.46	0.47	0.47	0.47
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

V FIELD (M/SEC)

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02
0.00	0.00	0.00	0.00	-0.11	-0.28	-0.27	-0.27	-0.28	-0.17	-0.01	0.01	0.04	0.03	0.02	0.01
0.00	0.00	0.00	-0.52	-1.32	-1.37	-0.99	-0.82	-0.22	0.65	0.75	0.26	0.12	0.07	0.04	0.03
0.00	0.00	0.00	-1.63	-2.98	-2.28	-1.58	-1.25	0.55	2.02	1.42	0.49	0.21	0.11	0.06	0.03
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

W FIELD (M/SEC)

0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.02	0.01	-0.01	-0.01	0.01	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.02	0.01	-0.01	-0.01	0.01	0.02	0.00	-0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

Figure 12. (continued)

```
TITLE:  EXAMPLE PROBLEM
        NOX-O3 SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED
```

KX FIELD (M**2/SEC)

0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.27	0.28	0.29	0.30	0.32	0.30	0.29	0.28
0.25	0.25	0.25	0.25	0.45	0.63	0.53	0.44	0.40	0.57	0.73	0.49	0.36	0.31	0.29	0.28
0.25	0.25	0.25	0.91	1.49	1.06	0.57	0.44	1.05	1.60	1.14	0.47	0.34	0.29	0.27	0.26
0.25	0.25	0.25	2.24	2.80	0.99	0.49	0.38	2.33	2.87	1.05	0.39	0.30	0.27	0.26	0.26
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

KZ FIELD (M**2/SEC)

0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10
0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.10	0.11	0.11	0.13	0.15	0.13	0.11	0.10
0.05	0.05	0.05	0.05	0.25	0.43	0.34	0.25	0.20	0.37	0.53	0.29	0.17	0.12	0.09	0.08
0.03	0.03	0.03	0.57	1.04	0.69	0.30	0.19	0.69	1.13	0.76	0.21	0.11	0.07	0.05	0.05
0.02	0.02	0.02	0.83	1.06	0.32	0.12	0.07	0.86	1.09	0.34	0.08	0.04	0.03	0.03	0.02
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

Figure 12. (continued)

```
TITLE:  EXAMPLE PROBLEM
        NOX-O3 SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED
```

NITROGEN OXIDE, NO (PPM) AT TIME 150.597061 SEC

0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.08	0.09	0.09	0.09
0.05	0.05	0.05	0.06	0.12	0.17	0.19	0.19	0.24	0.36	0.43	0.42	0.42	0.36	0.27	0.27
0.05	0.05	0.06	0.37	0.48	0.43	0.39	0.40	0.68	0.76	0.67	0.55	0.56	0.39	0.25	0.25
0.05	0.05	0.12	0.50	0.58	0.51	0.46	0.51	0.81	0.85	0.74	0.60	0.60	0.39	0.22	0.22
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

CARBON MONOXIDE, CO (PPM) AT TIME 150.597061 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.03	40.04	40.04
40.00	40.00	40.00	40.00	40.01	40.06	40.16	40.21	40.33	40.35	40.91	41.05	41.89	42.53	42.57	42.57
40.00	40.00	39.98	40.22	44.04	46.39	47.45	47.42	49.03	54.08	56.44	56.31	56.30	53.95	50.46	50.46
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.67	68.60	65.43	61.08	61.12	55.03	49.61	49.61
40.00	40.00	44.23	59.24	61.97	59.49	57.37	59.53	70.58	71.95	67.89	62.57	62.59	54.89	48.62	48.62
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

NITROGEN DIXOIDE, NO2 (PPM) AT TIME 150.597061 SEC

0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26	0.26	0.27	0.27	0.28	0.29	0.29	0.29
0.25	0.25	0.25	0.25	0.30	0.32	0.33	0.33	0.34	0.36	0.37	0.37	0.37	0.36	0.34	0.34
0.25	0.25	0.25	0.36	0.37	0.37	0.36	0.36	0.39	0.40	0.39	0.38	0.38	0.36	0.34	0.34
0.25	0.25	0.31	0.37	0.38	0.37	0.37	0.37	0.40	0.41	0.40	0.38	0.38	0.36	0.34	0.34
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

```
TITLE:  EXAMPLE PROBLEM
        NOX-O3 SIMULATION
        INTERMEDIATE PRINT OPTION EXERCISED
```

OZONE, O3 (PPM) AT TIME 150.597061 SEC

0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.08	0.07	0.07	0.07	0.07
0.10	0.10	0.10	0.10	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03
0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.03
0.10	0.10	0.05	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.03
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

Figure 12. (continued)

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

NITROGEN OXIDE, NO (PPM) AT TIME 300.751068 SEC

0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.08	0.09	0.10	0.10
0.05	0.05	0.05	0.06	0.12	0.17	0.19	0.19	0.23	0.37	0.43	0.43	0.42	0.38	0.36	0.36
0.05	0.05	0.06	0.37	0.48	0.43	0.39	0.40	0.68	0.77	0.68	0.56	0.53	0.46	0.42	0.42
0.05	0.05	0.12	0.50	0.58	0.51	0.46	0.51	0.82	0.86	0.75	0.60	0.56	0.48	0.44	0.44
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

CARBON MONOXIDE, CO (PPM) AT TIME 300.751068 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.01	40.03	40.05	40.05
40.00	40.00	40.00	40.00	40.00	40.07	40.15	40.24	40.29	40.44	40.85	41.38	41.67	42.51	42.90	42.90
40.00	40.00	39.98	40.22	44.03	46.39	47.44	47.48	48.90	54.34	56.60	56.44	56.33	54.63	53.70	53.70
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.74	68.82	65.79	61.28	60.01	57.49	56.14	56.14
40.00	40.00	44.23	59.24	61.97	59.49	57.38	59.55	70.68	72.16	68.29	62.74	61.14	58.34	56.81	56.81
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

NITROGEN DIXOIDE, NO2 (PPM) AT TIME 300.751068 SEC

0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.27	0.28	0.29	0.29	0.29
0.25	0.25	0.25	0.25	0.30	0.32	0.33	0.33	0.34	0.36	0.37	0.37	0.37	0.36	0.36	0.36
0.25	0.25	0.25	0.36	0.37	0.37	0.36	0.36	0.39	0.40	0.39	0.38	0.38	0.37	0.36	0.36
0.25	0.25	0.31	0.37	0.38	0.37	0.37	0.37	0.40	0.41	0.40	0.38	0.38	0.37	0.37	0.37
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

OZONE, O3 (PPM) AT TIME 300.751068 SEC

0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.06	0.06
0.10	0.10	0.10	0.10	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
0.10	0.10	0.05	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

Figure 12. (continued)

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

NITROGEN OXIDE, NO (PPM) AT TIME 450.905060 SEC

0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.08	0.09	0.10	0.10
0.05	0.05	0.05	0.06	0.12	0.17	0.19	0.19	0.23	0.37	0.43	0.43	0.42	0.38	0.36	0.36
0.05	0.05	0.06	0.37	0.48	0.43	0.39	0.40	0.68	0.78	0.68	0.56	0.52	0.46	0.43	0.43
0.05	0.05	0.12	0.50	0.58	0.51	0.46	0.51	0.82	0.86	0.75	0.60	0.56	0.48	0.45	0.45
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

CARBON MONOXIDE, CO (PPM) AT TIME 450.905060 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.01	40.03	40.05	40.05
40.00	40.00	40.00	40.00	40.00	40.07	40.15	40.24	40.29	40.44	40.65	41.38	41.67	42.51	42.90	42.90
40.00	40.00	39.98	40.22	44.03	46.39	47.44	47.48	48.91	54.33	56.59	56.45	56.33	54.64	53.79	53.79
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.73	68.80	65.77	61.35	59.99	57.49	56.37	56.37
40.00	40.00	44.23	59.24	61.97	59.49	57.38	59.55	70.68	72.15	68.26	62.83	61.10	58.33	57.13	57.13
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

NITROGEN DIXOIDE, NO2 (PPM) AT TIME 450.905060 SEC

0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.27	0.28	0.29	0.29	0.29
0.25	0.25	0.25	0.25	0.30	0.32	0.33	0.33	0.34	0.36	0.37	0.37	0.37	0.36	0.36	0.36
0.25	0.25	0.25	0.36	0.37	0.37	0.36	0.36	0.39	0.40	0.39	0.38	0.38	0.37	0.37	0.37
0.25	0.25	0.31	0.37	0.38	0.37	0.37	0.37	0.40	0.41	0.40	0.38	0.38	0.37	0.37	0.37
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

OZONE, O3 (PPM) AT TIME 450.905060 SEC

0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.06	0.06
0.10	0.10	0.10	0.10	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
0.10	0.10	0.05	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8

Figure 12. (continued)

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

NITROGEN OXIDE, NO (PPM) AT TIME 600.173218 SEC

0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.08	0.09	0.10	0.10
0.05	0.05	0.05	0.06	0.12	0.17	0.19	0.19	0.23	0.37	0.43	0.43	0.42	0.38	0.36	0.36
0.05	0.05	0.06	0.37	0.48	0.43	0.39	0.40	0.68	0.76	0.68	0.56	0.52	0.46	0.43	0.43
0.05	0.05	0.12	0.50	0.58	0.51	0.46	0.51	0.82	0.86	0.75	0.60	0.56	0.48	0.45	0.45
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

CARBON MONOXIDE, CO (PPM) AT TIME 600.173218 SEC

40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.01	40.01	40.03	40.05	40.05
40.00	40.00	40.00	40.00	40.00	40.07	40.15	40.24	40.29	40.44	40.65	41.38	41.67	42.51	42.90	42.90
40.00	40.00	39.98	40.22	44.03	46.39	47.44	47.48	48.91	54.33	56.59	56.45	56.33	54.64	53.79	53.79
40.00	40.00	40.16	54.25	58.56	56.53	54.99	55.27	65.73	68.80	65.77	61.35	59.99	57.49	56.38	56.38
40.00	40.00	44.23	59.24	61.97	59.49	57.38	59.55	70.68	72.15	68.26	62.83	61.10	58.33	57.13	57.13
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

NITROGEN DIXOIDE, NO2 (PPM) AT TIME 600.173218 SEC

0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.27	0.28	0.29	0.29	0.29
0.25	0.25	0.25	0.25	0.30	0.32	0.33	0.33	0.34	0.36	0.37	0.37	0.37	0.36	0.36	0.36
0.25	0.25	0.25	0.36	0.37	0.37	0.36	0.36	0.39	0.40	0.39	0.38	0.38	0.37	0.37	0.37
0.25	0.25	0.31	0.37	0.38	0.37	0.37	0.37	0.40	0.41	0.40	0.38	0.38	0.37	0.37	0.37
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
			----	----				----	----						

TITLE: EXAMPLE PROBLEM
NOX-O3 SIMULATION
INTERMEDIATE PRINT OPTION EXERCISED

OZONE, O3 (PPM) AT TIME 600.173218 SEC

0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.06	0.06
0.10	0.10	0.10	0.10	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
0.10	0.10	0.10	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
0.10	0.10	0.05	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
20.0	35.0	45.0	48.4	51.8	55.2	59.4	63.6	67.0	70.4	73.8	83.8	98.8	118.8	143.8	173.8
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*** NORMAL TERMINATION.

Figure 12. (continued)

SECTION 11

ERROR MESSAGES AND REMEDIAL ACTION

ROADWAY can generate up to 20 error messages, each of which causes program termination. Table 7 lists each message, along with error description and suggested corrective action. The table is ordered by error number.

TABLE 8. ERROR MESSAGES AND REMEDIAL ACTION

MESSAGE:	*** ERROR 1: SURFACE ROUGHNESS, Z0, IS LESS THAN ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	Surface roughness must be greater than zero.
ACTION:	Modify variable Z0 in record type 4.
MESSAGE:	*** ERROR 2: HEIGHT OF LOWER TEMPERATURE, Z1, IS LESS THAN ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	The instrument must be located above ground level.
ACTION:	Modify record type 4 so that Z1 is positive.
MESSAGE:	*** ERROR 3: HEIGHT OF UPPER TEMPERATURE INSTRUMENT, Z2, IS BELOW OR EQUAL TO THAT OF THE LOWER INSTRUMENT. *** EXECUTION TERMINATED
DESCRIPTION:	The height of the upper instrument must be greater than that of the lower instrument.
ACTION:	Modify record type 4 so that Z2 is greater than Z1.

TABLE 8. (continued)

MESSAGE:	*** ERROR 4: INPUT OPTIONS MUST EQUAL ZERO OR ONE. *** EXECUTION TERMINATED.
DESCRIPTION:	Branches in the source code assume that the input options are either equal to zero or one.
ACTION:	Modify record type 4. Make sure variables ICHEM, IANTI, and INTPR are initialized to either zero or one.
MESSAGE:	*** ERROR 5: TEMPERATURE AT HEIGHT Z1 IS NOT IN DEGREES KELVIN. *** EXECUTION TERMINATED.
DESCRIPTION:	The temperature at height Z1 given by the user is not in Kelvin units.
ACTION:	Make sure temperatures given in record type 5 are in Kelvin degrees.
MESSAGE:	*** ERROR 6: TEMPERATURE AT HEIGHT Z2 IS NOT IN DEGREES KELVIN. *** EXECUTION TERMINATED.
DESCRIPTION:	The temperature at height Z2 given by the user is not in Kelvin units.
ACTION:	Make sure temperatures given in record type 5 are in Kelvin degrees.
MESSAGE:	*** ERROR 7: INPUT WIND SPEED IS IN ERROR. *** EXECUTION TERMINATED.
DESCRIPTION:	The wind speed provided is either negative or too large.
ACTION:	Modify variable WSPD in record type 5.

TABLE 8. (continued)

MESSAGE:	*** ERROR 8: INPUT WIND DIRECTION IS IN ERROR. *** EXECUTION TERMINATED.
DESCRIPTION:	The input wind direction must be between 0° and 360°.
ACTION:	Modify variable WDIR on record type 5.
MESSAGE:	*** ERROR 9: HIGHWAY ORIENTATION IS INCORRECTLY SPECIFIED. *** EXECUTION TERMINATED.
DESCRIPTION:	The absolute value of RDANGL must be between 0° and 90°.
ACTION:	Modify variable RDANGL on record type 5.
MESSAGE:	*** ERROR 10: BACKGROUND POLLUTANT CONCENTRATIONS CANNOT BE LESS THAN ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	Background pollutant concentrations must be greater than or equal to zero.
ACTION:	Modify record type 6 so that all background concentrations are greater than or equal to zero.
MESSAGE:	*** ERROR 11: NUMBER OF TRAFFIC LANES IS INCORRECTLY SPECIFIED. *** EXECUTION TERMINATED.
DESCRIPTION:	The number of traffic lanes must be between 4 and 10 (inclusive) and must be evenly divisible by 2.
ACTION:	Modify variable NLANE on record type 7.
MESSAGE:	*** ERROR 12: WIDTH OF A TRAFFIC LANE CANNOT BE LESS THAN OR EQUAL TO ZERO. *** EXECUTION TERMINATED.

TABLE 8. (continued)

DESCRIPTION:	The width of a traffic lane must have a positive value.
ACTION:	Modify WIDL on record type 7.
MESSAGE:	*** ERROR 13: THE TRAFFIC MEDIAN CANNOT BE LESS THAN ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	The variable MEDN cannot be less than zero.
ACTION:	Modify MEDN on record type 7.
MESSAGE:	*** ERROR 14: TRAFFIC VOLUME CANNOT BE LESS THAN OR EQUAL TO ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	Variables NVEH and NVEH1 must be greater than zero.
ACTION:	Modify traffic volume input on record type 8.
MESSAGE:	*** ERROR 15: AVERAGE VEHICLE SPEED IS INCORRECTLY SPECIFIED. *** EXECUTION TERMINATED.
DESCRIPTION:	The average vehicle speed must be a positive number less than 200 km/hr.
ACTION:	Make sure variables VSPD and VSPD1 on record type 8 meet this criteria.
MESSAGE:	*** ERROR 16: AVERAGE VEHICLE DIMENSIONS ARE INCORRECTLY SPECIFIED. *** EXECUTION TERMINATED.
DESCRIPTION:	The user specified the vehicle dimensions to be either too large (i.e., greater than WIDL) or negative.

TABLE 8. (continued)

ACTION:	Modify variable VWID and VHGH on record type 8. Also make sure variable WIDL on record type 7 is properly initialized.
MESSAGE:	*** ERROR 17: VEHICLE EMISSION RATES MUST BE GREATER THAN ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	The vehicle emission rates must be greater than zero.
ACTION:	Make sure all the vehicle emission rates on record type 9 meet this criteria.
MESSAGE:	*** ERROR 18: CONVERSION FACTOR FOR G/SEC TO PPM IS INCORRECTLY SPECIFIED. *** EXECUTION TERMINATED.
DESCRIPTION:	The conversion factors supplied by the user are negative.
ACTION:	Make sure all conversion factors on record type 10 are positive.
MESSAGE:	*** ERROR 19: CHEMICAL REACTION RATES CANNOT BE LESS THAN ZERO. *** EXECUTION TERMINATED.
DESCRIPTION:	The chemical reaction rates (rate constants) supplied by the user are unrealistic.
ACTION:	Check variables K1 and K2 on record type 11 in units of ppm^{-1} min^{-1} and min^{-1}.
MESSAGE:	*** ERROR 20: N - M + 1 IS NOT ODD. *** EXECUTION TERMINATED.
DESCRIPTION:	Values of the indices passed in subroutine SIMPSN were incorrectly specified.
ACTION:	Check SIMPSN calls in subroutine WAKE.

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APPENDIX A

LISTING OF FORTRAN SOURCE CODE FOR ROADWAY

A listing of the FORTRAN source statements for ROADWAY is given here. The model consists of a main module, 19 subroutines, and 8 functions. Error-free compilations have been obtained using ANSI FORTRAN compilers running under Univac EXEC 8 and DEC VAX/VMS.

```
C * * *  PROGRAM ABSTRACT -- ROADWAY (VERSION 86010)
C
C           ROADWAY IS A FINITE DIFFERENCE MODEL WHICH PREDICTS
C        POLLUTANT CONCENTRATIONS NEAR A ROADWAY.  THIS PROGRAM SHOULD
C        BE USED AS AN ADJUNCT TO THE STANDARD GAUSSIAN HIGHWAY MODELS
C        SINCE IT IS MORE EXPENSIVE TO RUN.
C
C           THIS PROGRAM USES SURFACE LAYER SIMILARITY THEORY TO
C        PRODUCE VERTICAL WIND AND TURBULENCE PROFILES.  TEMPERATURES
C        AT TWO HEIGHTS AND WIND VELOCITY ARE REQUIRED.  THESE VALUES
C        ARE USUALLY OBTAINED FROM INSTRUMENTS LOCATED ON A TOWER
C        UPWIND OF THE ROADWAY.
C
C           ROADWAY IS UNIQUE IN THAT IT USES THE VEHICLE WAKE THEORY
C        DEVELOPED BY ESKRIDGE AND HUNT (1979) AND AS MODIFIED AND
C        VERIFIED BY ESKRIDGE AND THOMPSON (1982) USING WIND TUNNEL
C        EXPERIMENTS.  THIS THEORY PREDICTS THE VELOCITY AND TURBULENCE
C        ALONG A HIGHWAY.
C
C
C * * *  REFERENCES
C
C        ESKRIDGE, R. E. AND J. C. R. HUNT.  1979.  HIGHWAY MODELING.
C           PART I:  PREDICTION OF VELOCITY AND TURBULENCE FIELDS IN THE
C           WAKES OF VEHICLES.  J. APPL. METEOR. 18:  387.
C
C        ESKRIDGE, R. E., F. S. BINKOWSKI, J. C. R. HUNT, T. L. CLARK,
C           AND K. L. DEMERJIAN.  1979. HIGHWAY MODELING.  PART II:
C           ADVECTION AND DIFFUSION OF SF6 TRACER GAS.
C           J. APPL. METEOR. 18: 401-412.
C
C        ESKRIDGE, R. E. AND R. S. THOMPSON.  1982.  EXPERIMENTAL AND
C           THEORETICAL STUDY OF THE WAKE OF A BLOCK-SHAPED VEHICLE IN
C           A SHEAR-FREE BOUNDARY FLOW.  ATMOS. ENVIRON. 16:  2821.
C
C        ESKRIDGE, R. E. AND S. T. RAO.  1983.  MEASUREMENT AND PREDIC-
C           TION OF TRAFFIC-INDUCED TURBULENCE FIELDS NEAR ROADWAYS.
C           J. APPL. METEOR. 22:  1431-1443.
C
C
C * * *  PROGRAM WRITTEN AND SUPPORTED BY
C
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C        DIVISION OF METEOROLOGY (MD-80)
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C
C
C * * *  STRUCTURE AND MODULE SUMMARY
C
C MAIN - ROADWAY
C        READER -- READ INPUT DATA
C        ECHO   -- ECHO INPUT DATA
C        ZERO   -- INITIALIZE ARRAYS
C        SBLAYR -- SURFACE LAYER MODEL DRIVER
C                * RIBST  -- INITIALIZE SURFACE LAYER MODEL
C                * RIBTOZ -- ESTIMATE ZETA
C                * GETSFC -- CALCULATE U*, T*, AND T0
C                * PROFIL -- DETERMINE PROFILES OF WIND SPEED AND
C                            TEMPERATURE
C                * TURBC  -- CALCULATE TURBULENT MOMENTS
C        UVCMP  -- CONVERT WIND TO U AND V COMPONENTS
C        MOVE   -- INITIALIZE GRID IN X DIRECTION
C        WHEREX -- DETERMINE GRID SPACING IN X DIRECTION.  FILL IN
C                  EMISSION GRID.
C                  FILLIT -- FILL GRID POINT ARRAY
C        CENTER -- DETERMINE CENTER OF TRAFFIC LANES
C        WAKE   -- ADD VEHICLE WAKE EFFECTS TO WIND TURBULENCE FIELDS
C                # FC     -- 2-DIMENSIONAL FIT (X-Z PLANE) OF TURBULENT
C                            KINETIC ENERGY TERMS TO WIND TUNNEL DATA
C                # POLY   -- CURVE FIT OF VELOCITY DEFICIT BEHIND
C                            VEHICLES TO WIND TUNNEL DATA
C                  SIMPSN -- NUMERICAL INTEGRATION USING SIMPSON'S
C                             METHOD
```

```
C         NONDIV -- REMOVE DIVERGENCE FROM THE WIND FIELD
C         GRAPH  -- PRINT 2-DIMENSIONAL FIELD
C         ADVCHM -- ADVECT AND DIFFUSE POLLUTANTS.  CHEMISTRY PERFORMED
C                   HERE, IF SPECIFIED.
C                   TIMINC -- DETERMINE THE ADVECTION/DIFFUSION AND
C                             CHEMICAL REACTION TIME STEPS
C                   BNDRYC -- ESTABLISH BOUNDARY CONDITIONS FOR THE
C                             POLLUTANT DURING THE MARCHING PROCESS
C                 # ADU    -- CALCULATE TRANSPORT IN X DIRECTION
C                   BMOVE  --
C                 # ANTU   -- PERFORM ANTIDIFFUSION CALCULATION
C                 # ADW    -- CALCULATE TRANSPORT IN Z DIRECTION
C                 # ANTW   -- PERFORM ANTIDIFFUSION CALCULATION
C                 # DIFFX  -- DIFFUSION IN X DIRECTION
C                 # DIFFZ  -- DIFFUSION IN Z DIRECTION
C                   GRAPH  -- PRINT 2-DIMENSIONAL FIELD
C
C
C         *  ENTRY POINT IN SUBROUTINE RIBULK
C         #  FUNCTION
C
C
C * * *  INPUT/OUTPUT INFORMATION
C
C         FORTRAN       DATA SET            I/O UNIT
C          UNIT
C            5          CONTROL INPUT       READER OR DISK
C            6          OUTPUT              PRINTER OR DISK
C
C
      REAL K1,K2,NVEH,NVEH1,MEDN,KX,KXP,KZ,KZP
      REAL KXPAS,KYPAS,KYP
      DIMENSION XV(10),X(24),Z(8),DU(24,8),C1(24,8),C2(24,8),C3(24,8)
      DIMENSION UPRO(8),VPRO(8),DV(24,8),KX(8),KZ(8)
      DIMENSION SA(24),SB(24),SC(24),KXP(24,8),KZP(24,8)
      DIMENSION A(24,8,2),B(24,8,2),C(24,8,2),D(24,8,2)
      DIMENSION WDPRO(8),XD1(8),XD2(8),XD3(8),XD(8)
      DIMENSION KXPAS(24,8),KYPAS(24,8),KYP(24,8)
      DIMENSION HEAD1(20),HEAD2(20),HEAD3(20)
      DIMENSION HWAYL(24)
      COMMON /CALCOM/C1,C3,KMAX,KX,KZ,X,Z,TMSTOP,NX,KXP,KZP
      COMMON /INCOM/ BACKGA,BACKGB,BACKGC,BACKGD,CNA,CNB,CNC,CND,EMA,
     1               EMA1,EMB,EMB1,EMC,EMC1,K1,K2,MEDN,NVEH,NVEH1,
     2               RDANGL,T1,T2,VHGH,VWID,VSPD,VSPD1,WDIR,WIDL,WSPD,
     3               Z0,Z1,Z2,HEAD1,HEAD2,HEAD3,IANTI,ICHEM,INTPR,NLANE
      DATA XD1/30.,25.,20.,15.,10.,10.,15.,20./
      DATA XD2/25.,20.,15.,10.,10.,15.,20.,25./
      DATA XD3/20.,15.,10.,10.,15.,20.,25.,30./
      DATA Z/-1.,1.,2.,4.5,10.5,20.,50.,70./
      DATA IN/5/, IO/6/
C
C***      READ INPUT DATA.
C
   10 CALL READER(IERR,IEOF)
      IF (IERR .EQ. 0) GO TO 20
         WRITE(IO,1000)
         GO TO 999
   20 CONTINUE
      IF (IEOF .EQ. 0) GO TO 30
         WRITE(IO,1010)
         GO TO 999
   30 CONTINUE
C
C***      ECHO INPUT DATA.
C***      CALCULATE MEDIAN HALF WIDTH FOR SUBSEQUENT COMPUTATIONS.
C
      CALL ECHO
      MEDN = MEDN/2.
C
C***      INITIALIZE ARRAYS FOR THIS HOUR.
C
      CALL ZERO(ICHEM,SA,SB,SC,A,B,C,D)
C
C***      THE COORDINATE SYSTEM USED IN THIS PROGRAM ORIENTATES THE
C***      Y AXIS PARELLEL TO THE ROAD AND THE X AXIS NORMAL TO THE
```

```
C***      ROAD.  THE ROAD IS TREATED AS IF IT IS ORIENTATED IN A NORTH-
C***      SOUTH DIRECTION.
C
      WDIR = WDIR + RDANGL
C
C***      DETERMINE VELOCITY AND TURBULENCE PROFILES AND CALCULATE
C***      EDDY DIFFUSION COEFFICIENTS.
C
      CALL SBLAYR(Z0,Z1,Z2,T1,T2,WSPD,WDIR,8,Z,KX,KZ,RIB,WDPRO)
C
C***      CONVERT WIND TO U AND V COMPONENTS.
C
      DO 40 K = 2,8
         CALL UVCMP(WDIR,WDPRO(K),UPRO(K),VPRO(K))
   40 CONTINUE
C
C***      NUMBER OF VERTICAL GRID POINTS IS A FUNCTION OF THE NORMAL
C***      WIND VELOCITY.
C
      U = ABS(UPRO(2))
      KMAX = 6
      IF (U .LT. 0.5) KMAX = 7
      IF (U .LT. 0.1) KMAX = 8
      TMSTOP = 300.
      IF (KMAX .EQ. 7) TMSTOP = 600.
      IF (KMAX .EQ. 8) TMSTOP = 900.
C
C***      CALCULATE THE SOURCE STRENGTH FROM THE EMISSION STRENGTH.
C
      EA  = VSPD  * EMA/3600.
      EA1 = VSPD1 * EMA1/3600.
      IF (ICHEM .EQ. 1) GO TO 50
         EB  = VSPD  * EMB/3600.
         EB1 = VSPD1 * EMB1/3600.
         EC  = VSPD  * EMC/3600.
         EC1 = VSPD1 * EMC1/3600.
   50 CONTINUE
C
      VSPD  = VSPD/3.6
      VSPD1 = VSPD1/3.6
      DDX = WIDL
      DDZ = Z(2) + 0.5 * (Z(3) - Z(2))
      DVOL  = DDX * DDZ * ABS(-VSPD + VPRO(2))
      DVOL1 = DDX * DDZ * ABS(VSPD1 + VPRO(2))
C
      EA  = EA/DVOL
      EA1 = EA1/DVOL1
      IF (ICHEM .EQ. 1) GO TO 60
         EB1 = EB1/DVOL1
         EB  = EB/DVOL
         EC1 = EC1/DVOL1
         EC  = EC/DVOL
   60 CONTINUE
C
      QVA  = EA  * NVEH/3600.
      QVA1 = EA1 * NVEH1/3600.
      IF (ICHEM .EQ. 1) GO TO 70
         QVB  = EB  * NVEH/3600.
         QVB1 = EB1 * NVEH1/3600.
         QVC  = EC  * NVEH/3600.
         QVC1 = EC1 * NVEH1/3600.
   70 CONTINUE
C
C***      CALCULATE NUMBER AND SPACING OF GRID POINTS IN X DIRECTION.
C
      NX = 13 + NLANE
      IR1 = 4
      IF (WDIR .GT. 10.  .AND. WDIR .LT. 170.) IR1 = 5
      IF (WDIR .GT. 190. .AND. WDIR .LT. 350.) IR1 = 3
      IF (IR1 .EQ. 4) CALL MOVE(XD2,XD)
      IF (IR1 .EQ. 3) CALL MOVE(XD3,XD)
      IF (IR1 .EQ. 5) CALL MOVE(XD1,XD)
C
C***      FILL IN GRID POINT ARRAY ACCORDING TO THE NUMBER OF TRAFFIC
C***      LANES AND FILL IN THE CORRESPONDING EMISSION ARRAYS.
```

```
C
      CALL WHEREX(NLANE,IR1,WIDL,MEDN,XD,QVA,QVA1,QVB,QVB1,QVC,
     1            QVC1,X,SA,SB,SC)
C
C***     DETERMINE CENTER OF LANES FOR WAKE CALCULATION.
C
      CALL CENTER(HEAD1,HEAD2,HEAD3,IR1,NLANE,WIDL,X,NX,XV,HWAYL)
C
C***     INITIALLY SET WIND FIELD TO AMBIENT CONDITIONS.
C
      DO 90 I = 1,NX
         DO 80 K = 1,KMAX
            C1(I,K) = UPRO(K)
            C2(I,K) = VPRO(K)
   80    CONTINUE
   90 CONTINUE
C
C***     DETERMINE VEHICLE WAKE EFFECTS (DU, DV) AND ADD TO AMBIENT
C***     WIND (C1, C2).
C
      CALL WAKE(UPRO,VPRO,VSPD,VSPD1,VHGH,NVEH,NVEH1,VWID,X,Z,NX,
     1          KMAX,XV,NLANE,DU,DV,KXP,KZP,KXPAS,KYPAS,KYP,IERR)
      IF (IERR .EQ. 0) GO TO 95
         WRITE(IO,1000)
         GO TO 999
   95 CONTINUE
C
      DO 110 I = 1,NX
         DO 100 K = 1,KMAX
            C1(I,K) = C1(I,K) + DU(I,K)
            C2(I,K) = C2(I,K) + DV(I,K)
  100    CONTINUE
  110 CONTINUE
C
C***     REMOVE DIVERGENCE FROM THE WIND FIELD IN THE X-Z PLANE.
C
      CALL NONDIV(C1,NX,KMAX,X,Z,C3)
C
C***     SET WINDS AT SURFACE TO ZERO.
C
      DO 120 I = 1,NX
         C1(I,1) = 0.0
         C3(I,1) = -C3(I,2)
  120 CONTINUE
C
C***     OUTPUT VELOCITY FIELDS (U = C1, V = C2, W = C3).
C
      WRITE(IO,1020)
      WRITE(IO,1025)
      TIME = -1.0
      IF (INTPR .EQ. 1) GO TO 130
         WRITE(IO,1030) HEAD1,HEAD2,HEAD3
         WRITE(IO,1040)
         CALL GRAPH(C1,1,TIME,NX,KMAX,X,HWAYL)
         WRITE(IO,1050)
         CALL GRAPH(C2,1,TIME,NX,KMAX,X,HWAYL)
         WRITE(IO,1060)
         CALL GRAPH(C3,1,TIME,NX,KMAX,X,HWAYL)
  130 CONTINUE
C
C***     ADD WAKE TURBULENCE TO EDDY DIFFUSION COEFFICIENTS.
C
      DO 150 K = KMAX,1,-1
         DO 140 I = 1,NX
            KXP(I,K) = KXP(I,K) + KX(K)
            KZP(I,K) = KZP(I,K) + KZ(K)
  140    CONTINUE
  150 CONTINUE
C
C***     OUTPUT EDDY DIFFUSION COEFFICIENT FIELDS.
C
      IF (INTPR .EQ. 1) GO TO 160
         WRITE(IO,1030) HEAD1,HEAD2,HEAD3
         WRITE(IO,1070)
         CALL GRAPH(KXP,1,TIME,NX,KMAX,X,HWAYL)
```

```
         WRITE(IO,1080)
         CALL GRAPH(KZP,1,TIME,NX,KMAX,X,HWAYL)
  160 CONTINUE
C
C***       PERFORM CHEMISTRY, IF APPLICABLE, AND CALCULATE DIFFUSION.
C
      CALL ADVCHM(SA,SB,SC,A,B,C,D,HWAYL)
C
C***       GO BACK AND GET DATA FOR NEXT HOUR.
C
      GO TO 10
C
  999 STOP
C
C***       FORMAT STATEMENTS.
C
 1000 FORMAT('0*** EXECUTION TERMINATED.')
 1010 FORMAT('0*** NORMAL TERMINATION.')
 1020 FORMAT(1H0,//////////,25X,81('*'),/,
     1        25X,'*',79X,'*',/,
     2        25X,'*  THE FOLLOWING GRAPHICAL OUTPUT IS A CROSS SECTION',
     3            ' ACROSS THE HIGHWAY IN THE  *',/,
     4        25X,'*  X-Z PLANE.  IN EACH FIELD, THE BOTTOM LINE IS AT ',
     5            'Z = 1 METER, WITH HEIGHT    *',/,
     6        25X,'*  INCREASING TOWARD THE TOP OF THE PAGE.  SUCCEEDIN',
     7            'G LINES REPRESENT Z = 2,     *',/,
     8        25X,'*  4.5, 10.5, 20, 50, AND 70 METERS.  THE SPACING AC',
     9            'ROSS THE ROAD IS DETERMINED *')
 1025 FORMAT(25X,'*  BY STARTING AT THE BOTTOM LEFT POINT, WHICH CORRE',
     1            'SPONDS TO THE FIRST VALUE   *',/,
     2        25X,'*  OF THE X GRID PRINTED EARLIER, WITH INCREASING VA',
     3            'LUES TO THE RIGHT.  THE      *',/,
     4        25X,'*  LAST SET OF CONCENTRATION FIELDS REPRESENT THE ST',
     5            'EADY-STATE VALUES AND THE   *',/,
     6        25X,'*  AVERAGES FOR THE 30 MINUTE PERIOD.  THESE STEADY-',
     7            'STATE FIELDS OCCUR AT 300,  *',/,
     8        25X,'*  600, OR 900 SECONDS.                               ',
     9            '                            *',/,
     A        25X,'*',79X,'*',/,
     B        25X,81('*'))
 1030 FORMAT(1H1,'TITLE:  ',20A4,2(/,9X,20A4)/)
 1040 FORMAT(1H0,'U FIELD (M/SEC)')
 1050 FORMAT(1H0,'V FIELD (M/SEC)')
 1060 FORMAT(1H0,'W FIELD (M/SEC)')
 1070 FORMAT(1H0,'KX FIELD (M**2/SEC)')
 1080 FORMAT(1H0,'KZ FIELD (M**2/SEC)')
      END
C
C=======================================================================
C
      SUBROUTINE READER(IERR,IEOF)
C
C        PARAMETER LIST:
C          OUTPUT:  IERR - INPUT ERROR INDICATOR (0 = NO ERROR)
C                   IEOF - END OF FILE INDICATOR (1 = END OF FILE)
C
C        CALLING ROUTINE:
C          MAIN
C
C        DESCRIPTION:
C          THIS MODULE READS ALL INPUT DATA FROM FORTRAN UNIT 5.  THE
C          INPUT DATA IS SCREENED TO DETECT ERRORS.  IF AN ERROR IS
C          DETECTED, THEN A NONZERO VALUE IS ASSIGNED TO IERR, AN ERROR
C          MESSAGE IS PRINTED, AND CONTROL IS RETURNED TO THE MAIN
C          ROUTINE.  INPUT DATA IS PASSED TO THE MAIN ROUTINE VIA
C          COMMON /INCOM/.
C
C* * * * * * * * * * * * CONTROL INPUT DATA (UNIT 5) * * * * * * * * * * *
C
C
C***   RECORD TYPES 1-3:  ALPHANUMERIC DATA FOR TITLES.  FORMAT (20A4)
C
C        HEAD1     - 80 CHARACTER TITLE
C        HEAD2     - 80 CHARACTER TITLE
C        HEAD3     - 80 CHARACTER TITLE
```

```
C
C***    RECORD TYPE 4:  FORMAT (FREE)
C
C         Z0         - SURFACE ROUGHNESS (METERS)
C         Z1         - HEIGHT OF LOWER TEMPERATURE INSTRUMENT (METERS)
C         Z2         - HEIGHT OF UPPER TEMPERATURE INSTRUMENT AND
C                        ANEMOMETER (METERS)
C         ICHEM      - CHEMISTRY OPTION
C                         0, INCLUDE NO, CO, NO2, AND O3 CHEMISTRY
C                         1, NO CHEMISTRY
C         IANTI      - ANTIDIFFUSION CALCULATION OPTION
C                         0, DO ANTIDIFFUSION CALCULATION
C                         1, SKIP ANTIDIFFUSION CALCULATION
C         INTPR      - INTERMEDIATE PRINT OPTION
C                         0, PRINT FIELDS OF METEOROLOGICAL VARIABLES AND
C                              INTERMEDIATE CONCENTRATION FIELDS
C                         1, PRINT ONLY FINAL CONCENTRATION FIELDS
C
C***    RECORD TYPE 5:  FORMAT (FREE)
C
C         T1         - TEMPERATURE AT HEIGHT, Z1 (KELVIN)
C         T2         - TEMPERATURE AT HEIGHT, Z2 (KELVIN)
C         WSPD       - HOURLY AVERAGE WIND SPEED) (M/SEC)
C         WDIR       - HOURLY AVERAGE WIND DIRECTION (METEOROLOGICAL
C                        COORDINATES)
C         RDANGL     - ANGLE BETWEEN ROAD AND LINE RUNNING NORTH-SOUTH.
C                        THE ANGLE STARTS AT ZERO DEGREES NORTH.  COUNTER-
C                        CLOCKWISE IS POSITIVE AND CLOCKWISE IS NEGATIVE.
C                        THE ANGLE IS ALWAYS LESS THAN 90 DEGREES.
C
C***    RECORD TYPE 6:  BACKGROUND CONCENTRATIONS.  FORMAT (FREE)
C
C         BACKGA     - BACKGROUND CONCENTRATION OF NO  (PPM)
C         BACKGB     - BACKGROUND CONCENTRATION OF CO  (PPM)
C         BACKGC     - BACKGROUND CONCENTRATION OF NO2 (PPM)
C         BACKGD     - BACKGROUND CONCENTRATION OF O3  (PPM)
C
C       IF ICHEM = 1, THEN:
C          (1)  BACKGA IS THE BACKGROUND CONCENTRATION OF THE POLLUTANT
C                 (PPM) AND
C          (2)  BACKGB, BACKGC, BACKGD ARE NOT PROVIDED.
C
C***    RECORD TYPE 7:  HIGHWAY INFORMATION.  FORMAT (FREE)
C
C         NLANE      - NUMBER OF TRAFFIC LANES.  MAXIMUM IS 10; MINIMUM IS
C                        4.  MUST BE IN INCREMENTS OF 2.
C         WIDL       - WIDTH OF ONE LANE (METERS)
C         MEDN       - WIDTH OF TRAFFIC MEDIAN (METERS)
C
C***    RECORD TYPE 8:  TRAFFIC INFORMATION.  FORMAT (FREE)
C
C         NVEH       - NUMBER OF VEHICLES PER SOUTHBOUND LANE IN AN HOUR
C                        PERIOD
C         NVEH1      - NUMBER OF VEHICLES PER NORTHBOUND LANE IN AN HOUR
C                        PERIOD
C         VSPD       - AVERAGE VEHICLE SPEED IN SOUTHBOUND LANES (KM/HR)
C         VSPD1      - AVERAGE VEHICLE SPEED IN NORTHBOUND LANES (KM/HR)
C         VWID       - AVERAGE WIDTH OF VEHICLES (METERS)
C         VHGH       - AVERAGE HEIGHT OF VEHICLES (METERS)
C
C***    RECORD TYPE 9:  EMISSION INFORMATION.  FORMAT (FREE)
C
C         EMA        - NO  EMISSION RATE FOR SOUTHBOUND LANES (G/KM/VEH)
C         EMB        - CO  EMISSION RATE FOR SOUTHBOUND LANES (G/KM/VEH)
C         EMC        - NO2 EMISSION RATE FOR SOUTHBOUND LANES (G/KM/VEH)
C         EMA1       - NO  EMISSION RATE FOR NORTHBOUND LANES (G/KM/VEH)
C         EMB1       - CO  EMISSION RATE FOR NORTHBOUND LANES (G/KM/VEH)
C         EMC1       - NO2 EMISSION RATE FOR NORTHBOUND LANES (G/KM/VEH)
C
C       IF ICHEM = 1, THEN:
C          (1)  EMA  = POLLUTANT EMISSION RATE FOR SOUTHBOUND LANES
C               EMA1 = POLLUTANT EMISSION RATE FOR NORTHBOUND LANES
C          (2)  EMB, EMC, EMB1, EMC1 ARE NOT PROVIDED.
C
C***    RECORD TYPE 10:  CONVERSION FACTORS.  FORMAT (FREE)
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C
C        CNA       - CONVERSION FROM G/SEC TO PPM FOR NO
C        CNB       - CONVERSION FROM G/SEC TO PPM FOR CO
C        CNC       - CONVERSION FROM G/SEC TO PPM FOR NO2
C        CND       - CONVERSION FROM G/SEC TO PPM FOR O3
C
C      IF ICHEM = 1, THEN:
C         (1)  CNA = CONVERSION FROM G/SEC TO PPM FOR THE POLLUTANT
C         (2)  CNB, CNC, CND ARE NOT PROVIDED
C
C***   RECORD TYPE 11:  CHEMICAL REACTION RATES.  FORMAT (FREE)
C         READ ONLY IF ICHEM = 0
C
C        K1        - CHEMICAL REACTION RATE (1/SEC) FOR THE FOLLOWING:
C                    NO + O3 ---• NO2 + O2
C        K2        - CHEMICAL REACTION RATE (1/SEC) FOR THE FOLLOWING:
C                    NO2 + O2 ---• NO + O3
C
      REAL K1,K2,NVEH,NVEH1,MEDN
      DIMENSION HEAD1(20),HEAD2(20),HEAD3(20)
      COMMON /INCOM/ BACKGA,BACKGB,BACKGC,BACKGD,CNA,CNB,CNC,CND,EMA,
     1               EMA1,EMB,EMB1,EMC,EMC1,K1,K2,MEDN,NVEH,NVEH1,
     2               RDANGL,T1,T2,VHGH,VWID,VSPD,VSPD1,WDIR,WIDL,WSPD,
     3               Z0,Z1,Z2,HEAD1,HEAD2,HEAD3,IANTI,ICHEM,INTPR,NLANE
      DATA IN/5/, IO/6/
C
C***     INITIALIZE.
C
      IERR = 0
      IEOF = 0
C
C***     READ RECORD TYPE 1-3.
C
      READ(IN,1000,END=990) HEAD1,HEAD2,HEAD3
C
C***     READ RECORD TYPE 4 AND PERFORM SCREENING.
C
      READ(IN,*) Z0,Z1,Z2,ICHEM,IANTI,INTPR
      IF (Z0 .GT. 0.) GO TO 20
         IERR = 1
         WRITE(IO,2010) IERR
         GO TO 999
   20 CONTINUE
      IF (Z1 .GE. 0.) GO TO 30
         IERR = 2
         WRITE(IO,2020) IERR
         GO TO 999
   30 CONTINUE
      IF (Z2 .GT. Z1) GO TO 40
         IERR = 3
         WRITE(IO,2030) IERR
         GO TO 999
   40 CONTINUE
      IF ((ICHEM .NE. 0) .AND. (ICHEM .NE. 1)) IERR = 4
      IF ((IANTI .NE. 0) .AND. (IANTI .NE. 1)) IERR = 4
      IF ((INTPR .NE. 0) .AND. (INTPR .NE. 1)) IERR = 4
      IF (IERR .EQ. 0) GO TO 50
         WRITE(IO,2040) IERR
         GO TO 999
   50 CONTINUE
C
C***     READ RECORD TYPE 5 AND PERFORM SCREENING.
C
      READ(IN,*) T1,T2,WSPD,WDIR,RDANGL
      IF (T1 .GT. 200.) GO TO 60
         IERR = 5
         WRITE(IO,2050) IERR
         GO TO 999
   60 CONTINUE
      IF (T2 .GT. 200.) GO TO 70
         IERR = 6
         WRITE(IO,2060) IERR
         GO TO 999
   70 CONTINUE
      IF ((WSPD .GT. 0.) .AND. (WSPD .LT. 99.)) GO TO 80
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         IERR = 7
         WRITE(IO,2070) IERR
         GO TO 999
   80 CONTINUE
      IF ((WDIR .GE. 0.) :AND. (WDIR .LE. 360.)) GO TO 90
         IERR = 8
         WRITE(IO,2080) IERR
         GO TO 999
   90 CONTINUE
      IF ((ABS(RDANGL) .GE. 0.) .AND. (ABS(RDANGL) .LT. 90.)) GO TO 100
         IERR = 9
         WRITE(IO,2090) IERR
         GO TO 999
  100 CONTINUE
C
C***      READ RECORD TYPE 6 PERFORM SCREENING.
C
      IF (ICHEM .EQ. 0) GO TO 105
      READ(IN,*) BACKGA
      IF (BACKGA .GE. 0.) GO TO 110
         IERR = 10
         WRITE(IO,2100) IERR
         GO TO 999
  105 CONTINUE
      READ(IN,*) BACKGA,BACKGB,BACKGC,BACKGD
      IF (BACKGA .LT. 0.) IERR = 10
      IF (BACKGB .LT. 0.) IERR = 10
      IF (BACKGC .LT. 0.) IERR = 10
      IF (BACKGD .LT. 0.) IERR = 10
      IF (IERR .EQ. 0) GO TO 110
         WRITE(IO,2100) IERR
         GO TO 999
  110 CONTINUE
C
C***      READ RECORD TYPE 7 AND PERFORM SCREENING.
C
      READ(IN,*) NLANE,WIDL,MEDN
      IF ((NLANE.GE.4) .AND. (NLANE.LE.10) .AND.
     1                       (MOD(NLANE,2).EQ.0)) GO TO 120
         IERR = 11
         WRITE(IO,2110) IERR
         GO TO 999
  120 CONTINUE
      IF (WIDL .GT. 0.) GO TO 130
         IERR = 12
         WRITE(IO,2120) IERR
         GO TO 999
  130 CONTINUE
      IF (MEDN .GE. 0.) GO TO 140
         IERR = 13
         WRITE(IO,2130) IERR
         GO TO 999
  140 CONTINUE
C
C***      READ RECORD TYPE 8 AND PERFORM SCREENING.
C
      READ(IN,*) NVEH,NVEH1,VSPD,VSPD1,VWID,VHGH
      IF ((NVEH .GT. 0) .AND. (NVEH1 .GT. 0)) GO TO 150
         IERR = 14
         WRITE(IO,2140) IERR
         GO TO 999
  150 CONTINUE
      IF ((VSPD  .GT. 0.) .AND. (VSPD  .LT. 200.) .AND.
     1    (VSPD1 .GT. 0.) .AND. (VSPD1 .LT. 200.)) GO TO 160
         IERR = 15
         WRITE(IO,2150) IERR
         GO TO 999
  160 CONTINUE
      IF ((VWID .GT. 0.) .AND. (VWID .LT. WIDL) .AND.
     1    (VHGH .GT. 0.) .AND. (VHGH .LT. 10.)) GO TO 170
         IERR = 16
         WRITE(IO,2160) IERR
         GO TO 999
  170 CONTINUE
C
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C***       READ RECORD TYPE 9 AND PERFORM SCREENING.
C
      IF (ICHEM .EQ. 0) GO TO 175
      READ(IN,*) EMA,EMA1
      IF ((EMA .GT. 0.) .AND. (EMA1 .GT. 0.)) GO TO 180
         IERR = 17
         WRITE(IO,2170) IERR
         GO TO 999
  175 READ(IN,*) EMA,EMB,EMC,EMA1,EMB1,EMC1
      IF ((EMA .LE. 0.) .OR. (EMA1 .LE. 0.)) IERR = 17
      IF ((EMB .LE. 0.) .OR. (EMB1 .LE. 0.)) IERR = 17
      IF ((EMC .LE. 0.) .OR. (EMC1 .LE. 0.)) IERR = 17
      IF (IERR .EQ. 0) GO TO 180
         WRITE(IO,2170) IERR
         GO TO 999
C
C***       READ RECORD TYPE 10 AND PERFORM SCREENING.
C
  180 IF (ICHEM .EQ. 0) GO TO 185
      READ(IN,*) CNA
      IF (CNA .GT. 0.) GO TO 999
         IERR = 18
         WRITE(IO,2180) IERR
         GO TO 999
  185 READ(IN,*) CNA,CNB,CNC,CND
      IF (CNA .LE. 0.) IERR = 18
      IF (CNB .LE. 0.) IERR = 18
      IF (CNC .LE. 0.) IERR = 18
      IF (CND .LE. 0.) IERR = 18
      IF (IERR .EQ. 0) GO TO 190
         WRITE(IO,2180) IERR
         GO TO 999
C
C***       READ RECORD TYPE 11 IF APPLICABLE AND PERFORM SCREENING.
C
  190 READ(IN,*) K1,K2
      IF ((K1 .GE. 0.) .AND. (K2 .GE. 0.)) GO TO 999
         IERR = 19
         WRITE(IO,2190) IERR
         GO TO 999
C
C***       END OF FILE PROCESSING.
C
  990 IEOF = 1
C
  999 RETURN
C
C***       INPUT FORMATS.
C
 1000 FORMAT(20A4/20A4/20A4)
C
C***       ERROR STATEMENT FORMATS.
C
 2010 FORMAT('0*** ERROR ',I2,':  SURFACE ROUGHNESS, Z0, IS LESS THAN ',
     1       'ZERO.')
 2020 FORMAT('0*** ERROR ',I2,':  HEIGHT OF LOWER TEMPERATURE ',
     1       'INSTRUMENT, Z1, IS LESS THAN ZERO.')
 2030 FORMAT('0*** ERROR ',I2,':  HEIGHT OF UPPER TEMPERATURE ',
     1       'INSTRUMENT, Z2, IS BELOW OR EQUAL THAT OF THE LOWER ',
     2       'INSTRUMENT.')
 2040 FORMAT('0*** ERROR ',I2,':  INPUT OPTIONS MUST EQUAL ZERO OR ',
     1       'ONE.')
 2050 FORMAT('0*** ERROR ',I2,':  TEMPERATURE AT HEIGHT Z1 IS NOT IN ',
     1       'DEGREES KELVIN.')
 2060 FORMAT('0*** ERROR ',I2,':  TEMPERATURE AT HEIGHT Z2 IS NOT IN ',
     1       'DEGREES KELVIN.')
 2070 FORMAT('0*** ERROR ',I2,':  INPUT WIND SPEED IS IN ERROR.')
 2080 FORMAT('0*** ERROR ',I2,':  INPUT WIND DIRECTION IS IN ERROR.')
 2090 FORMAT('0*** ERROR ',I2,':  HIGHWAY ORIENTATION IS INCORRECTLY ',
     1       'SPECIFIED.')
 2100 FORMAT('0*** ERROR ',I2,':  BACKGROUND POLLUTANT CONCENTRATIONS ',
     1       'CANNOT BE LESS THAN ZERO.')
 2110 FORMAT('0*** ERROR ',I2,':  NUMBER OF TRAFFIC LANES IS ',
     1       'INCORRECTLY SPECIFIED.')
 2120 FORMAT('0*** ERROR ',I2,':  WIDTH OF A TRAFFIC LANE CANNOT BE ',
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     1          'LESS THAN OR EQUAL TO ZERO.')
 2130 FORMAT('0*** ERROR ',I2,':  THE TRAFFIC MEDIAN CANNOT BE LESS',
     1          ' THAN ZERO.')
 2140 FORMAT('0*** ERROR ',I2,':  TRAFFIC VOLUME CANNOT BE LESS THAN ',
     1          'OR EQUAL TO ZERO.')
 2150 FORMAT('0*** ERROR ',I2,':  AVERAGE VEHICLE SPEED IS INCORRECTLY',
     1          ' SPECIFIED.')
 2160 FORMAT('0*** ERROR ',I2,':  AVERAGE VEHICLE DIMENSIONS ARE ',
     1          'INCORRECTLY SPECIFIED.')
 2170 FORMAT('0*** ERROR ',I2,':  VEHICLE EMISSION RATES MUST BE ',
     1          'GREATER THAN ZERO.')
 2180 FORMAT('0*** ERROR ',I2,':  CONVERSION FACTOR FOR G/SEC TO PPM ',
     1          'IS INCORRECTLY SPECIFIED.')
 2190 FORMAT('0*** ERROR ',I2,':  CHEMICAL REACTION RATES CANNOT BE ',
     1          'LESS THAN ZERO.')
      END
C
C=======================================================================
C
      SUBROUTINE ECHO
C
C        CALLING ROUTINE:
C          MAIN
C
C        DESCRIPTION:
C          THIS MODULE ECHOES THE INPUT DATA.  THE DATA IS PASSED TO
C          THIS SUBROUTINE VIA COMMON /INCOM/.
C
      REAL K1,K2,NVEH,NVEH1,MEDN
      DIMENSION HEAD1(20),HEAD2(20),HEAD3(20)
      COMMON /INCOM/ BACKGA,BACKGB,BACKGC,BACKGD,CNA,CNB,CNC,CND,EMA,
     1               EMA1,EMB,EMB1,EMC,EMC1,K1,K2,MEDN,NVEH,NVEH1,
     2               RDANGL,T1,T2,VHGH,VWID,VSPD,VSPD1,WDIR,WIDL,WSPD,
     3               Z0,Z1,Z2,HEAD1,HEAD2,HEAD3,IANTI,ICHEM,INTPR,NLANE
      DATA IN/5/, IO/6/, IVER/86010/
C
C***     PRINT TITLE.
C
      WRITE(IO,1000) IVER,HEAD1,HEAD2,HEAD3
C
C***     PRINT OPTIONS.
C
      WRITE(IO,1010) ICHEM,IANTI,INTPR
C
C***     PRINT METEOROLOGICAL INFORMATION.
C
      WRITE(IO,1020) Z0,Z1,Z2,T1,T2,WSPD,WDIR
C
C***     PRINT HIGHWAY INFORMATION.
C
      WRITE(IO,1030) NLANE,WIDL,MEDN,RDANGL
      WRITE(IO,1035) NVEH,NVEH1,VSPD,VSPD1,VWID,VHGH
C
C***     PRINT EMISSIONS INFORMATION.
C
      IF (ICHEM .EQ. 0) GO TO 10
         WRITE(IO,1040) BACKGA,EMA,EMA1,CNA
         GO TO 999
   10 CONTINUE
      WRITE(IO,1005) HEAD1,HEAD2,HEAD3
      WRITE(IO,1050) BACKGA,BACKGB,BACKGC,BACKGD
      WRITE(IO,1060) EMA,EMB,EMC,EMA1,EMB1,EMC1
      WRITE(IO,1070) CNA,CNB,CNC,CND,K1,K2
C
  999 RETURN
C
C***     FORMAT STATEMENTS.
C
 1000 FORMAT(1X,33X,'* * * ROADWAY (VERSION ',I5,') * * *',///,
     1       1X,'TITLE:  ',20A4,2(/,9X,20A4)/)
 1005 FORMAT(1H1,'TITLE:  ',20A4,2(/,9X,20A4)/)
 1010 FORMAT(1H0,'O P T I O N S',/,
     1       1H0,4X,'CHEMISTRY OPTION (ICHEM) ',29('.'),4X,I8,/,
     2        1X,4X,'ANTIDIFFUSION CALCULATION OPTION (IANTI) ',13('.'),
     3              4X,I8,/,
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     4        1X,4X,'INTERMEDIATE PRINT OPTION (INTPR) ',20('.'),4X,I8/)
 1020 FORMAT(1H0,'M E T E O R O L O G Y',/,
     1       1H0,4X,'SURFACE ROUGHNESS (Z0) ',31('.'),2X,F10.4,' M',/,
     2        1X,4X,'HEIGHT OF TEMPERATURE INSTRUMENTS',/,
     3        1X,7X,'LOWER (Z1) ',40('.'),2X,F10.2,' M',/,
     4        1X,7X,'UPPER (Z2) ',40('.'),2X,F10.2,' M',/,
     5        1X,4X,'TEMPERATURE AT HEIGHT:',/,
     6        1X,7X,'Z1 (T1) ',43('.'),2X,F10.2,' K',/,
     7        1X,7X,'Z2 (T2) ',43('.'),2X,F10.2,' K',/,
     8        1X,4X,'WIND SPEED (WSPD) ',36('.'),2X,F10.2,' M/SEC',/,
     9        1X,4X,'WIND DIRECTION (WDIR) ',32('.'),2X,F10.2,' DEG',/)
 1030 FORMAT(1H0,'H I G H W A Y   I N F O R M A T I O N',/,
     1       1H0,4X,'NUMBER OF TRAFFIC LANES (NLANE) ',22('.'),4X,I8,/,
     2        1X,4X,'WIDTH OF EACH LANE (WIDL) ',28('.'),2X,F10.2,' M',/
     3        1X,4X,'WIDTH OF MEDIAN (MEDN) ',31('.'),2X,F10.2,' M',/
     4        1X,4X,'ANGLE BETWEEN ROAD AND LINE RUNNING N-S (RDANGL) ',
     5        5('.'),2X,F10.2,' DEG')
 1035 FORMAT( 1X,4X,'TRAFFIC VOLUME',/,
     1        1X,7X,'SOUTHBOUND LANES (NVEH) ',27('.'),4X,F8.0,
     2              ' VEH/HR',/,
     3        1X,7X,'NORTHBOUND LANES (NVEH1) ',26('.'),4X,F8.0,
     4              ' VEH/HR',/,
     5        1X,4X,'AVERAGE VEHICLE SPEED',/,
     6        8X,'SOUTHBOUND LANES (VSPD) ',27('.'),2X,F10.2,' KM/HR',/,
     7        8X,'NORTHBOUND LANES (VSPD1) ',26('.'),2X,F10.2,' KM/HR'/,
     8        1X,4X,'AVERAGE DIMENSIONS OF VEHICLES',/,
     9        1X,7X,'WIDTH (VWID) ',38('.'),2X,F10.2,' M',/,
     A        1X,7X,'HEIGHT (VHGH) ',37('.'),2X,F10.2,' M',/)
 1040 FORMAT(1H0,'E M I S S I O N   I N F O R M A T I O N',/,
     1       1H0,4X,'BACKGROUND CONCENTRATION (BACKGA) ',20('.'),2X,
     2              F10.4,' PPM',/,
     3        1X,4X,'EMISSION RATES:',/,
     4        1X,7X,'SOUTHBOUND LANES (EMA)  ',27('.'),2X,F10.4,
     5              ' G/KM/VEH',/,
     6        1X,7X,'NORTHBOUND LANES (EMA1) ',27('.'),2X,F10.4,
     7              ' G/KM/VEH',/,
     8        1X,4X,'CONVERSION FACTOR FOR G/SEC TO PPM (CNA) ',13('.'),
     9        2X,F10.4)
 1050 FORMAT(1H0,'E M I S S I O N   I N F O R M A T I O N',/,
     1       1H0,4X,'BACKGROUND CONCENTRATIONS:',/,
     2        1X,7X,'NO  (BACKGA) ',38('.'),2X,F10.4,' PPM',/,
     3        1X,7X,'CO  (BACKGB) ',38('.'),2X,F10.4,' PPM',/,
     4        1X,7X,'NO2 (BACKGC) ',38('.'),2X,F10.4,' PPM',/,
     5        1X,7X,'O3  (BACKGD) ',38('.'),2X,F10.4,' PPM')
 1060 FORMAT( 1X,4X,'EMISSION RATES FOR THE SOUTHBOUND LANES:',/,
     1        1X,7X,'NO  (EMA) ',41('.'),2X,F10.4,' G/KM/VEH',/,
     2        1X,7X,'CO  (EMB) ',41('.'),2X,F10.4,' G/KM/VEH',/,
     3        1X,7X,'NO2 (EMC) ',41('.'),2X,F10.4,' G/KM/VEH',/,
     4        1X,4X,'EMISSION RATES FOR THE NORTHBOUND LANES:',/,
     5        1X,7X,'NO  (EMA1) ',40('.'),2X,F10.4,' G/KM/VEH',/,
     6        1X,7X,'CO  (EMB1) ',40('.'),2X,F10.4,' G/KM/VEH',/,
     7        1X,7X,'NO2 (EMC1) ',40('.'),2X,F10.4,' G/KM/VEH')
 1070 FORMAT( 1X,4X,'CONVERSION FACTORS (G/SEC TO PPM) FOR:',/,
     1        1X,7X,'NO  (CNA) ',41('.'),2X,F10.4,/,
     2        1X,7X,'CO  (CNB) ',41('.'),2X,F10.4,/,
     3        1X,7X,'NO2 (CNC) ',41('.'),2X,F10.4,/,
     4        1X,7X,'O3  (CND) ',41('.'),2X,F10.4,/,
     5        1X,4X,'CHEMICAL REACTION RATES FOR THE FOLLOWING:',/,
     6        1X,7X,'NO  + O3 ---* NO2 + O2 '28('.'),2X,F10.4,
     7              ' 1/(PPM MIN)',/
     8        1X,7X,'NO2 + O2 ---* NO  + O3 '28('.'),2X,F10.4,' 1/MIN')
      END
C
C========================================================================
C
      SUBROUTINE ZERO(ICHEM,SA,SB,SC,A,B,C,D)
C
C         PARAMETER LIST:
C           INPUT:   ICHEM - CHEMISTRY OPTION
C           OUTPUT:  SA    - NO  EMISSION GRID (G/M**3/SEC).
C                            IF ICHEM = 1, THEN SA IS THE POLLUTANT
C                            EMISSION GRID AND SB AND SC ARE IRRELEVANT.
C                    SB    - CO  EMISSION GRID (G/M**3/SEC)
C                    SC    - NO2 EMISSION GRID (G/M**3/SEC)
C                    A     - NO  CONCENTRATION FIELD (PPM).
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C                          IF ICHEM = 1, THEN A IS THE POLLUTANT
C                          CONCENTRATION FIELD AND B, C, AND D ARE
C                          IRRELEVANT.
C                  B     - CO  CONCENTRATION FIELD (PPM)
C                  C     - NO2 CONCENTRATION FIELD (PPM)
C                  D     - O3  CONCENTRATION FIELD (PPM)
C
C       CALLING ROUTINE:
C         MAIN
C
C       DESCRIPTION:
C         THIS MODULE PERFORMS THE NECESSARY INITIALIZATION PRIOR TO
C         CALCULATIONS.
C
      DIMENSION A(24,8,2),B(24,8,2),C(24,8,2),D(24,8,2)
      DIMENSION SA(24),SB(24),SC(24)
C
      DO 300 I = 1,24
         SA(I) = 0.0
         IF (ICHEM .EQ. 1) GO TO 10
            SB(I) = 0.0
            SC(I) = 0.0
   10    CONTINUE
         DO 200 K = 1,8
            DO 100 L = 1,2
               A(I,K,L) = 0.0
               IF (ICHEM .EQ. 1) GO TO 20
                  B(I,K,L) = 0.0
                  C(I,K,L) = 0.0
                  D(I,K,L) = 0.0
   20          CONTINUE
  100       CONTINUE
  200    CONTINUE
  300 CONTINUE
C
      RETURN
      END
C
C=====================================================================
C
      SUBROUTINE SBLAYR(Z0,Z1,H,T1,T2,WSP,WDIR,KMAX,Z,KX,KZ,RIB,WSPD)
C
C        PARAMETER LIST:
C          INPUT:   Z0    - SURFACE ROUGHNESS (METERS)
C                   Z1    - HEIGHT OF LOWER TEMPERATURE INSTRUMENT
C                           (METERS)
C                   H     - HEIGHT OF UPPER TEMPERATURE INSTRUMENT AND
C                           ANEMOMETER (METERS)
C                   T1    - TEMPERATURE AT HEIGHT, Z1 (KELVIN)
C                   T2    - TEMPERATURE AT HEIGHT,  H (KELVIN)
C                   WSP   - HOURLY AVERAGE WIND SPEED (M/SEC)
C                   WDIR  - HOURLY AVERAGE WIND DIRECTION (RELATIVE TO
C                           THE HIGHWAY)
C                   KMAX  - NUMBER OF VERTICAL LEVELS (KMAX = 8)
C                   Z     - ARRAY CONTAINING HEIGHTS OF VERTICAL LEVELS
C                           (METERS)
C          OUTPUT:  KX    - HORIZONTAL EDDY DIFFUSION COEFFICIENTS
C                           (M**2/SEC)
C                   KZ    - VERTICAL   EDDY DIFFUSION COEFFICIENTS
C                           (M**2/SEC)
C                   RIB   - BULK RICHARDSON NUMBER
C                   WSPD  - VELOCITY PROFILE ARRAY (M/SEC)
C
C          CALLING ROUTINE:
C            MAIN
C
C          SUBPROGRAMS CALLED:
C            RIBST*, RIBTOZ*, GETSFC*, PROFIL*, TURBC*
C
C            *  INDICATES ENTRY POINT IN SUBROUTINE RIBULK
C
C          DESCRIPTION:
C            THIS MODULE IS THE DRIVING ROUTINE FOR THE SURFACE LAYER
C            MODEL WRITTEN BY FRANK BINKOWSKI USING SIMILARITY THEORY.
C            THIS SUBROUTINE FINDS THE VELOCITY PROFILE, TURBULENCE
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C           PROFILES, AND CALCULATES EDDY DIFFUSION COEFFICIENTS.
C
      REAL LAMDA,KX,KZ,L
      DIMENSION KX(8),KZ(8),WSPD(8),Z(8)
      DATA G/9.80616/, GAMD/.00976/
C
C***      INITIALIZE SURFACE LAYER MODEL.
C
      DELZ = H - Z1
      THETA1 = T1 + GAMD * Z1
      THETA2 = T2 + GAMD * H
      DTEMP = THETA2 - THETA1
      RIB = H * G * DTEMP/(THETA2 * WSP**2)
      IF(RIB .GT. 0.20) RIB = 0.20
C
      CALL RIBST(H,Z1,Z0,1)
C
C***      GET ESTIMATE OF ZETA.
C
      CALL RIBTOZ(RIB,ZETA)
C
C***      CALCULATE U*, T*, AND T0.
C
      CALL GETSFC(ZETA,WSP,THETA2,DTEMP,USTAR,TSTAR,T0)
      L = H/ZETA
C
C***      CALCULATE VERTICAL WIND PROFILE AND EDDY DIFFUSION
C***      COEFFICIENTS.
C
      DO 20 K = 2,KMAX
         ZL = Z(K)/L
C
C***         OBTAIN WIND SPEED, TEMPERATURE, AND GRADIENTS OF THESE
C***         PARAMETERS AT HEIGHT ZL.
C
         CALL PROFIL(Z(K),ZL,USTAR,TSTAR,T0,WSPD(K),TH,DUDZ,DTHDZ)
         ZETA = Z(K)/L
C
C***         OBTAIN TURBULENT MOMENTS USING BINKOWSKI?S CLOSURE MODEL.
C
         CALL TURBC(ZETA,SU,SV,SW,ST,UT,SQ,FM)
C
         SU = SU * USTAR
         SV = SV * USTAR
         SW = SW * USTAR
         IF (WDIR .LT.  90.) WD1 = 90. - WDIR
         IF (WDIR .GE.  90. .AND. WDIR .LT. 180.) WD1 = WDIR - 90.
         IF (WDIR .GE. 180. .AND. WDIR .LT. 270.) WD1 = 270. - WDIR
         IF (WDIR .GT. 270.) WD1 = WDIR - 270.
         WD1 = WD1 * 3.14159265/180.
         SU1 =  SU * COS(WD1) + SV * SIN(WD1)
         SV1 = -SU * SIN(WD1) + SV * COS(WD1)
         LAMDA = Z(K)/FM
         KZ(K) = .125 * SW * LAMDA
         IF (ZETA .LT. 0. .AND. K .GT. 2) GO TO 10
            KX(K) = ABS(SU1) * LAMDA
   10    CONTINUE
   20 CONTINUE
C
      DO 30 K = 3,KMAX
         KX(K) = KX(2)
   30 CONTINUE
      KX(1) = KX(2)
C
      RETURN
      END
C
C=====================================================================
C
      SUBROUTINE RIBULK(H,Z1,Z0,NTYPE,ZZ,RIB)
C
C     THIS ROUTINE CALCULATES SURFACE QUANTITIES SUCH AS U* AND T* USING
C     USING SIMILARITY THEORY.
C     REFERENCES:
C     NICKERSON AND SMILEY JAM(14) 297-300 1975.
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C      BENOIT JAM(16) 859-860 1977
C
C      NOTE: THE STABLE PROFILES ARE INTEGRATED FROM Z0/L TO Z/L ALSO.
C      THIS IS AN EXTENSION OF NICKERSON & SMILEY(1975),BENOIT(1977).
C
C      THE CALLING SEQUENCES ARE:
C      CALL RIBST(H,Z1,Z0,NTYPE)
C      WHERE:
C      H IS  ANEMOMETER HEIGHT (METERS)
C      Z1 IS THE LOWER THERMOMETER HEIGHT (METERS)
C      Z0 IS  THE ROUGHNESS HEIGHT (METERS)
C      NTYPE IS A PROFILE INDICATOR.
C         NTYPE=1; DYER PROFILES
C         NTYPE=2; BUSINGER PROFILES..
C      THIS INITIALIZES THE ROUTINE.
C
C      NOW TO OBTAIN AN ESTIMATE OF ZETA FROM A VALUE OF RIB:
C      CALL RIBTOZ(RIB,ZETA)
C
C      TO OBTAIN U*, T* AND T0:
C      CALL GETSFC(ZL,UH,THETA,DT,USTAR,TSTAR,T0)
C      WHERE:
C      ZL IS A VALUE OR ESTIMATE OF ZETA.
C      UH IS  THE WIND SPEED AT H (METERS/SECOND)
C      THETA IS THE POTENTIAL TEMPERATURE AT H (DEGREES KELVIN)
C      DT IS THE TEMPERATURE DIFFERENCE BETWEEN H AND Z1 (DEGREES)
C      USTAR IS U* AT Z0 (METERS/SECOND)
C      TSTAR IS T* AT Z0 (DEGREES KELVIN)
C ***  T0 IS THE EXTRAPOLATED TEMPERATURE AT Z0 (DEGREES KELVIN)
C
C      TO OBTAIN VALUES OF WIND SPEED, TEMPERATURE AND THE GRADIENTS
C      OF THESE QUANTITIES AT VARIOUS HEIGHTS:
C
C      CALL PROFIL(HZ,ZL,USTAR,TSTAR,T0,UP,TP,DUDZ,DTHDZ)
C      WHERE:
C      HZ IS THE HEIGHT (METERS) AND MUST BE GREATER THAN Z0.
C      ZL IS THE VALUE OF ZETA AT HZ.
C      USTAR,TSTAR,T0 ARE AS ABOVE.
C      UP IS THE PREDICTED WIND SPEED AT HZ (METERS/SECOND).
C      TP IS THE PREDICTED POTENTIAL TEMPERATURE AT  HZ (DEGREES KELVIN).
C      DUDZ AND DTHDZ ARE THE PREDICTED WIND SHEAR (1/SECONDS) AND
C      POTENTIAL TEMPERATURE GRADIENT (DEGREES/METER) AT HZ.
C
C       TO OBTAIN TURBULENT MOMENTS USING BINKOWSKI'S CLOSURE MODEL:
C      CALL TURBC(Z,SU,SV,SW,ST,UT,SQ,FM)
C      WHERE:
C      Z IS Z/L
C      SU,SV,SW ARE THE NORMALIZED RMS TURBULENT VELOCITY COMPONENTS.
C      THEY ARE NORMALIZED BY USTAR AND THUS ARE NON-DIMENSIONAL.
C      ST IS THE NORMALIZED RMS TURBULENT TEMPERATURE FLUCTUATION.
C      IT IS NORMALIZED BY TSTAR AND IS NON-DIMENSIONAL.
C      UT IS NORMALIZED LONGITUDINAL KINEMATIC HEAT FLUX. IT IS NORMAL-
C      IZED BY USTAR*TSTAR AND IS NONDIMENSIONAL.
C      SQ IS THE NORMALIZED RMS TURBULENT VELOCITY FLUCTUATION. IT IS
C      NORMALIZED BY USTAR AND IS NON-DIMENSIONAL.
C      FM IS THE NON-DIMENSIONAL FREQUENCY OF THE PEAK IN THE W SPECTRUM.
C      THIS CALL SHOULD ONLY BE USED WHEN  NTYPE =1 ABOVE.
C
C      CODED BY DR FRANCIS S. BINKOWSKI 1977.
C
       DATA GRAV/9.80616/, ONE3/0.333333/
C
C * * * * * * * * * * * * STATEMENT FUNCTIONS * * * * * * * * * * * *
C
       FAC1(X1,X2)=ALOG( (X1*X1+1.0)*(X1+1.0)*(X1+1.0)/(
      1              (X2*X2+1.0)*(X2+1.0)*(X2+1.0)  )  )
       FAC2(Y1,Y2)=2.0*(ALOG( (Y1+1.0)/(Y2+1.0) ) )
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
       ENTRY RIBST(H,Z1,Z0,NTYPE)
COMMENT: INITIALIZE   THE CONSTANTS AND PARAMETERS.
       IF(NTYPE .EQ. 2)  GO TO 1
C ***  DYER PROFILES.
       GAMA1= 16.0
```

```
      GAMA2=16.0
      BETA = 5.0
      VK=0.4
      R=1.0
      ARIB2=8.612
      GO TO 3
C *** BUSINGER PROFILES
    1 GAMA1=15.0
      GAMA2=9.0
      BETA=4.7
      VK=0.35
      R=0.74
      ARIB2=6.424
    3 ALNZ=ALOG(H/Z0)
      ALNZT=ALOG(H/Z1)
      ALNZ1=ALOG(Z1/Z0)
      F2GN=ALNZ*ALNZ/(R*ALNZT)
      Z1H=Z1/H
      Z0H=Z0/H
      Z01=Z0/Z1
      GM1HZ0=GAMA1*Z0H
      GM2HZ1=GAMA2*Z1H
      GM2HZ0=GAMA2*Z0H
      VKGH=VK*GRAV*H
      RETURN
C
      ENTRY ZTORIB(ZL,RIB)
      HL=ZL
      ASSIGN 5 TO ISTAT
      GO TO 109
    5 BB=HL*G/(VK*F*F)
      RIB=BB
      RETURN
C
      ENTRY RIBTOZ(RIB,ZEST)
      ACC=0.0
      ITERM=3
      IF( RIB .LT. 0.04 ) GO TO 65
      ITERM=5
      ACC=ARIB2
   65 HL=F2GN*(1.0 + ACC*RIB)*RIB
C *** ITERATE TO RECOVER Z/L.
      DO 61 ITER=1,ITERM
      ASSIGN 8 TO ISTAT
      GO TO 109
    8 ZEST=(VK*F*F/G)*RIB
      HL=ZEST
   61 CONTINUE
      RETURN
C
      ENTRY GETSFC(ZL,UH,THETA,DT,USTAR,TSTAR,T0)
      HL=ZL
      ASSIGN 6 TO ISTAT
      GO TO 109
    6 IF(HL.LT. 0.0 ) GO TO 4
      BYT0=BETA*HL*Z1H*(1.0-Z01)
      G0=(R*ALNZ1 + BYT0)/VK
      GO TO 7
    4 ETA0=SQRT(1.0-GM2HZ0*HL)
      G0=R*(ALNZ1 + FAC2(ETA0,ETA1) )/VK
    7 USTAR=UH/F
      TSTAR=DT/G
      T0=THETA - DT - TSTAR*G0
      RETURN
C
  109 IF(HL .LT. 0.0 ) GO TO 101
C *** STABLE
      BYU=BETA*HL*(1.0-Z0H)
      BYT=BETA*HL*(1.0-Z1H)
      F=(ALNZ + BYU)/VK
      G=( R*ALNZT + BYT)/VK
      GO TO 105
C *** UNSTABLE
  101 ZETA0=SQRT( SQRT( 1.0 - GM1HZ0*HL )  )
      ETA1=SQRT(1.0-GM2HZ1*HL)
```

```
      ZETAH=SQRT(SQRT(1.0-GAMA1*HL) )
      ETAH=SQRT(1.0-GAMA2*HL )
      F=(ALNZ + FAC1(ZETA0,ZETAH)+2.0*(ATAN(ZETAH)-ATAN(ZETA0)))/VK
      G=R*( ALNZT + FAC2(ETA1,ETAH) )/VK
  105 GO TO ISTAT,(5,6,8)
C
      ENTRY PROFIL(HZ,ZL,USTAR,TSTAR,T0,UP,TP,DUDZ,DTHDZ)
      HL=ZL
      VKHZ=VK*HZ
      ALNX=ALOG(HZ/Z0)
      IF( HL .LT. 0.0 ) GO TO 44
      BY=BETA*HL*(1.0-Z0/HZ)
      F=(ALNX + BY)/VK
      G=( R*ALNX + BY)/VK
      DUDZ=USTAR*(1.0 + BY)/VKHZ
      DTHDZ=TSTAR*(R +BY)/VKHZ
      GO TO 55
C *** UNSTABLE
   44 GMAHZ0=GAMA1*Z0/HZ
      GMBHZ0=GAMA2*Z0/HZ
      ZETA0=SQRT( SQRT( 1.0 - GMAHZ0*HL )  )
      ETA0=SQRT(1.0-GMBHZ0*HL)
      ZETAH=SQRT(SQRT(1.0-GAMA1*HL) )
      ETAH=SQRT(1.0-GAMA2*HL )
      F=(ALNX + FAC1(ZETA0,ZETAH)+2.0*(ATAN(ZETAH)-ATAN(ZETA0)))/VK
      G=R*(ALNX + FAC2(ETA0,ETAH) )/VK
      DUDZ=USTAR/(VKHZ*ZETAH)
      DTHDZ=R*TSTAR/(VKHZ*ETAH)
   55 UP = USTAR*F
      TP=T0 + TSTAR*G
      RETURN
C
      ENTRY TURBC(Z,SU,SV,SW,ST,UT,SQ,FM)
      IF( Z .LT. 0.0 ) GO TO 91
C *** STABLE
      PHIM = 1.0 + 5.0*Z
      GO TO 95
C *** UNSTABLE
   91 PHIM=1.0/SQRT( SQRT( 1.0-16.0*Z  )  )
   95 RF=Z/PHIM
      GAMMA = RF/(1.0 - RF)
      ALFAT=2.63*( (0.30*PHIM-Z)/(0.79*PHIM-Z) )
      PHIH=PHIM/ALFAT
C *** USE INTERNAL ALFAT TO GET PHIH.
      SCALE=1.0
      IF( Z .GT. 0.0 ) SCALE = 1.0 + 3.39*Z - 0.25*Z*Z
      IF( Z .GE. 2.0 ) SCALE = 6.78 + 2.39*( Z - 2.0 )
C *** THIS MAKE FM PROPORTIONAL TO Z/L FOR LARGE Z/L.
      IF( Z .LT. 0.0 ) SCALE = 0.40 + 0.60*EXP(4.0*Z)
      SCALE2=SCALE*SCALE
      FM=0.4*SCALE
      D1=1.0/FM
      SW=((PHIM-Z)/(1.20*FM))**0.333333
      SWFM=0.4*SW
      W2=SW*SW
      Q2=W2*(3.0 + 0.75*(1.0 + D1) + 1.80*GAMMA)
      V2=ONE3*Q2 - W2*(0.08*GAMMA + 0.13*(2.0-D1) )
      U2=Q2 - ( V2 + W2)
      T2=2.5*PHIH/SWFM
      IF( Z .GT. 0.0) T2=T2/SCALE2
      SU=SQRT(U2)
      UT=0.53*(PHIH + 1.9*PHIM)/SWFM
      IF( Z .GT. 0.0 ) UT=UT/SCALE2
      ST=SQRT(T2)
      SV=SQRT(V2)
      SQ=SQRT(Q2)
      RETURN
      END
C
C=======================================================================
C
      SUBROUTINE UVCMP(DIR,SPD,U,V)
C
C         PARAMETER LIST:
C           INPUT:   DIR - WIND DIRECTION (RELATIVE TO HIGHWAY)
```

```
C                SPD - WIND SPEED (M/SEC)
C        OUTPUT: U   - EAST-WEST COMPONENT (RELATIVE TO A N-S
C                      HIGHWAY) OF THE WIND (M/SEC)
C                V   - NORTH-SOUTH COMPONENT (RELATIVE TO A N-S
C                      HIGHWAY) OF THE WIND (M/SEC)
C
C      CALLING ROUTINE:
C        MAIN
C
C      DESCRIPTION:
C        THE SUBROUTINE CONVERTS WIND VELOCITY INTO ITS U AND V
C        COMPONENTS.
C
      PI = 3.141592654
      U = -SPD * SIN(DIR * PI/180.)
      V = -SPD * COS(DIR * PI/180.)
C
      RETURN
      END
C
C=======================================================================
C
      SUBROUTINE MOVE(XX,YY)
C
C      PARAMETER LIST:
C        INPUT:  XX - INITIALIZING ARRAY
C        OUTPUT: YY - ARRAY TO BE INITIALIZED
C
C      CALLING ROUTINE:
C        MAIN
C
C      DESCRIPTION:
C        THIS MODULE INITIALIZES THE GRID IN THE X DIRECTION.
C
C
      DIMENSION XX(8),YY(8)
C
      DO 10 I = 1,8
         YY(I) = XX(I)
   10 CONTINUE
C
      RETURN
      END
C
C=======================================================================
C
      SUBROUTINE WHEREX(NLANE,IR1,WIDL,RMEDN,XD,QVA,QVA1,QVB,QVB1,QVC,
     1                  QVC1,X,SA,SB,SC)
C
C      PARAMETER LIST:
C        INPUT:  NLANE - NUMBER OF TRAFFIC LANES
C                IR1   - WIND DIRECTION INDICATOR
C                WIDL  - WIDTH OF ONE LANE
C                RMEDN - HALF WIDTH OF TRAFFIC MEDIAN (METERS)
C                XD    - GRID SPACING PARAMETERS (METERS)
C                QVA   - NO SOURCE STRENGTH OF SOUTHBOUND LANES
C                        (G/SEC/M**3)
C                QVA1  - NO SOURCE STRENGTH OF NORTHBOUND LANES
C                        (G/SEC/M**3)
C                QVB   - CO SOURCE STRENGTH OF SOUTHBOUND LANES
C                        (G/SEC/M**3)
C                QVB1  - CO SOURCE STRENGTH OF NORTHBOUND LANES
C                        (G/SEC/M**3)
C                QVC   - NO2 SOURCE STRENGTH OF SOUTHBOUND LANES
C                        (G/SEC/M**3)
C                QVC1  - NO2 SOURCE STRENGTH OF NORTHBOUND LANES
C                        (G/SEC/M**3)
C        OUTPUT: X     - GRID POINTS IN THE X DIRECTION (METERS)
C                SA    - NO  EMISSION GRID (G/M**3/SEC)
C                SB    - CO  EMISSION GRID (G/M**3/SEC)
C                SC    - NO2 EMISSION GRID (G/M**3/SEC)
C
C      CALLING ROUTINE:
C        MAIN
C
```

```
C        SUBPROGRAMS CALLED:
C          FILLIT
C
C        DESCRIPTION:
C          THIS MODULE CALCULATES THE NUMBER AND SPACING OF GRID POINTS
C          IN THE X-DIRECTION AND FILLS THE ARRAYS CONTAINING THE
C          EMISSIONS AT EACH LANE LOCATION
C
      DIMENSION SA(24),SB(24),SC(24),X(24),XD(8)
C
C***     CALCULATE THE NUMBER OF LANES ON EACH SIDE OF THE MEDIAN.
C
      MLANE = NLANE/2
C
C***     FILL IN GRID POINTS TO THE LEFT OF THE HIGHWAY.
C
      X(1) = 0.0
      DO 10 I = 1,IR1
         X(I+1) = X(I) + XD(I)
   10 CONTINUE
C
C***     FILL IN GRID POINTS THRU LEFT LANES AND LEFT SIDE OF MEDIAN.
C
      NSTART = IR1 + 2
      NMAX = NSTART + MLANE
      CALL FILLIT (WIDL,NSTART,NMAX,X)
      X(NMAX+1) = X(NMAX) + (RMEDN - WIDL/2)
C
C***     FILL IN EMISSION GRID FOR LEFT LANES.
C
      DO 30 K = 1,MLANE
         SA(IR1+K+1) = QVA
         IF (ICHEM .EQ. 1) GO TO 20
            SB(IR1+K+1) = QVB
            SC(IR1+K+1) = QVC
   20    CONTINUE
   30 CONTINUE
C
C***     FILL IN GRID POINTS THRU RIGHT SIDE OF MEDIAN AND RIGHT LANES.
C
      X(NMAX+2) = X(NMAX+1) + (RMEDN - WIDL/2)
      NSTART = NMAX + 3
      NMAX = NSTART + MLANE
      CALL FILLIT(WIDL,NSTART,NMAX,X)
C
C***     FILL IN EMISSION GRID FOR RIGHT LANES.
C
      INDX = IR1 + MLANE + 3
      DO 50 K = 1,MLANE
         SA(INDX+K+1) = QVA1
         IF (ICHEM .EQ. 1) GO TO 40
            SB(INDX+K+1) = QVB1
            SC(INDX+K+1) = QVC1
   40    CONTINUE
   50 CONTINUE
C
C***     FILL IN GRID POINTS TO THE RIGHT OF THE HIGHWAY.
C
      NSTART = NMAX + 1
      NMAX = NSTART + 8 - IR1 - 1
      K = IR1
      DO 60 I = NSTART,NMAX
         K = K + 1
         X(I) = X(I-1) + XD(K)
   60 CONTINUE
C
      RETURN
      END
C
C=======================================================================
C
      SUBROUTINE FILLIT(ADDTV,IBEG,IEND,POINTX)
C
C        PARAMETER LIST:
C          INPUT:  ADDTV  - THE AMOUNT TO BE ADDED
```

```
C                 IBEG   - BEGINNING INDEX
C                 IEND   - ENDING INDEX
C         I/O:    POINTX - ARRAY TO BE FILLED
C
C       CALLING ROUTINES:
C         WHEREX
C
C       DESCRIPTION:
C         THIS MODULE FILLS IN THE GRID POINTS USING THE SPECIFIED
C         INDICES AND THE SUPPLIED AMOUNT TO BE ADDED.
C
       DIMENSION POINTX(24)
C
      DO 10 K = IBEG,IEND
         POINTX(K) = POINTX(K-1) + ADDTV
   10 CONTINUE
C
      RETURN
      END
C
C======================================================================
C
      SUBROUTINE CENTER(HEAD1,HEAD2,HEAD3,IR1,NLANE,WIDL,X,NX,XV,HWAYL)
C
C       PARAMETER LIST:
C         INPUT:    HEAD1 - 80 CHARACTER TITLE (1ST LINE)
C                   HEAD2 - 80 CHARACTER TITLE (2ND LINE)
C                   HEAD3 - 80 CHARACTER TITLE (3RD LINE)
C                   IR1   - WIND DIRECTION INDICATOR
C                   NLANE - NUMBER OF TRAFFIC LANES (AT LEAST 4; MAXIMUM
C                           OF 10; INCREMENTS OF 2 ONLY)
C                   WIDL  - WIDTH OF ONE LANE (METERS)
C                   X     - GRID POINTS IN THE X DIRECTION.  CONTAINED
C                           IN THIS ARRAY ARE THE LANE LOCATIONS.
C                   NX    - NUMBER OF GRID POINTS IN THE X DIRECTION
C         OUTPUT:   XV    - ARRAY CONTAINING CENTER OF TRAFFIC LANES
C                           (METERS)
C                   HWAYL - OUTPUT ARRAY CONTAINING LANE LOCATIONS
C
C       CALLING ROUTINE:
C         MAIN
C
C       DESCRIPTION:
C         THIS SUBROUTINE DETERMINES THE CENTER OF EACH TRAFFIC LANE.
C         THE X DIRECTION GRID POINTS AND TRAFFIC LANE LOCATIONS ARE
C         OUTPUT HERE.
C
      DIMENSION HEAD1(20),HEAD2(20),HEAD3(20)
      DIMENSION X(24),XV(10),HWAYL(24),HWAYST(24)
      DATA BLNKL/'    '/, BLNKST/' '/, XLANE/'----'/, STAR/'*'/
      DATA IN/5/, IO/6/
C
C***      INITIALIZE.
C
      DO 10 I = 1,24
         HWAYL(I)  = BLNKL
         HWAYST(I) = BLNKST
   10 CONTINUE
C
C***      DETERMINE THE NUMBER OF LANES ON EITHER SIDE OF MEDIAN.
C
      MLANE = NLANE/2
C
C***      FIND THE CENTER OF THE LEFTMOST LANE.
C
      XV(1) =  X(IR1+2)
      HWAYL(IR1+2)  = XLANE
      HWAYST(IR1+2) = STAR
C
C***      FIND THE CENTER OF THE REMAINING LEFT LANES.  FLAG THEIR
C***      LOCATIONS.
C
      I = 0
      DO 20 K = 2,MLANE
         XV(K) = XV(K-1) + WIDL
```

```
            I = I + 1
            HWAYL(IR1+2+I)  = XLANE
            HWAYST(IR1+2+I) = STAR
   20 CONTINUE
C
C***      DETERMINE NEXT ELEMENT TO BE FILLED IN THE LANE CENTER ARRAY
C***      (XV) AND THE CORRESPONDING INDEX IN THE GRID ARRAY (X).
C
      INDX  = MLANE + 1
      INDX2 = MLANE + IR1 + 5
C
C***      FIND THE CENTER OF THE LANE JUST TO THE RIGHT OF THE MEDIAN.
C
      XV(INDX) =  X(INDX2)
C
C***      DETERMINE THE BEGINNING AND ENDING INDICES TO COMPLETE
C***      FILLING THE RIGHT LANE CENTERS.  FILL THE LANE CENTER ARRAY.
C
      IBEG = INDX + 1
      IEND = INDX + MLANE - 1
      HWAYL(INDX2)  = XLANE
      HWAYST(INDX2) = STAR
C
      I = 0
      DO 30 K = IBEG,IEND
         XV(K) = XV(K-1) + WIDL
         I = I + 1
         HWAYL(INDX2 + I)  = XLANE
         HWAYST(INDX2 + I) = STAR
   30 CONTINUE
C
C***      OUTPUT THE X GRID DISTANCES AND LANE LOCATIONS (METERS).
C
      WRITE(IO,1000) HEAD1,HEAD2,HEAD3
      WRITE(IO,1010) (X(K),HWAYST(K), K = 2,NX)
      WRITE(IO,1020)
C
      RETURN
C
C***      FORMAT STATEMENTS.
C
 1000 FORMAT(1H1,'TITLE:  ',20A4,2(/,9X,20A4)/)
 1010 FORMAT(1H0,50X,'GRID POINTS IN X DIRECTION FROM',/,
     1         1X,50X,' LEFT TO RIGHT ACROSS ROADWAY',/,
     2         1X,50X,'              (METERS)',/,
     3        1H0,62X,F5.1,1X,A1,23(/,63X,F5.1,1X,A1))
 1020 FORMAT(1H0,50X,'* INDICATES LOCATION OF TRAFFIC LANE CENTER.')
      END
C
C=======================================================================
C
      SUBROUTINE WAKE(UB,VB,VSPD,VSPD1,H,NV,NV1,WID,X,Z,NX,
     1                KMAX,XV,NLANE,DU,DV,KXP,KZP,KXPAS,KYPAS,KYP,IERR)
C
C         PARAMETER LIST:
C           INPUT:    UB     - VERTICAL PROFILE OF U COMPONENT OF WIND
C                              (M/SEC)
C                     VB     - VERTICAL PROFILE OF V COMPONENT OF WIND
C                              (M/SEC)
C                     VSPD   - AVERAGE VEHICLE SPEED IN SOUTHBOUND LANES
C                              (M/SEC)
C                     VSPD1  - AVERAGE VEHICLE SPEED IN NORTHBOUND LANES
C                              (M/SEC)
C                     H      - AVERAGE HEIGHT OF VEHICLES (METERS)
C                     NV     - SOUTHBOUND TRAFFIC VOLUME (VEH/HR)
C                     NV1    - NORTHBOUND TRAFFIC VOLUME (VEH/HR)
C                     WID    - AVERAGE WIDTH OF VEHICLES (METERS)
C                     X      - GRID POINTS IN THE X DIRECTION (METERS)
C                     Z      - GRID POINTS IN THE Z DIRECTION (METERS)
C                     NX     - NUMBER OF GRID POINTS IN X DIRECTION
C                     KMAX   - NUMBER OF GRID POINTS IN Z DIRECTION
C                     XV     - LANE CENTER ARRAY
C                     NLANE  - NUMBER OF TRAFFIC LANES
C                     DU     - VEHICLE WAKE EFFECTS ON THE U FIELD
C                     DV     - VEHICLE WAKE EFFECTS ON THE V FIELD
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C                  KXP    - WAKE TURBULENCE IN X DIRECTION (M**2/SEC)
C                  KZP    - WAKE TURBULENCE IN Z DIRECTION (M**2/SEC)
C                  KXPAS  - WAKE PASSING EFFECT IN X DIRECTION
C                           (M**2/SEC)
C                  KYPAS  - WAKE PASSING EFFECT IN Y DIRECTION
C                           (M**2/SEC)
C                  KYP    - WAKE TURBULENCE IN Y DIRECTION (M**2/SEC)
C                  IERR   - ERROR INDICATOR (0 = NO ERROR)
C
C       CALLING ROUTINE:
C         MAIN
C
C       SUBPROGRAMS CALLED:
C         FC*, POLY*, SIMPSN
C
C         * INDICATES FUNCTION CALL
C
C       DESCRIPTION:
C         THIS SUBROUTINE CALCULATES THE CHANGES IN THE WIND AND
C         TURBULENCE FIELDS DUE TO THE VEHICLE WAKES.  IT CAN ALSO
C         CALCULATE THE WAKE PASSING EFFECT (ESKRIDGE AND RAO, 1983),
C         BUT IT DOES NOT DO THESE CALCULATIONS NORMALLY.
C
C       DEFINITIONS OF IMPORTANT VARIABLES:
C         ALP    - ANGLE BETWEEN Y-AXIS AND S-AXIS
C         BETA   - ANGLE BETWEEN X-AXIS AND S-AXIS
C         RHO    - DENSITY OF AIR
C         RX     - ARRAY OF X-AXIS GRID POINTS PROJECTED ON R-AXIS
C
      REAL KPX,KPY,NV,NV1,KXP,KZP,KXPAS,KYPAS,OMEGA,KYP
      REAL KXI,KYI,KZI
      DIMENSION KPX(41),KPY(41),UB(8),DV(24,8),VB(8),DU(24,8),XV(10)
      DIMENSION KXP(24,8),KYP(24,8),KZP(24,8),RX(41)
      DIMENSION KXI(41),KYI(41),KZI(41),X(24),Z(8),YV(41)
      DIMENSION S(41),DQ(41),KXPAS(24,8),KYPAS(24,8)
      DATA PI/3.141592654/,GAMA/.095/
      DATA CD/.45/,A1/.048/,A2/.040/,A3/.030/
      DATA IN/5/, IO/6/
C
C***      INITIALIZE.
C
      IWAKEP = 0
C         WAKE PASSING EFFECT TURNED OFF.
      DO 20 I = 1,NX
         DO 10 K = 1,KMAX
            KXP(I,K)   = 0.0
            KZP(I,K)   = 0.0
            KYP(I,K)   = 0.0
            KXPAS(I,K) = 0.0
            KYPAS(I,K) = 0.0
            DU(I,K)    = 0.0
            DV(I,K)    = 0.0
   10    CONTINUE
   20 CONTINUE
      VSP = -VSPD
      FNV = NV
      DO 250 J = 1,NLANE
      IF (J .GT. NLANE/2) VSP = ABS(VSPD1)
      IF (J .GT. NLANE/2) FNV = NV1
      BETA = ATAN(ABS((VSP + VB(2))/UB(2)))
      ALP = 0.5 * PI - ABS(BETA)
C
C***      FOR THE GRID POINT X(I) AND A GIVEN WIND SPEED AND VEHICLE
C***      SPEED THE INTERCEPT OF THE CENTERLINE OF THE WAKE ON THE
C***      Y-AXIS AND THRU X(I) IS DETERMINED.  DELY IS DETERMINED SO
C***      THAT DX WILL PROPERLY RESOLVE THE WAKE AS IT PASSES THE
C***      POINT X(I).
C
C***      AT THE POINT (X,Z) THE INTEGRAL THAT YIELDS THE WAKE
C***      PROPERTIES HAS AN INTEGRATION RANGE OVER WHICH THE FUNCTION
C***      THAT IS BEING INTEGRATED IS MAINLY ZERO.  THEREFORE A MODIFIED
C***      APPROACH IS TAKEN.  AN INTEGRATION RANGE OF (X-2, X+2) AROUND
C***      THE X GRID POINT IS CHOSEN.  ASSUMING WHEN WAKE CENTERLINE IS
C***      OUT OF THIS RANGE THE WAKE DOES NOT HAVE AN EFFECT AT THE
C***      POINT, AND THEN THE POSITION OF THE VEHICLE IS DETERMINED.
```

```
C
      DO 200 I = 1,NX
      XDST = X(I) - XV(J)
      XLRG = 2.
      XDL = XDST - XLRG
      XDR = XDST + 2.
      IF (XDL*XDR .GT. 0.0) GO TO 30
C
C***      CASE WHERE X(I) = XV(J) MUST BE HANDLED SEPARATELY.
C
      IF (UB(2) .LT. 0.0) XDR = -0.1
      IF (UB(2) .LT. 0.0) XLRG = 1.8
      IF (UB(2) .GT. 0.0) XLRG = 0.1
      IF (UB(2) .GT. 0.0) XDL = 0.1
   30 XRNG = ABS(XDR - XDL)
      DX = XRNG * 0.025
      DELY = ABS(DX/TAN(ALP))
      SLOPE = ((VSP + VB(2))/(-UB(2)))
C
C***      TEST TO SEE IF VEHICLE IS UPWIND OF X-AXIS GRID POINT.
C
      B2 = -SLOPE * (X(I))
      YVEH = SLOPE * XV(J) + B2
      IF ((VSP + VB(2)) * YVEH .LT. 0.0) GO TO 200
      DO 50 N = 1,41
         XD = (X(I) - XLRG) + (N-1) * DX
C
C***         Y = SLOPE * X + B0, SOLVE FOR B0 WHICH IS THE Y-AXIS
C***         INTERCEPT, XD IS THE X-AXIS INTERCEPT, Y0 THE VEHICLE
C***         POSITION.  Y = -1/SLOPE + B1 LINE THRU X(I) NORMAL TO
C***         CENTERLINE OF WAKE.
C
         B0 = -SLOPE * XD
         Y0 = SLOPE * XV(J) + B0
         B1 = X(I)/SLOPE
C
C***         INTERSECTION OF THE TWO LINES DETERMINES S AND RX
C***         S  = DIST( (XV(J),Y0),(XI,YI) )
C***         RX = DIST( ( X(I), 0),(XI,YI) )
C
         XI = (B1 - B0)/(SLOPE + 1./SLOPE)
         YI = SLOPE * XI + B0
         S(N)  = SQRT((XI - XV(J))**2 + (Y0 - YI)**2)
         RX(N) = SQRT((X(I) - XI)**2 + YI**2)
   50 CONTINUE
C
C***      THE FOLLOWING CODE DOES THE WAKE CALCULATION AND SUMS THE
C***      EFFECTS OF THE WAKES.
C
      QB = SQRT((VSP + VB(2))**2 + UB(2)**2)
      A = (CD/(32. * PI * EXP(.5) * 1.14 * GAMA**3))**0.25
      DO 150 K = 2,KMAX
         SCALNZ = Z(K)
         IF (Z(K) .GT. 2.45) SCALNZ = 2.45
         DO 100 M = 1,41
            IF (S(M) .LE. 0.0) S(M) = 1.E6
            FAC = 1.0
            IF (ABS(RX(M)) .LT. WID) FAC = 0.48 + 0.52 * ABS(RX(M))/WID
            ZETA = (Z(K)/H)/((S(M)/H)**.25 * GAMA * A)
            IF (ABS(ZETA) .LT. 1.E-20) ZETA = 0.0
            ETA = RX(M)/(1.14 * GAMA * WID * A * (S(M)/H)**.25)
            IF (ABS(ETA) .LT. 1.E-20) ETA = 0.0
            CHI = RX(M)/(WID * (S(M)/H)**.4)
            IF (ABS(CHI) .LT. 1.E-20) CHI = 0.0
            OMEGA = Z(K)/(H * (S(M)/H)**.4)
            IF (ABS(OMEGA) .LT. 1.E-20) OMEGA = 0.0
            KXI(M) = FAC * ((A * QB)**2 * (S(M)/H)**(-1.2) *
     1               (A1 * FC(CHI,OMEGA) * SIN(ALP) + A2 * FC(CHI,OMEGA)
     2               * COS(ALP))) * WID
            KYI(M) = FAC * ((A * QB)**2 * (S(M)/H)**(-1.2) *
     1               (A1 * FC(CHI,OMEGA) * COS(ALP) + A2 * FC(CHI,OMEGA)
     2               * SIN(ALP))) * WID
            KZI(M) = FAC * ((A * QB)**2 * (S(M)/H)**(-1.2) *
     1               A3 * FC(CHI,OMEGA)) * SCALNZ
            DQ(M) = FAC * QB * A * (H/S(M))**0.75 * POLY(ZETA) *
```

```
     1              EXP(-ETA**2/8.)
 100      CONTINUE
          CALL SIMPSN(1,41,DELY,KXI,AN1,IERR)
          IF (IERR .NE. 0) GO TO 999
          CALL SIMPSN(1,41,DELY,KYI,AN2,IERR)
          IF (IERR .NE. 0) GO TO 999
          CALL SIMPSN(1,41,DELY,KZI,AN3,IERR)
          IF (IERR .NE. 0) GO TO 999
          CALL SIMPSN(1,41,DELY,DQ,AN4,IERR)
          IF (IERR .NE. 0) GO TO 999
          KXP(I,K) = KXP(I,K) + FNV * AN1/(3600. * ABS(VSP))
          KYP(I,K) = KYP(I,K) + FNV * AN2/(3600. * ABS(VSP))
          KZP(I,K) = KZP(I,K) + FNV * AN3/(3600. * ABS(VSP))
          DU(I,K) = DU(I,K) - SIGN(1.,UB(2)) * FNV * AN4 * COS(BETA)/
     1              (3600. * ABS(VSP))
          DV(I,K) = DV(I,K) + SIGN(1.,VSP)   * FNV * AN4 * SIN(BETA)/
     1              (3600. * ABS(VSP))
  150 CONTINUE
      DO 170 N = 1,41
          RX(N)  = 0.0
          YV(N)  = 0.0
          KXI(N) = 0.0
          KYI(N) = 0.0
          KZI(N) = 0.0
          S(N)   = 0.0
  170 CONTINUE
  200 CONTINUE
  250 CONTINUE
      IF (IWAKEP .EQ. 0) GO TO 999
C
C***      THE FOLLOWING SECTION OF CODE HAS BEEN IMMOBILIZED VIA IWAKEP.
C***      IT CAN BE USED TO CALCULATE THE WAKE PASSING EFFECTS BY
C***      SETTING IWAKEP TO 1 (SEE FIRST EXECUTABLE STATEMENT IN MODULE)
C
      VSP = -VSPD
      FNV = NV
      DO 650 J = 1,NLANE
      IF (J .GT. NLANE/2) VSP = ABS(VSPD1)
      IF (J .GT. NLANE/2) FNV = NV1
      BETA = ATAN(ABS((VSP + VB(2))/UB(2)))
      ALP = 0.5 * PI - ABS(BETA)
C
C***      AT THE POINT (X,Z) THE INTEGRAL THAT YIELDS THE WAKE
C***      PROPERTIES HAS AN INTEGRATION RANGE OVER WHICH THE FUNCTION
C***      THAT IS BEING INTEGRATED IS MAINLY ZERO.  THERFORE A MODIFIED
C***      APPROACH IS TAKEN.  AN INTEGRATION RANGE OF (X-2, X+2) AROUND
C***      THE X GRID POINT IS CHOSEN, ASSUMING WHEN WAKE CENTERLINE IS
C***      OUT OF THIS RANGE THE WAKE DOES NOT HAVE AN EFFECT AT THE
C***      POINT, AND THEN THE POSITION OF THE VEHICLE IS DETERMINED.
C
      DO 600 I = 1,NX
      XDST = X(I) - XV(J)
      XLRG = 2.0
      XDL = XDST - 2.0
      IF (UB(2) .GT. 0.0) XLRG = 0.1
      XDR = XDST + 2.
      IF (XDL*XDR .GT. 0.0) GO TO 350
C
C***      CASE WHERE X(I) = XV(J) MUST BE HANDLED SEPARATELY.
C
      IF (UB(2) .LT. 0.0) XDR = -0.1
      IF (UB(2) .GT. 0.0) XDL =  0.1
  350 XRNG = ABS(XDR - XDL)
      DX = XRNG * 0.025
      SLOPE = ((VSP + VB(2))/(-UB(2)))
C
C***      TEST TO SEE IF VEHICLE IS UPWIND OF X-AXIS GRID POINT.
C
      B2 = -SLOPE * X(I)
      YVEH = SLOPE * XV(J) + B2
      IF ((VSP+VB(2))*YVEH .LT. 0.0) GO TO 600
      DO 400 N = 1,41
          XD = (X(I) - XLRG) + (N - 1) * DX
C
C***          Y = SLOPE * X + B0, SOLVE FOR B0 WHICH IS THE Y-AXIS
```

```
C***          INTERCEPT, XD IS THE X-AXIS INTERCEPT.
C***          Y = -1/SLOPE + B1 LINE THRU XD NORMAL TO CENTERLINE OF WAKE
C
      B0 = -SLOPE * XD
      Y0 = SLOPE * XV(J) + B0
      B1 = XD/SLOPE
C
C***          INTERSECTION OF THE TWO LINES DETERMINES S AND RX
C***          S  = DIST( (XV(J),Y0),(XI,YI) )
C***          RX = DIST( ( X(I), 0),(XI,YI) )
C
      XI = (B1 - B0)/(SLOPE + 1./SLOPE)
      YI = SLOPE * XI + B0
      S(N)  = SQRT((XI - XV(J))**2 + (Y0 - YI)**2)
      RX(N) = SQRT((X(I) - XI)**2 + YI**2)
  400 CONTINUE
C
C***       THE FOLLOWING CODE DOES THE WAKE PASSING TURBULENCE
C***       CALCULATION.
C
      DO 500 K = 2,KMAX
         DO 450 M = 1,41
            IF (S(M) .LE. 0.0) S(M) = 1.E6
            FAC = 1.0
            IF (ABS(RX(M)) .LT. WID) FAC = 0.48 + 0.52 * ABS(RX(M))/WID
            ZETA = (Z(K)/H)/((S(M)/H)**.25 * GAMA * A)
            IF (ABS(ZETA) .LT. 1.E-20) ZETA = 0.0
            ETA = RX(M)/(1.14 * GAMA * WID * A * (S(M)/H)**.25)
            IF (ABS(ETA) .LT. 1.E-20) ETA = 0.0
            DQ1 = FAC * QB * A * (H/S(M))**0.75 * POLY(ZETA) *
     1            EXP(-ETA**2/8.)
            KPX(M) = ((UB(K) - SIGN(1.,UB(2)) * DQ1 * COS(BETA)) -
     1               (UB(K) + DU(I,K)))**2
            KPY(M) = ((VB(K) + SIGN(1.,VSP)    * DQ1 * SIN(BETA)) -
     1               (VB(K) + DV(I,K)))**2
  450    CONTINUE
         CALL SIMPSN(1,41,DELY,KPX,AN6,IERR)
         IF (IERR .NE. 0) GO TO 999
         CALL SIMPSN(1,41,DELY,KPY,AN7,IERR)
         IF (IERR .NE. 0) GO TO 999
         KXPAS(I,K) = KXPAS(I,K) + FNV * AN6/(3600. * ABS(VSP))
         KYPAS(I,K) = KYPAS(I,K) + FNV * AN7/(3600. * ABS(VSP))
  500 CONTINUE
      DO 520 N = 1,41
         KPX(N) = 0.0
         KPY(N) = 0.0
  520 CONTINUE
  600 CONTINUE
  650 CONTINUE
C
  999 RETURN
      END
C
C======================================================================
C
      FUNCTION FC(Y,Z)
C
C        PARAMETER LIST:
C          INPUT:   Y  - SIMILARITY COORDINATE IN Y DIRECTION
C                   Z  - SIMILARITY COORDINATE IN Z DIRECTION
C          OUTPUT:  FC - TURBULENT KINETIC ENERGY IN THE Y-Z PLANE
C
C        CALLING ROUTINE:
C          WAKE
C
C        DESCRIPTION:
C          THIS FUNCTION DOES A 2-DIMENSIONAL FIT TO WIND TUNNEL DATA
C          OF THE TURBULENT KINETIC ENERGY TERMS IN THE Y-Z PLANE (SEE
C          ESKRIDGE AND THOMPSON, 1982)
C
      DATA A00/ .3511237E-1/, A01/ .1255308E+2/, A02/-.4796241E+2/,
     *     A03/ .6732523E+2/, A04/-.3572466E+2/, A20/-.1890581   /,
     1     A21/-.9345507E+1/, A22/-.1871427E+3/, A23/ .5617911E+3/,
     2     A24/-.3995373E+3/, A40/ .2649465   /, A41/-.9434068E+2/,
     3     A42/ .1034830E+4/, A43/-.2348153E+4/, A44/ .1510437E+4/
```

```
C
      FC = A00 + Z * (A01 + Z * (A02 + Z * (A03 + Z * A04))) +
     1         Y*Y * (A20 + Z * (A21 + Z * (A22 + Z * (A23 + Z * A24))))
     2      + Y**4 * (A40 + Z * (A41 + Z * (A42 + Z * (A43 + Z * A44))))
C
      IF ((ABS(Y) .GE. 0.55) .OR. (ABS(Z) .GE. 0.64)) FC = 0.0
      IF ((Y .LT. 0.0) .AND. (Z .GT. ( 1.82*Y+1.15))) FC = 0.0
      IF ((Y .GT. 0.0) .AND. (Z .GT. (-1.82*Y+1.15))) FC = 0.0
      IF (FC .GT. 1.0) FC = 1.0
C
      RETURN
      END
C
C======================================================================
C
      FUNCTION POLY(Z)
C
C        PARAMETER LIST:
C          INPUT:   Z     - SIMILARITY COORDINATE VALUE IN Z DIRECTION
C          OUTPUT:  POLY  - DETERMINES VERTICAL VARIATION OF WAKE
C                           VELOCITY DEFICIT
C
C        CALLING ROUTINE:
C          WAKE
C
C        DESCRIPTION:
C          THE MODIFIED THEORY OF ESKRIDGE AND THOMPSON WAS STILL
C          INADEQUATE TO DESCRIBE THE VELOCITY DEFICIT BEHIND THE
C          VEHICLES.  THUS, A CURVE FIT WAS MADE TO WIND TUNNEL DATA.
C          CURVE FIT TO NORMALIZED VELOCITY AT X/H=30 OM CENTERLINE.
C
      DATA IN/5/, IO/6/
      POLY =  .0179349 + Z * (2.576587  + Z * (-2.3062584 + Z *
     1       (.8951468 + Z * (-.1758604 + Z * (.016997    - Z *
     2        .0006404)))))
      IF (Z .GT. 8.2) POLY = 0.0
      IF (POLY .GT. 1.1) WRITE(IO,1000) Z,POLY
C
      RETURN
 1000 FORMAT(1X,'ZETA=',F10.5,5X,'UNORM=',F10.5)
      END
C
C======================================================================
C
      SUBROUTINE SIMPSN(M,N,DH,F,ANS,IERR)
C
C        PARAMETER LIST:
C          INPUT:   M     - STARTING INDEX
C                   N     - STOPPING INDEX.  N - M + 1 MUST BE ODD.
C                   DH    - LENGTH OF EQUAL INTERVALS.
C                   F     - ARRAY CONTAINING FUNCTIONAL VALUES TO BE
C                           INTEGRATED
C          OUTPUT:  ANS   - VALUE OF INTEGRAL
C                   IERR  - ERROR INDICATOR (0 = NO ERROR)
C
C        CALLING ROUTINE:
C          WAKE
C
C        DESCRIPTION:
C          THIS MODULE PERFORMS NUMERICAL INTEGRATION USING SIMPSON'S
C          METHOD.
C
      DIMENSION F(N)
      DATA IN/5/, IO/6/
C
C***       TEST FOR M - N + 1 ODD.
C
      ITST = MOD(N-M+1,2)
      IF (ITST .EQ. 1) GO TO 100
         IERR = 20
         WRITE(IO,1000) IERR
         GO TO 999
  100 CONTINUE
C
C***       PERFORM NUMERICAL INTEGRATION.
```

```
C
      SUM = 0.0
      SUM = F(M) + F(N)
      K = 0
      JJ = M + 1
      KK = N - 1
      DO 110 I = JJ,KK,1
         IF (K .EQ. 1) GO TO 105
            SUM = SUM + 4.0 * F(I)
            K = 1
            GO TO 110
  105    CONTINUE
         SUM = SUM + 2.0 * F(I)
         K = 0
  110 CONTINUE
      ANS = SUM * DH/3.
C
  999 RETURN
C
 1000 FORMAT('0*** ERROR ',I2,':  N - M + 1 IS NOT ODD.')
      END
C
C=======================================================================
C
      SUBROUTINE NONDIV(U,NX,KMAX,X,Z,W)
C
C        PARAMETER LIST:
C          INPUT:   U    - U COMPONENT FIELD (M/SEC)
C                   NX   - NUMBER OF GRID POINTS IN X DIRECTION
C                   KMAX - NUMBER OF GRID POINTS IN Z DIRECTION
C                   X    - GRID POINTS IN THE X DIRECTION (METERS)
C                   Z    - GRID POINTS IN THE Z DIRECTION (METERS)
C          OUTPUT:  W    - VERTICAL VELOCITY FIELD (M/SEC)
C
C        CALLING ROUTINE:
C          MAIN
C
C        DESCRIPTION:
C          THE VERTICAL VELOCITY IS COMPUTED BY CALCULATING THE INFLOW
C          AND OUTFLOW IN THE X-DIRECTION FROM THE U FIELD AND THE
C          VERTICAL INFLOW IN THE BOTTOM OF A BOX AROUND EACH GRID
C          POINT.  THE VERTICAL VELOCITY AT THE GRID POINT IS A LINEAR
C          INTERPOLATION OF THE VERTICAL VELOCITY AT THE BOTTOM AND TOP
C          BOUNDARIES OF THE BOX.  TO THE DEGREE THAT THE WIND FIELD
C          CONTAINS DIVERGENCE, ERROR IS INTRODUCED IN THE COMPUTATIONS.
C
      DIMENSION WTOP(24),WBOT(24),X(24),Z(8),W(24,8),U(24,8)
C
      NX1 = NX - 1
      KM = KMAX - 1
      DO 20 K = 2,KM
         DO 10 I = 2,NX1
            X2 = (X(I+1) + X(I)  )/2.
            X1 = (X(I)   + X(I-1))/2.
            DELX = X2 - X1
            U2 = (U(I+1,K) + U(I,K)  )/2.
            U1 = (U(I,K)   + U(I-1,K))/2.
            DELU = U2 - U1
            Z2 = (Z(K+1) + Z(K)  )/2.
            Z1 = (Z(K)   + Z(K-1))/2.
            DELZ = Z2 - Z1
            IF (K .GT. 2) WBOT(I) = WTOP(I)
            IF (K .EQ. 2) WBOT(I) = 0.0
            WTOP(I) = WBOT(I) - DELZ * DELU/DELX
            W(I,K)  = (WTOP(I) + WBOT(I))/2.
   10    CONTINUE
   20 CONTINUE
C
      DO 30 K = 1,KMAX
         W(1,K)  = W(2,K)
         W(NX,K) = W(NX1,K)
   30 CONTINUE
C
      DO 40 I = 1,NX
         W(I,KMAX) = W(I,KMAX-1)
```

```
   40 CONTINUE
C
      RETURN
      END
C
C=======================================================================
C
      SUBROUTINE ADVCHM(SA,SB,SC,A,B,C,D,HWAYL)
C
C        PARAMETER LIST:
C          INPUT:  SA    - NO  EMISSION GRID (G/M**3/SEC).
C                          IF ICHEM = 1, THEN SA IS THE POLLUTANT EMIS-
C                          SION GRID AND SB AND SC ARE IRRELEVANT.
C                  SB    - CO  EMISSION GRID (G/M**3/SEC)
C                  SC    - NO2 EMISSION GRID (G/M**3/SEC)
C                  A     - NO  CONCENTRATION FIELD (PPM).
C                          IF ICHEM = 1, THEN A IS THE POLLUTANT
C                          CONCENTRATION FIELD AND B, C, AND D ARE
C                          IRRELEVANT.
C                  B     - CO  CONCENTRATION FIELD (PPM)
C                  C     - NO2 CONCENTRATION FIELD (PPM)
C                  D     - O3  CONCENTRATION FIELD (PPM)
C                  HWAYL - OUTPUT ARRAY CONTAINING LANE LOCATIONS
C
C        CALLING ROUTINE:
C          MAIN
C
C        SUBPROGRAMS CALLED:
C          TIMINC, BNDRYC, ADU*, BMOVE, ANTU*, ADW*, ANTW*, DIFFX*,
C          DIFFZ*, GRAPH
C
C          *  INDICATES FUNCTION CALL
C
C        DESCRIPTION:
C          THIS MODULE IS A CONTROLLING ROUTINE WHICH CALLS VARIOUS
C          ADVECTION AND DIFFUSION ROUTINES.  THE CHEMICAL CALCULATIONS
C          ARE ALSO PERFORMED HERE.
C
      REAL K1,K2,KXP,KZP,KX,KZ
      DIMENSION AA(24,8),BB(24,8),CC(24,8),DD(24,8)
      DIMENSION AI(24,8),BI(24,8),CI(24,8),DI(24,8)
      DIMENSION U(24,8),W(24,8),A(24,8,2),B(24,8,2)
      DIMENSION KXP(24,8),KZP(24,8),C(24,8,2),D(24,8,2)
      DIMENSION SA(24),SB(24),SC(24),DUMMY(24),X(24),Z(8),KX(8),KZ(8)
      DIMENSION HEAD1(20),HEAD2(20),HEAD3(20)
      DIMENSION HWAYL(24)
      COMMON /CALCOM/U,W,KMAX,KX,KZ,X,Z,TMSTOP,NX,KXP,KZP
      COMMON /INCOM/ BACKGA,BACKGB,BACKGC,BACKGD,CNA,CNB,CNC,CND,EMA,
     1               EMA1,EMB,EMB1,EMC,EMC1,K1,K2,MEDN,NVEH,NVEH1,
     2               RDANGL,T1,T2,VHGH,VWID,VSPD,VSPD1,WD,WIDL,WSPD,
     3               Z0,Z1,Z2,HEAD1,HEAD2,HEAD3,IANTI,ICHEM,INTPR,NLANE
      DATA N/1/,NP/2/
      DATA BB/192*0./,CC/192*0./,DD/192*0./,BI/192*0./,CI/192*0./
      DATA DI/192*0./
      DATA DUMMY/24*0./
      DATA IN/5/, IO/6/
C
C***     FIND MAXIMUM VELOCITY AND THEN DETERMINE THE ADVECTIVE AND
C***     CHEMICAL TIME STEPS.
C
      JTEST = 1
      IF (WD .LE. 180.) JTEST = 2
      CALL TIMINC(ICHEM,K1,K2,DTADV,DTCHM,NUMCHM)
      NZ1 = KMAX - 1
      NX1 = NX - 1
      IPRINT = 0
      NPRINT = (TMSTOP/4.)/DTADV + 1
      TIME = DTADV
      KOUNTP = 0
C
C***     ESTABLISH BACKGROUND VALUES OF POLLUTANTS.
C
      DO 50 I = 1,NX
         DO 40 J = 1,KMAX
            DO 30 K = 1,2
```

```
               A(I,J,K) = BACKGA
               IF (ICHEM .EQ. 1) GO TO 20
                  B(I,J,K) = BACKGB
                  C(I,J,K) = BACKGC
                  D(I,J,K) = BACKGD
   20          CONTINUE
   30       CONTINUE
   40    CONTINUE
   50 CONTINUE
C
C***      THE ADVECTION CALCULATION IS PERFORMED USING FRACTIONAL
C***      STEPS.  THE PROCEDURE USED IN THIS PRGRAM IS TO:  FIRST,
C***      CALCULATE THE ADVECTION, SECOND DO A FLUX CORRECTION.
C
C***      CALCULATE ADVECTION ALONG THE X-AXIS AND ADD EMISSIONS.
C
  100 DO 120 I = 1,NX
         A(I,2,N) = A(I,2,N) + SA(I) * DTADV * CNA
         IF (ICHEM .EQ. 1) GO TO 110
            B(I,2,N) = B(I,2,N) + SB(I) * DTADV * CNB
            C(I,2,N) = C(I,2,N) + SC(I) * DTADV * CNC
  110    CONTINUE
  120 CONTINUE
C
      CALL BNDRYC(BACKGA,N,NX,KMAX,JTEST,A)
      IF (ICHEM .EQ. 1) GO TO 150
         CALL BNDRYC(BACKGB,N,NX,KMAX,JTEST,B)
         CALL BNDRYC(BACKGC,N,NX,KMAX,JTEST,C)
         CALL BNDRYC(BACKGD,N,NX,KMAX,JTEST,D)
  150 CONTINUE
C
      DO 200 K = 2,NZ1
         DO 190 I = 2,NX1
            AA(I,K) = ADU(A,N,U,X,DTADV,I,K)
            IF (ICHEM .EQ. 1) GO TO 180
               BB(I,K) = ADU(B,N,U,X,DTADV,I,K)
               CC(I,K) = ADU(C,N,U,X,DTADV,I,K)
               DD(I,K) = ADU(D,N,U,X,DTADV,I,K)
  180       CONTINUE
  190    CONTINUE
  200 CONTINUE
C
C***      SET SIDE AND TOP BOUNDARY CONDITIONS.
C
      CALL BNDRYC(BACKGA,1,NX,KMAX,JTEST,AA)
      IF (ICHEM .EQ. 1) GO TO 210
         CALL BNDRYC(BACKGB,1,NX,KMAX,JTEST,BB)
         CALL BNDRYC(BACKGC,1,NX,KMAX,JTEST,CC)
         CALL BNDRYC(BACKGD,1,NX,KMAX,JTEST,DD)
  210 CONTINUE
C
C***      THE FLUX LIMITER CALCULATION ELIMINATES MOST OF THE ARTIFICAL
C***      DIFFUSION.
C
      IF (IANTI .EQ. 0) GO TO 225
         CALL BMOVE(AA,192,AI)
         IF (ICHEM .EQ. 1) GO TO 220
            CALL BMOVE(BB,192,BI)
            CALL BMOVE(CC,192,CI)
            CALL BMOVE(DD,192,DI)
  220    CONTINUE
      GO TO 260
  225 CONTINUE
C
      DO 250 K = 2,NZ1
         DO 240 I = 2,NX1
            AI(I,K) = ANTU(AA,U,X,I,K,DTADV,A,N,NX,SA)
            IF (ICHEM .EQ. 1) GO TO 230
               BI(I,K) = ANTU(BB,U,X,I,K,DTADV,B,N,NX,SB)
               CI(I,K) = ANTU(CC,U,X,I,K,DTADV,C,N,NX,SC)
               DI(I,K) = ANTU(DD,U,X,I,K,DTADV,D,N,NX,DUMMY)
  230       CONTINUE
  240    CONTINUE
  250 CONTINUE
C
```

```
C***      SET SIDE AND TOP BOUNDARY CONDITIONS.
C
      CALL BNDRYC(BACKGA,1,NX,KMAX,JTEST,AI)
      IF (ICHEM .EQ. 1) GO TO 260
         CALL BNDRYC(BACKGB,1,NX,KMAX,JTEST,BI)
         CALL BNDRYC(BACKGC,1,NX,KMAX,JTEST,CI)
         CALL BNDRYC(BACKGD,1,NX,KMAX,JTEST,DI)
  260 CONTINUE
C
C***      CALCULATE ADVECTION IN Z DIRECTION.
C
      DO 300 K = 2,NZ1
         DO 290 I = 2,NX1
            AA(I,K) = ADW(AI,W,Z,DTADV,I,K)
            IF (ICHEM .EQ. 1) GO TO 280
               BB(I,K) = ADW(BI,W,Z,DTADV,I,K)
               CC(I,K) = ADW(CI,W,Z,DTADV,I,K)
               DD(I,K) = ADW(DI,W,Z,DTADV,I,K)
  280       CONTINUE
  290    CONTINUE
  300 CONTINUE
C
C***      SET SIDE AND TOP BOUNDARY CONDITIONS.
C
      CALL BNDRYC(BACKGA,1,NX,KMAX,JTEST,AA)
      IF (ICHEM .EQ. 1) GO TO 310
         CALL BNDRYC(BACKGB,1,NX,KMAX,JTEST,BB)
         CALL BNDRYC(BACKGC,1,NX,KMAX,JTEST,CC)
         CALL BNDRYC(BACKGD,1,NX,KMAX,JTEST,DD)
  310 CONTINUE
C
C***      ANTIDIFFUSION CALCULATION FOR Z-AXIS.
C
      IF (IANTI .EQ. 0) GO TO 325
         CALL BMOVE(AA,192,AI)
         IF (ICHEM .EQ. 1) GO TO 320
            CALL BMOVE(BB,192,BI)
            CALL BMOVE(CC,192,CI)
            CALL BMOVE(DD,192,DI)
  320    CONTINUE
         GO TO 360
  325 CONTINUE
C
      DO 350 I = 2,NX1
         DO 340 K = 2,KMAX
            AI(I,K) = ANTW(AA,W,Z,I,K,DTADV,AI,KMAX)
            IF (ICHEM .EQ. 1) GO TO 330
               BI(I,K) = ANTW(BB,W,Z,I,K,DTADV,BI,KMAX)
               CI(I,K) = ANTW(CC,W,Z,I,K,DTADV,CI,KMAX)
               DI(I,K) = ANTW(DD,W,Z,I,K,DTADV,DI,KMAX)
  330       CONTINUE
  340    CONTINUE
  350 CONTINUE
C
C***      SET SIDE AND TOP BOUNDARY CONDITIONS.
C
      CALL BNDRYC(BACKGA,1,NX,KMAX,JTEST,AI)
      IF (ICHEM .EQ. 1) GO TO 360
         CALL BNDRYC(BACKGB,1,NX,KMAX,JTEST,BI)
         CALL BNDRYC(BACKGC,1,NX,KMAX,JTEST,CI)
         CALL BNDRYC(BACKGD,1,NX,KMAX,JTEST,DI)
  360 CONTINUE
C
C***      CALCULATION DIFFUSION IN X DIRECTION.
C
      DO 400 I = 2,NX1
         DO 390 K = 2,NZ1
            AA(I,K) = AI(I,K) + DIFFX(AI,X,DTADV,I,K,KXP)
            IF (ICHEM .EQ. 1) GO TO 370
               BB(I,K) = BI(I,K) + DIFFX(BI,X,DTADV,I,K,KXP)
               CC(I,K) = CI(I,K) + DIFFX(CI,X,DTADV,I,K,KXP)
               DD(I,K) = DI(I,K) + DIFFX(DI,X,DTADV,I,K,KXP)
  370       CONTINUE
  390    CONTINUE
  400 CONTINUE
```

```
C
C***      SET SIDE AND TOP BOUNDARY CONDITIONS.
C
      CALL BNDRYC(BACKGA,1,NX,KMAX,JTEST,AA)
      IF (ICHEM .EQ. 1) GO TO 410
         CALL BNDRYC(BACKGB,1,NX,KMAX,JTEST,BB)
         CALL BNDRYC(BACKGC,1,NX,KMAX,JTEST,CC)
         CALL BNDRYC(BACKGD,1,NX,KMAX,JTEST,DD)
  410 CONTINUE
C
C***      CALCULATION DIFFUSION IN Z DIRECTION.
C
      DO 450 I = 2,NX1
         DO 440 K = 2,NZ1
            AI(I,K) = AA(I,K) + DIFFZ(AA,Z,DTADV,I,K,KZP)
            IF (ICHEM .EQ. 1) GO TO 430
               BI(I,K) = BB(I,K) + DIFFZ(BB,Z,DTADV,I,K,KZP)
               CI(I,K) = CC(I,K) + DIFFZ(CC,Z,DTADV,I,K,KZP)
               DI(I,K) = DD(I,K) + DIFFZ(DD,Z,DTADV,I,K,KZP)
  430       CONTINUE
  440    CONTINUE
  450 CONTINUE
C
C***      SET SIDE AND TOP BOUNDARY CONDITIONS.
C
      CALL BNDRYC(BACKGA,1,NX,KMAX,JTEST,AI)
      IF (ICHEM .EQ. 1) GO TO 460
         CALL BNDRYC(BACKGB,1,NX,KMAX,JTEST,BI)
         CALL BNDRYC(BACKGC,1,NX,KMAX,JTEST,CI)
         CALL BNDRYC(BACKGD,1,NX,KMAX,JTEST,DI)
  460 CONTINUE
C
C***      DO ROADWAY CHEMISTRY VIA EXPLICIT METHOD FOR NO, NO2, O3, CO
C***      NUMERICAL STABILITY FOR THE CHEMICAL CALCULATIONS GENERALLY
C***      REQUIRES A SMALLER TIME STEP THAN THE ADVECTION TIME STEP.
C***      HENCE THE METHOD IS TO DO THE ADVECTION AND THEN DO THE
C***      CHEMISTRY IN SMALLER TIME STEPS TO CATCH UP (SEE ESKRIDGE
C***      AND DEMERJIAN, 1977 ATMOS. ENVIRONM.).
C
      IF (ICHEM .EQ. 1) GO TO 540
      DO 530 L = 1,NUMCHM
         DO 520 I = 2,NX1
            DO 510 K = 2,NZ1
               A(I,K,NP) = AI(I,K) + DTCHM *
     1                  (-K1 * DI(I,K) * AI(I,K) + K2 * CI(I,K))
               B(I,K,NP) = BI(I,K)
               C(I,K,NP) = CI(I,K) + DTCHM *
     1                  ( K1 * AI(I,K) * DI(I,K) - K2 * CI(I,K))
               D(I,K,NP) = DI(I,K) + DTCHM *
     1                  (-K1 * DI(I,K) * AI(I,K) + K2 * CI(I,K))
C
               AI(I,K) = A(I,K,NP)
               BI(I,K) = B(I,K,NP)
               CI(I,K) = C(I,K,NP)
               DI(I,K) = D(I,K,NP)
  510       CONTINUE
  520    CONTINUE
  530 CONTINUE
      CALL BNDRYC(BACKGA,NP,NX,KMAX,JTEST,A)
      CALL BNDRYC(BACKGB,NP,NX,KMAX,JTEST,B)
      CALL BNDRYC(BACKGC,NP,NX,KMAX,JTEST,C)
      CALL BNDRYC(BACKGD,NP,NX,KMAX,JTEST,D)
      GO TO 560
C
C***
C
  540 DO 560 I = 1,NX
         DO 550 K = 1,KMAX
            A(I,K,NP) = AI(I,K)
  550    CONTINUE
  560 CONTINUE
C
C***      PRINT INTERMEDIATE RESULTS.
C
      IF (ICHEM .EQ. 1) GO TO 585
```

```
      IF(IPRINT .LT. NPRINT) GO TO 580
         IF (INTPR .NE. 0) GO TO 570
            WRITE(IO,1000) HEAD1,HEAD2,HEAD3
            WRITE(IO,1010)
            CALL GRAPH(A,NP,TIME,NX,KMAX,X,HWAYL)
            WRITE(IO,1020)
            CALL GRAPH(B,NP,TIME,NX,KMAX,X,HWAYL)
            WRITE(IO,1030)
            CALL GRAPH(C,NP,TIME,NX,KMAX,X,HWAYL)
            WRITE(IO,1000) HEAD1,HEAD2,HEAD3
            WRITE(IO,1040)
            CALL GRAPH(D,NP,TIME,NX,KMAX,X,HWAYL)
  570    CONTINUE
         IPRINT = 0
  580 CONTINUE
      GO TO 600
C
  585 IF (IPRINT .LT. NPRINT) GO TO 600
         IF (INTPR .EQ. 1) GO TO 595
            IF (KOUNTP/4*4 .NE. KOUNTP) GO TO 590
            WRITE(IO,1000) HEAD1,HEAD2,HEAD3
  590       WRITE(IO,1050)
            CALL GRAPH(A,NP,TIME,NX,KMAX,X,HWAYL)
            KOUNTP = KOUNTP + 1
  595    CONTINUE
         IPRINT = 0
  600 CONTINUE
C
C***
C
      NP = NP + 1
      IF (NP .EQ. 3) NP = 1
      N = N + 1
      IF (N .EQ. 3) N = 1
      TIME = TIME + DTADV
      IF (TIME .GE. TMSTOP) GO TO 700
         IPRINT = IPRINT + 1
         GO TO 100
  700 CONTINUE
      NP = NP - 1
      IF (NP .EQ. 0) NP = 2
C
C***      PRINT FINAL RESULTS.
C
      IF (ICHEM .EQ. 1) GO TO 750
         WRITE(IO,1000) HEAD1,HEAD2,HEAD3
         WRITE(IO,1010)
         CALL GRAPH(A,NP,TIME,NX,KMAX,X,HWAYL)
         WRITE(IO,1020)
         CALL GRAPH(B,NP,TIME,NX,KMAX,X,HWAYL)
         WRITE(IO,1030)
         CALL GRAPH(C,NP,TIME,NX,KMAX,X,HWAYL)
         WRITE(IO,1000) HEAD1,HEAD2,HEAD3
         WRITE(IO,1040)
         CALL GRAPH(D,NP,TIME,NX,KMAX,X,HWAYL)
         GO TO 999
  750 CONTINUE
C
      WRITE(IO,1000) HEAD1,HEAD2,HEAD3
      WRITE(IO,1050)
      CALL GRAPH(A,NP,TIME,NX,KMAX,X,HWAYL)
C
  999 RETURN
C
C***      FORMAT STATMENTS.
C
 1000 FORMAT(1H1,'TITLE:  ',20A4,2(/,9X,20A4)/)
 1010 FORMAT(1H0,'NITROGEN OXIDE, NO (PPM)')
 1020 FORMAT(1H0,'CARBON MONOXIDE, CO (PPM)')
 1030 FORMAT(1H0,'NITROGEN DIXOIDE, NO2 (PPM)')
 1040 FORMAT(1H0,'OZONE, O3 (PPM)')
 1050 FORMAT(1H0,'POLLUTANT CONCENTRATIONS (PPM)')
      END
C
C=======================================================================
```

```
C
      SUBROUTINE TIMINC(ICHEM,K1,K2,DTADV,DTCHM,NUMCHM)
C
C        PARAMETER LIST:
C          INPUT:   ICHEM   - CHEMISTRY OPTION (IF ICHEM = 1, THEN K1,
C                             K2, DTCHM, AND NUMCHM ARE IRRELEVANT)
C                   K1      - CHEMICAL REACTION RATE (1/(PPM MIN) FOR:
C                             NO  + O3 ---• NO2 + O2
C                   K2      - CHEMICAL REACTION RATE (1/MIN) FOR:
C                             NO2 + O2 ---• NO  + O3
C          OUTPUT:  DTADV   - ADVECTIVE/DIFFUSION TIME STEP (SEC)
C                   DTCHM   - CHEMICAL REACTION TIME STEP (SEC)
C                   NUMCHM  - NUMBER OF CHEMICAL REACTION TIME STEPS PER
C                             ADVECTIVE/DIFFUSION TIME STEP
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THIS SUBROUTINE FINDS THE MAXIMUM ALLOWABLE TIME STEP FOR
C          ADVECTIVE AND DIFFUSION TO ASSURE STABILITY.  IT ALSO
C          DETERMINES THE CHEMICAL REACTION TIME STEP AND THE NUMBER OF
C          TIME STEPS PER ADVECTIVE/DIFFUSION TIME STEP.
C
      REAL KXP,KZP,KX,KZ,K1,K2
      DIMENSION X(24),Z(8),KXP(24,8),KZP(24,8),U(24,8),W(24,8),KX(8)
      DIMENSION KZ(8)
      COMMON /CALCOM/U,W,KMAX,KX,KZ,X,Z,TMSTOP,NX,KXP,KZP
C
      DT1 = 1000.
      DT2 = 1000.
      DT3 = 1000.
      DT4 = 1000.
      DO 20 I = 2,NX
         DO 10 K = 2,KMAX
            DX = X(I) - X(I-1)
            DZ = Z(K) - Z(K-1)
            D1 = 0.95 * DX/ABS(U(I,K))
            IF (D1 .LT. DT1) DT1 = D1
            D3 = 0.5 * DZ * DZ/KZP(I,K)
            IF (D3 .LT. DT3) DT3 = D3
            D4 = 0.5 * DX * DX/KXP(I,K)
            IF (D4 .LT. DT4) DT4 = D4
   10    CONTINUE
   20 CONTINUE
C
      DTADV = AMIN1(DT1,DT3,DT4)
      IF (ICHEM .EQ. 1) GO TO 30
         FK = AMAX1(K1,K2)
         DTCHM = 1./FK
         NUMCHM = DTADV/DTCHM + 1.
         DTCHM = DTADV/FLOAT(NUMCHM)
   30 CONTINUE
C
      RETURN
      END
C
C======================================================================
C
      SUBROUTINE BNDRYC(BACKGR,L,NX,KMAX,JTEST,RHO)
C
C        PARAMETER LIST:
C          INPUT:  BACKGR - BACKGROUND POLLUTANT CONCENTRATIONS (PPM)
C                  L      - INDEX
C                  NX     - NUMBER OF GRID POINTS IN X DIRECTION
C                  KMAX   - NUMBER OF GRID POINTS IN Z DIRECTION
C                  JTEST  - WIND DIRECTION INDICATOR
C          I/O:    RHO    - ARRAY FOR WHICH BOUNDARY CONDITIONS ARE TO
C                           BE ESTABLISHED
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THIS SUBROUTINE ESTABLISHES BOUNDARY CONDITIONS FOR A
```

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C          POLLUTANT DURING THE MARCHING PROCESS.
C
      DIMENSION RHO(24,8,2)
C
C***       LOWER BOUNDARY CONDITION IS THAT THE GRADIENT IS ZERO.
C
      DO 10 I = 1,NX
         RHO(I,1,L) = RHO(I,2,L)
   10 CONTINUE
C
C***       TOP BOUNDARY ASSUMES BACKGROUND.
C
      DO 110 I = 1,NX
         RHO(I,KMAX,L) = BACKGR
  110 CONTINUE
C
C***       THE OUTFLOW CONDITIONS ARE JUST AN EXTROPLATION OF INSIDE
C***       VALUE TO THE BOUNDARY POINTS ASSUMING EQUAL GRADIENT OF
C***       POLLUTANT.
C
      IF (JTEST .EQ. 1) GO TO 300
C
C***       SET OUTFLOW  CONDITION TO CONSTANT GRADIENT AT WEST
C***       BOUNDARY INFLOW TO BACKGROUND.
C
      DO 210 K = 2,KMAX
         RHO( 1,K,L) = RHO(2,K,L)
         RHO(NX,K,L) = BACKGR
  210 CONTINUE
      GO TO 999
C
C***       SET OUTFLOW  CONDITION TO CONSTANT GRADIENT AT EAST BOUNDARY
C***       BOUNDARY INFLOW TO BACKGROUND
C
  300 DO 310 K = 2,KMAX
         RHO(NX,K,L) = RHO(NX-1,K,L)
         RHO( 1,K,L) = BACKGR
  310 CONTINUE
C
  999 RETURN
      END
C
C=====================================================================
C
      FUNCTION ADU(RHO,L,U,X,DT,I,K)
C
C        PARAMETER LIST:
C          INPUT:   RHO - ARRAY OF SUBSTANCE TO BE ADVECTED (PPM)
C                   L   - LIMITING INDEX (TIME LEVEL 1 OR 2)
C                   U   - U COMPONENT FIELD (M/SEC)
C                   X   - GRID POINTS IN X DIRECTION (METERS)
C                   DT  - ADVECTIVE TIME STEP (SEC)
C                   I   - INDEX FOR X DIRECTION
C                   K   - INDEX FOR Z DIRECTION
C          OUTPUT:  ADU - CONCENTRATION FIELD ADVECTED IN X DIRECTION
C                         FOR ONE TIME STEP
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          TRANSPORT IN THE X DIRECTION IS DETERMINED USING AN UPSTREAM
C          FLUX CORRECTED METHOD.  THE METHOD IS PREFERRED SINCE ONLY
C          ONE BOUNDARY POINT IS REQUIRED.
C
      DIMENSION X(24),RHO(24,8,2),U(24,8)
C
C * * * * * * * * * * * * * STATEMENT FUNCTIONS * * * * * * * * * * * * *
C
      DX(I) = X(I) - X(I-1)
      XL(I,K) = X(I) + U(I,K) * DT
      UP(I,K) = .5 * (U(I,K) + U(I+1,K))
      RHOP(I,K) = (RHO(I,K,L)) * DX(I+1)/(XL(I+1,K) - XL(I,K))
      RHOM(I,K) = (RHO(I,K,L)) * DX(I)  /(XL(I,K)   - XL(I-1,K))
C
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      IF (UP(I,K) .GE. 0.0) GO TO 10
         DMP = UP(I,K) * DT * RHOM(I+1,K)
         GO TO 20
   10 CONTINUE
         DMP = UP(I,K) * DT * RHOP(I,K)
   20 CONTINUE
C
      IF(UP(I-1,K).GE. 0.0) GO TO 110
         DMM = UP(I-1,K) * DT * RHOM(I,K)
         GO TO 120
  110 CONTINUE
         DMM = UP(I-1,K) * DT * RHOP(I-1,K)
  120 CONTINUE
C
      FM = RHO(I,K,L) * .5 * (DX(I+1) + DX(I))
      ADU = (FM + DMM - DMP)/(.5 * (DX(I+1) + DX(I)))
C
      RETURN
      END
C
C======================================================================
C
      SUBROUTINE BMOVE(A,N,B)
C
C        PARAMETER LIST:
C          INPUT:   A - ARRAY USED FOR INITIALIZATION
C                   N - ENDING INDEX
C          OUTPUT:  B - ARRAY TO BE INITIALIZED
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THE PURPOSE OF THIS MODULE IS TO INITIALIZE AN ARRAY.
C
      DIMENSION A(N),B(N)
C
      DO 10 I = 1,N
         B(I) = A(I)
   10 CONTINUE
C
      RETURN
      END
C
C======================================================================
C
      FUNCTION ANTU(RHOT,U,X,I,K,DT,RHO,L,NX,S)
C
C        PARAMETER LIST:
C          INPUT:   RHOT - POLLUTION FIELD WHICH HAS BEEN ADVECTED IN
C                          X DIRECTION
C                   U    - U COMPONENT FIELD (M/SEC)
C                   X    - GRID POINTS IN X DIRECTION (METERS)
C                   I    - INDEX FOR X DIRECTION
C                   K    - INDEX FOR Z DIRECTION
C                   DT   - ADVECTIVE TIME STEP (SEC)
C                   RHO  - POLLUTANT FIELD (PPM) WITHOUT ADVECTION IN
C                          X DIRECTION
C                   L    - LIMITING INDEX
C                   NX   - NUMBER OF GRID POINTS IN X DIRECTION
C                   S    - EMISSION GRID (G/M**3/SEC)
C          OUTPUT:  ANTU - NUMERICAL DISPERSION TENDS TO "DIFFUSE" THE
C                          CONCENTRATION FIELDS ARTIFICIALLY, THE OUTPUT
C                          OF THIS FUNCTION IS THE CONCENTRATION FIELD
C                          WITH "MOST" OF THE NUMERICAL DISPERSION
C                          REMOVED
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THIS FUNCTION PERFORMS THE ANTIDIFFUSION OR FLUX LIMITER
C          CALCULATION.
```

```
C
      DIMENSION S(24),X(24),RHOT(24,8),U(24,8),RHO(24,8,2)
C
C * * * * * * * * * * * * * STATEMENT FUNCTIONS * * * * * * * * * * * * *
C
      DX(I) = X(I) - X(I-1)
      XL(I,K) = X(I) + U(I,K) * DT
      UP(I,K) = .5 * (U(I,K) + U(I+1,K))
      RHOP(I,K) = (RHO(I,K,L) + F * DT * S(I))    * DX(I+1)/
     1            (XL(I+1,K) - XL(I,K))
      RHOM(I,K) = (RHO(I,K,L) + F * DT * S(I-1)) * DX(I)  /
     1            (XL(I,K)    - XL(I-1,K))
      ASP(I,K) = (RHOM(I+1,K) - RHOP(I,K)) * .5 * DT * ABS(UP(I,K)) *
     1           (1.-DT * ABS(UP(I,K))/(XL(I+1,K) - XL(I,K)))
      DEL(I,K) = RHOT(I+1,K) - RHOT(I,K)
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      F = 1.
      IF (K .GT. 2) F = 0.0
      NX1 = NX - 1
      X1 = SIGN(1.,ASP(I,K))
      Y1 = SIGN(1.,ASP(I-1,K))
      ZZ1 = 0.0
      IF (I .LT. NX1) ZZ1 = DEL(I+1,K)
      ZZ2 = 0.0
      IF (I .GT. 2) ZZ2 = DEL(I-1,K)
      XX = X1 * AMAX1(0.0,AMIN1(X1 * ZZ2 * (.5 * (X(I+1) - X(I-1))),
     1          ABS(ASP(I,K)),X1 * ZZ1 * (.5 * (X(I+2) - X(I)))))
C
      IF (I .GT. 2) GO TO 10
         Z1 = 0.0
         Z2 = X(2) - X(1)
         GO TO 20
   10 CONTINUE
         Z1 = DEL(I-2,K)
         Z2 = .5 * (X(I) - X(I-2))
   20 CONTINUE
C
      Y = Y1 * AMAX1(0.0,AMIN1(Y1 * Z1 * (Z2),
     1       ABS(ASP(I-1,K)),Y1 * DEL(I,K) * (.5 * (X(I+1) - X(I-1)))))
      ANTU = RHOT(I,K) + (Y -XX)/(.5 * (X(I+1) - X(I-1)))
C
      RETURN
      END
C
C=======================================================================
C
      FUNCTION ADW(RHO,W,Z,DT,I,K)
C
C        PARAMETER LIST:
C          INPUT:    RHO - POLLUTANT CONCENTRATION FIELD (PPM)
C                    W   - W COMPONENT FIELD (M/SEC)
C                    Z   - GRID POINTS IN Z DIRECTION (METERS)
C                    DT  - ADVECTIVE TIME STEP (SEC)
C                    I   - INDEX FOR X DIRECTION
C                    K   - INDEX FOR Z DIRECTION
C          OUTPUT:   ADW - POLLUTANT CONCENTRATION FIELD (PPM) ADVECTED
C                          IN Z DIRECTION FOR ONE TIME STEP
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THIS FUNCTION CALCULATES TRANSPORT IN THE Z DIRECTION USING
C          AN UPSTREAM FLUX CORRECTED METHOD.  THE METHOD IS PREFERRED
C          SINCE ONLY ONE BOUNDRY POINT IS NEEDED.
C
      DIMENSION Z(8),RHO(24,8),W(24,8)
C
C * * * * * * * * * * * * * STATEMENT FUNCTIONS * * * * * * * * * * * * *
C
      DZ(K) = Z(K) - Z(K-1)
      ZL(I,K) = Z(K) + W(I,K) * DT
      WP(I,K) = .5 * (W(I,K) + W(I,K+1))
```

```
      RHOP(I,K) = RHO(I,K) * DZ(K+1)/(ZL(I,K+1) - ZL(I,K))
      RHOM(I,K) = RHO(I,K) * DZ(K)  /(ZL(I,K)   - ZL(I,K-1))
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      IF (WP(I,K) .GE. 0.0) GO TO 10
         DMP = WP(I,K) * DT * RHOM(I,K+1)
         GO TO 20
   10 CONTINUE
         DMP = WP(I,K) * DT * RHOP(I,K)
   20 CONTINUE
C
      IF (WP(I,K-1) .GE. 0.0) GO TO 110
         DMM = WP(I,K-1) * DT * RHOM(I,K)
         GO TO 120
  110 CONTINUE
         DMM = WP(I,K-1) * DT * RHOP(I,K-1)
  120 CONTINUE
C
      FM = RHO(I,K) * .5 * (DZ(K+1) + DZ(K))
      ADW = (FM + DMM - DMP)/(.5 * (DZ(K+1) + DZ(K)))
C
      RETURN
      END
C
C=======================================================================
C
      FUNCTION ANTW(RHOT,W,Z,I,K,DT,RHO,KMAX)
C
C        PARAMETER LIST:
C          INPUT:    RHOT - CONCENTRATION FIELD WHICH HAS BEEN ADVECTED
C                           IN Z DIRECTION
C                    W    - W COMPONENT FIELD (M/SEC)
C                    Z    - GRID POINTS IN Z DIRECTION (METERS)
C                    I    - INDEX FOR X DIRECTION
C                    K    - INDEX FOR Z DIRECTION
C                    DT   - ADVECTIVE TIME STEP
C                    RHO  - CONCENTRATION FIELD WITHOUT ADVECTION IN
C                           Z DIRECTION
C                    KMAX - NUMBER OF GRID POINTS IN Z DIRECTION
C          OUTPUT:   ANTW - NUMERICAL DISPERSION TENDS TO "DIFFUSE" THE
C                           CONCENTRATION FIELDS ARTIFICIALLY, THE OUTPUT
C                           OF THIS FUNCTION IS THE CONCENTRATION FIELD
C                           WITH "MOST" OF THE NUMERICAL DISPERSION
C                           REMOVED
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THIS FUNCTION PERFORMS THE ANTIDIFFUSION OR FLUX DELIMITER
C          CALCULATION.
C
      DIMENSION Z(24),RHOT(24,8),W(24,8),RHO(24,8)
C
C * * * * * * * * * * * * STATEMENT FUNCTIONS * * * * * * * * * * * * *
C
      DZ(K) = Z(K) - Z(K-1)
      ZL(I,K) = Z(K) + W(I,K) * DT
      WP(I,K)= .5 * (W(I,K) + W(I,K+1))
      RHOP(I,K) = RHO(I,K) * DZ(K+1)/(ZL(I,K+1) - ZL(I,K))
      RHOM(I,K) = RHO(I,K) * DZ(K)  /(ZL(I,K)   - ZL(I,K-1))
      ASP(I,K) = (RHOM(I,K+1) - RHOP(I,K)) * .5 * DT * ABS(WP(I,K)) *
     1           (1. - DT * ABS(WP(I,K))/(ZL(I,K+1) - ZL(I,K)))
      DEL(I,K) = RHOT(I,K+1) - RHOT(I,K)
C
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
      KMAX1 = KMAX - 1
      X1 = SIGN(1.,ASP(I,K))
      Y1 = SIGN(1.,ASP(I,K-1))
      ZZ1 = 0.0
      IF (K .LT. KMAX1) ZZ1 = DEL(I,K+1)
      ZZ2 = 0.0
      IF (K .GT. 2) ZZ2 = DEL(I,K-1)
```

```
      XX = X1 * AMAX1(0.0,AMIN1(X1 * ZZ2 * (.5 * (Z(K+1) - Z(K-1))),
     1             ABS(ASP(I,K)),X1 * ZZ1 * (.5 * (Z(K+2) - Z(K)))))
C
      IF (K .GT. 2) GO TO 10
         Z1 = 0.
         Z2 = Z(2) - Z(1)
         GO TO 20
   10 CONTINUE
         Z1 = DEL(I,K-2)
         Z2 = .5 * (Z(K) - Z(K-2))
   20 CONTINUE
C
      Y = Y1 * AMAX1(0.0,AMIN1(Y1 * Z1 * (Z2),
     1         ABS(ASP(I,K-1)),Y1 * DEL(I,K) * (.5 * (Z(K+1) - Z(K-1)))))
      ANTW = RHOT(I,K) + (Y - XX)/(.5 * (Z(K+1) - Z(K-1)))
C
      RETURN
      END
C
C======================================================================
C
      FUNCTION DIFFX(RHO,X,DT,I,K,KXP)
C
C        PARAMETER LIST:
C          INPUT:  RHO   - CONCENTRATION FIELD (PPM)
C                  X     - GRID POINTS IN THE X DIRECTION (METERS)
C                  DT    - DIFFUSION TIME STEP (SEC)
C                  I     - INDEX FOR X DIRECTION
C                  K     - INDEX FOR Z DIRECTION
C                  KXP   - HORIZONTAL EDDY DIFFUSION COEFFICIENTS
C                          (M**2/SEC)
C          OUTPUT: DIFFX - CONCENTRATION VALUES DIFFUSED IN THE X
C                          DIRECTION
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
C          THIS FUNCTION CALCULATES THE DIFFUSION IN THE X DIRECTION
C          BY CENTERED IN SPACE DIFFERENCES MAKING ALLOWANCES FOR
C          UNEQUAL SPACING.
C
      REAL KXP
      DIMENSION X(24),RHO(24,8),KXP(24,8)
C
      DXH = X(I)   - X(I-1)
      DXK = X(I+1) - X(I)
      DXD = X(I+1) - X(I-1)
      DIFFX =((KXP(I+1,K) + KXP(I,K))    * (RHO(I+1,K) - RHO(I,K))  /DXK
     1       - (KXP(I,K)   + KXP(I-1,K)) * (RHO(I,K)   - RHO(I-1,K))/DXH)
     2       /DXD
      DIFFX = DIFFX * DT
C
      RETURN
      END
C
C======================================================================
C
      FUNCTION DIFFZ(RHO,Z,DT,I,K,KZP)
C
C        PARAMETER LIST:
C          INPUT:  RHO   - CONCENTRATION FIELD (PPM)
C                  Z     - GRID POINTS IN THE Z DIRECTION (METERS)
C                  DT    - DIFFUSION TIME STEP (SEC)
C                  I     - INDEX FOR X DIRECTION
C                  K     - INDEX FOR Z DIRECTION
C                  KZP   - VERTICAL EDDY DIFFUSION COEFFICIENTS
C                          (M**2/SEC)
C          OUTPUT: DIFFZ - CONCENTRATION VALUES DIFFUSED IN THE Z
C                          DIRECTION
C
C        CALLING ROUTINE:
C          ADVCHM
C
C        DESCRIPTION:
```

```
C          THIS FUNCTION CALCULATES THE DIFFUSION IN THE Z DIRECTION
C          BY CENTERED IN SPACE DIFFERENCES MAKING ALLOWANCES FOR
C          UNEQUAL SPACING.
C
      REAL KZP
      DIMENSION Z(8),RHO(24,8),KZP(24,8)
C
      DZK = Z(K+1) - Z(K)
      DZH = Z(K)   - Z(K-1)
      DZD = Z(K+1) - Z(K-1)
      DIFFZ =((KZP(I,K+1) + KZP(I,K))   * (RHO(I,K+1) - RHO(I,K))  /DZK
     1      - (KZP(I,K)   + KZP(I,K-1)) * (RHO(I,K)   - RHO(I,K-1))/DZH)
     2      /DZD
      DIFFZ = DIFFZ * DT
C
      RETURN
      END
C
C======================================================================
C
      SUBROUTINE GRAPH(PRTARR,L,TIME,NX,KMAX,X,HWAYL)
C
C        PARAMETER LIST:
C          INPUT:  PRTARR - POLLUTANT FIELD TO BE PRINTED (PPM)
C                  L      - LIMITING INDEX
C                  TIME   - TIME OF THE POLLUTANT FIELD (SEC)
C                  NX     - NUMBER OF GRID POINTS IN THE X DIRECTION
C                  KMAX   - NUMBER OF GRID POINTS IN THE Z DIRECTION
C                  X      - GRID POINTS IN THE X DIRECTION (METERS)
C                  HWAYL  - OUTPUT ARRAY CONTAINING LANE LOCATIONS
C
C        CALLING ROUTINES:
C          MAIN, ADVCHM
C
C        DESCRIPTION:
C          THIS SUBROUTIME OUTPUTS VELOCITY, DIFFUSIVITY, AND
C          POLLUTANT FIELDS.
C
      DIMENSION PRTARR(24,8,2),X(24),HWAYL(24),DASH(24)
      DATA DASH/24*'----'/
      DATA IN/5/, IO/6/
C
      IF (TIME .GT. 0.0) WRITE(IO,1000) TIME
      DO 10 K = KMAX,2,-1
         WRITE(IO,1010) (PRTARR(I,K,L), I = 2,NX)
   10 CONTINUE
      WRITE(IO,1020) (DASH(I),  I = 2,NX)
      WRITE(IO,1030) (X(I),     I = 2,NX)
      WRITE(IO,1040) (HWAYL(I), I = 2,NX)
      RETURN
C
C***      FORMAT STATEMENTS.
C
 1000 FORMAT(1H+,73X,'AT TIME',F12.6,1X,'SEC')
 1010 FORMAT(1H0,22(1X,F5.2))
 1020 FORMAT( 1X,'-',22(A4,'--'))
 1030 FORMAT( 1X,22(1X,F5.1))
 1040 FORMAT( 1X,2X,22(A4,2X))
      END
```

APPENDIX B

PERFORMANCE COMPARISON OF ROADWAY, HIWAY-2 AND CALINE3

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TURBULENT DIFFUSION BEHIND VEHICLES: EVALUATION OF ROADWAY MODELS

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Abstract—This paper presents a statistical evaluation of three highway air pollution models (CALINE3, HIWAY-2, and ROADWAY) using the tracer data from the General Motors Sulfate Dispersion Experiment. Since the models predict the ensemble mean whereas any given observation reflects a single realization or an event from a population, it should be recognized that the model predictions will almost always differ from the corresponding observations, even if the models and the input data for the models are perfect. The bootstrap resampling procedure is used to quantify the variability in the observed concentrations due to the stochastic nature of the atmosphere. The results suggest that the variability in the observations due to the random nature of the atmosphere is about 30%. Therefore, if the predicted values are within ±30% of the measured concentrations, the differences between model predictions and observations should not be considered to be significant. Thus a 'perfect' air quality model should predict to within ±30% of its corresponding observed concentrations. Comparisons of the model predictions paired and unpaired in time with measurements suggest that HIWAY-2 and ROADWAY perform best, but the performance of CALINE3 is acceptable. Application of the extreme value theory and the bootstrap resampling procedure to the modeled and measured data (unpaired) shows that all three models are capable of predicting the extreme concentrations within the model performance criteria set forth above.

1. INTRODUCTION

The passage of the National Environmental Policy Act of 1969 initiated modeling of pollution due to vehicles. This act requires that for new highways that are partially funded by federal funds an environmental impact statement should be prepared before construction begins. A number of highway air pollution models were developed in the early 1970s such as CALINE (Beaton *et al.*, 1972), EGAMA (Egan *et al.*, 1973), and HIWAY (Zimmerman and Thompson, 1975). Attempts to validate and evaluate these models with experimental data taken near highways were not satisfactory because of the uncertainty in the estimate of the emissions from vehicles. In field experiments the background of measured pollutants was nonhomogeneous. Also, the statistical tests used in previous model evaluations were rather simple. In 1975 General Motors, with the cooperation of Ford Motor Co., the Chrysler Corp. and the U.S. Environmental Protection Agency, conducted a well conceived and controlled highway experiment at the General Motors test facility (Cadle *et al.*, 1976). The tracer data from this experiment furnished for the first time an outstanding data set for model evaluation and development.

The Environmental Protection Agency funded the American Meteorology Society to establish a group of scientists to evaluate and recommend techniques for use in model evaluation. The recommendations of this group are given by Fox (1981). In a response to the recommendations of the American Meteorological Society, Willmott (1982) made a number of important suggestions.

In the late 1970s and early 1980s a number of highway models were developed, and many of these were evaluated by Rao *et al.* (1980) using the General Motors data and many of the techniques recommended by Fox (1981). In this paper three highway models (CALINE3, HIWAY-2 and ROADWAY) will be evaluated using the General Motors tracer data and the statistical techniques suggested by Fox and Willmott, extreme value statistics (Tabony, 1983), and the 'bootstrap' method (Diaconis and Efron, 1983).

2. HIGHWAY MODELS

(a) *The CALINE3 model*

CALINE3 is a line source model developed by the California Department of Transportation (Benson, 1979). It is based on the Gaussian diffusion equation

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†On assignment from NOAA, and to whom correspondence should be addressed.

and employs a mixing zone concept to characterize pollutant diffusion over the roadway. The model divides individual highway sections into a series of elements from which incremental concentrations are computed from an approximation to the crosswind finite line source equation and summed to form a total concentration estimate at a particular receptor location. Each element is modeled as an equivalent finite line source positioned normal to the wind direction and centered at the element midpoint. The region directly over the highway is treated as a zone of uniform emissions and turbulence.

The vertical diffusion parameter is a modification of the curves suggested by Pasquill (1974) to incorporate the initial diffusion over the highway. The horizontal diffusion curves are identical to those suggested by Turner (1970) except for averaging time and surface roughness power law adjustments similar to those made for the vertical diffusion curves.

(b) *The HIWAY-2 model*

The HIWAY-2 model (Rao and Keenan, 1980) is basically a Gaussian diffusion model developed for at grade and cut section roadway configurations. Highway emissions are considered to be equivalent to a series of finite line sources. Each lane of traffic is modeled as if it were a straight, continuous, finite line source with a uniform emission rate. A highway is simulated with an increasing number of point sources with the total contribution of all points computed by a trapezoidal integration of the Gaussian point source equation over a finite length until the solution converges.

The diffusion parameters used in HIWAY-2 were determined from the tracer data collected during the General Motors Experiment and the Long Island Expressway Experiment (Sistla *et al.*, 1979). Downwind diffusion is a function of initial diffusion and stability class. Three stability regimes are utilized to characterize downwind diffusion. The initial spread has incorporated in it a vehicle-induced drag factor that accounts for the initial dilution of the pollutant over the roadway, and allows the model to make reasonable estimates of concentrations when the wind speed is low and the wind direction is parallel to the roadway.

(c) *The ROADWAY model*

The ROADWAY model solves a conservation of species equation via finite-difference approximations. The model assumes a surface layer describable by surface layer similarity theory with the superposition of the effects of vehicle wakes. The vehicle wakes affect the wind field and the turbulence fields, and it is assumed in the model that the effect is linear. The unique part of the ROADWAY model is the vehicle wake theory, which was originally developed by Eskridge and Hunt (1979), and modified by Eskridge and Thompson (1982) and Eskridge and Rao (1983, 1986).

A vehicle wake is a region of increased turbulence and decreased velocity relative to the vehicle. The intensity of the wake is a function of vehicle speed, downwind distance, and distance from the center of the wake. An averaged velocity and turbulence field is calculated across the highway based upon the number of vehicles, vehicle speeds, and ambient, atmospheric (upwind) conditions. Using the calculated velocity and turbulence fields, pollutant concentration predictions are made over, upwind and downwind of the highway. It is worth noting that unlike CALINE3 and HIWAY-2, the ROADWAY model development was independent of the General Motors data.

3. EVALUATION AND COMPARISON OF HIGHWAY POLLUTION MODELS

In this section the performance characteristics of three diffusion models, HIWAY-2, CALINE3 and ROADWAY, will be determined using the data from the General Motors Sulfate Dispersion Experiment. It should be borne in mind that HIWAY-2 and CALINE3 are expected to perform well when tested against the data from which they were developed. Further, it is worth noting that the physics of the problem is handled differently in all three of these models. By making intercomparison of model results it is possible to make an assessment of each model's simulation capability as a function of different treatments of modeling of pollutant transport and diffusion near roadways.

Two techniques are used to compare the predicted and measured concentrations, namely paired and unpaired comparisons. A paired analysis allows a direct comparison of individual predictions with measured values, while unpaired techniques determine model behavior on a statistical basis, without regard to the spatial and temporal correspondence between measured and predicted concentrations. The techniques used in the paired and unpaired analysis are described in Fox (1981) and Rao *et al.* (1985), and the unpaired (bootstrap) is described below. The results from the paired analyses, summarized in Table 1, indicate that HIWAY-2, ROADWAY and CALINE3 explain about 70%, 65% and 29% of the variance, respectively. The slopes of the regression lines are close to unity with small intercept values for all three models. The Index of Agreement, which reflects the degree to which the observation is accurately simulated by the model, shows that HIWAY-2 is 5% better than ROADWAY and both are considerably better than CALINE3. A second st. ong measure of model performance is the root-mean-square error (RMSE) which indicates the size of the error produced in the model; Table 1 shows that HIWAY-2 and ROADWAY perform considerably better than CALINE3. The mean fractional error shows that CALINE3 tends to underpredict slightly and HIWAY-2 and ROADWAY tend to overpredict. Mean fractional error is not a good measure by itself, as it would

Table 1. Comparison of model results using the GM data

	OBSERVED	HIWAY-2	CALINE3	ROADWAY
Range	0.01–4.92	0.01–4.68	0.09–17.97	0.02–5.29
Mean	0.96	1.07	0.96	1.20
Standard deviation	0.74	0.77	1.31	0.92
R^2		0.70	0.29	0.65
Slope		0.87	0.96	1.00
Intercept		0.23	0.04	0.25
Mean of (P/O)		1.30	1.23	1.40
Standard Deviation of (P/O)		0.99	1.20	1.02
Mean difference (d)		0.11	0.00	0.25
Variance of the difference (S_d^2)		0.18	1.23	0.29
Average absolute gross error $(\|d\|)$		0.30	0.41	0.41
Root-mean-square error $(RMSE_d)$		0.44	1.11	0.60
Index of agreement (D)		0.91	0.64	0.86
Mean fractional error (MFE)		−0.12	0.04	−0.21
Unsystematic mean square error (MSE_u)		0.18	1.22	0.29
Systematic mean square error (MSE_s)		0.02	0.00	0.06
Mean square error (MSE)		0.20	1.22	0.35
MSE_u/MSE		89%	100%	83%
MSE_s/MSE		11%	0%	17%

$N = 594$.

indicate here that CALINE3 is the best model, but the other statistical tests indicate otherwise. The mean fractional error could be small if there are large overpredictions balanced by large underpredictions. The average errors between predictions and measurements are similar for ROADWAY and HIWAY-2, although the simulation of HIWAY-2 is slightly better than that of ROADWAY. Particularly noteworthy is the fact that the errors of all three models are mostly unsystematic. For a good model the systematic difference should approach zero and the unsystematic difference should approach the root-mean-square error. The fact that similar results are found for both HIWAY-2 and ROADWAY is indicative of the appropriateness of the methodologies utilized in these models, even though they are based on completely different treatments of the physics of the problem. The ROADWAY model uses vehicle wake theory, while HIWAY-2 uses simple parameterizations of traffic-induced turbulence from a Gaussian approach to handle the transport and diffusion of pollutants near roadways.

In the following analysis, account is taken of the fact that the observations include measurement error, as well as the variability due to the stochastic or random nature of the atmosphere. It is imperative that this variability be considered in model evaluation. Any model prediction represents an ensemble average, while any given observation reflects a specific realization from a population that will almost always differ from the prediction, even if the model and the input data are perfect. Thus, it should be recognized that there is no significant difference between model predictions and observations as long as the predictions are contained within the natural variability of the observed concentrations. Assuming that the concentrations are directly proportional to the emission strength and indirectly proportional to the wind speed, the variability in the normalized concentration CU/Q (where C is the tracer gas concentration, U is the wind speed, and Q is the emission strength) can be determined using the General Motors data at the nearest roadside ground level receptor under nearly perpendicular wind–road orientations. Since previous investigations (Eskridge and Rao, 1983; Eskridge *et al.*, 1979; Rao *et al.*, 1979) on the role of traffic-induced turbulence imply the concentrations immediately adjacent to the roadway in the downwind direction are independent of the atmospheric stability, and that pollutant diffusion is dictated by the locally generated turbulence, it is reasonable to combine all data from the nearest roadside ground level (0.5 m height) monitor in the downwind direction to investigate the atmospheric–experimental variability. Furthermore, the data are restricted to the 18 cases with wind direction nearly perpendicular to the roadway, since then the transport and diffusion from the source to the receptor are well defined. The design of the General Motors experiment ensures that the mechanical turbulence generated by the moving vehicles will be approximately the same for all tracer experiments, because of constant vehicle speed as well as spacing of vehicle packs and vehicles in the packs. Thus, the analysis of the normalized concentration CU/Q for all perpendicular wind–road orientation cases allows an estimation of the magnitude of the atmospheric–experimental variability (stochastic process).

The cumulative probability plot of normalized concentration is shown in Fig. 1. The computed mean for CU/Q, the standard deviation of CU/Q, and the coefficient of variation (ratio of the standard deviation to the mean) about the mean are 0.587, 0.154 and 26%, respectively. Thus, the mean for this sample can be reported as $\hat{\rho} = 0.587 \pm 0.154$. This indicates that the best guess of the unknown true value ρ is $\hat{\rho} = 0.587$,

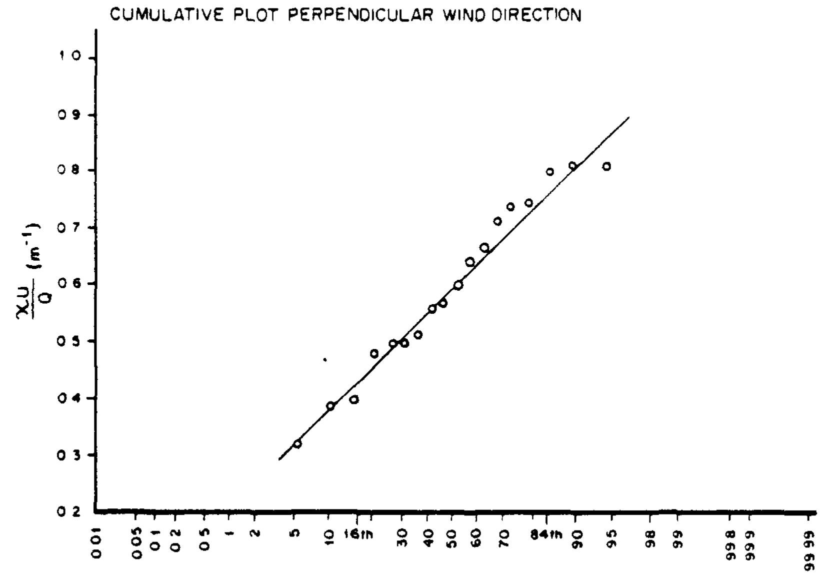

Fig. 1. Cumulative frequency distribution of the normalized concentrations at the nearest roadside receptor under perpendicular wind–road orientation.

with an expected root-mean-square error of 0.154 for $(\rho - \hat{\rho})$. If $(\rho - \hat{\rho})$ has roughly a normal distribution (this may always be the case for large data sets), then the accuracy statement can be interpreted as PROB $\{\rho \in [0.587 - 0.154, 0.587 + 0.154]\} = 0.68$. The above statement is based upon the fact that for a normal distribution, 68% of the data are within one standard deviation of the mean. The accuracy of the estimated mean value can be assessed using the 'bootstrap' method (see Diaconis and Efron (1983) for a detailed description of the method) which is as follows:

(a) Let F be the set of the observed data points (18 in this analysis).

(b) Use a random number generator to draw a set of 18 points independently from F, so that each member of the set is an independent random selection of one of the 18 original data points. This new data set, called the bootstrap sample, is a subset of the original set, which is plotted in Fig. 1. Some of the original points will have been selected zero times, some once, some twice, etc.

(c) Compute the mean $(\hat{\rho}^*)$, the standard deviation $(\hat{\sigma}^*)$, and the coefficient of variation $(\hat{\theta}^*)$ of the bootstrap set.

(d) Repeat steps (b) and (c) above, a large number of times, say N ($N = 1000$ here), each time using an independent set of new random numbers to generate the bootstrap set. Denote the resulting sequence of bootstrap means by $\hat{\rho}^{*1}, \hat{\rho}^{*2}, \ldots, \hat{\rho}^{*N}$.

(e) Construct a histogram plot of $(\hat{\rho}^{*1} - \hat{\rho})$, $(\hat{\rho}^{*2} - \hat{\rho}), \ldots, (\hat{\rho}^{*N} - \hat{\rho})$ based on the N bootstrap sets (called replications).

The histograms based on the 1000 bootstrap replications of the mean of the sample, the standard deviation, and the coefficient of variation are plotted in Fig. 2. The coefficient of variation from the bootstrap replications was found to vary as much as 5% from the estimate based on the original sample (26%). Thus, the overall variation in the original sample will be *approximately* 30%. This limit of plus or minus 30% of the observed normalized concentrations represents the variability in the observed concentration due to the stochastic nature of the atmosphere and should be taken into account in model evaluation studies. Figure 3 shows a scatter plot of observed concentrations, under near perpendicular cases for the GM data, and the predicted concentrations from the HIWAY-2, CALINE3 and ROADWAY models for the data set used in the bootstrap analysis. From the scatter plot, it is observed that 64% of the data points from the three models are within the natural variability. There is a bias towards over predicting in the three models. The models cannot be expected to perform better than plus or minus 30% of the observed concentrations. Table 2 shows how each model performed with the GM data in predicting the maximum concentrations for each tracer experiment, as well as for the entire data set taken downwind of the road. Again, it is worth noting the similarity of performance between the HIWAY-2 and ROADWAY models in predicting the maximum concentrations. When the entire data set is considered, HIWAY-2 and ROADWAY performed somewhat better than CALINE3, but all have an acceptable level of performance. Table 2 shows that when all data are considered the models perform about the same. Included in Table 2 are the results from the HIWAY model to facilitate a comparison among the models and to document the improvement over the HIWAY model.

While the three models perform well in terms of the GM data base as a whole, their ability to predict high

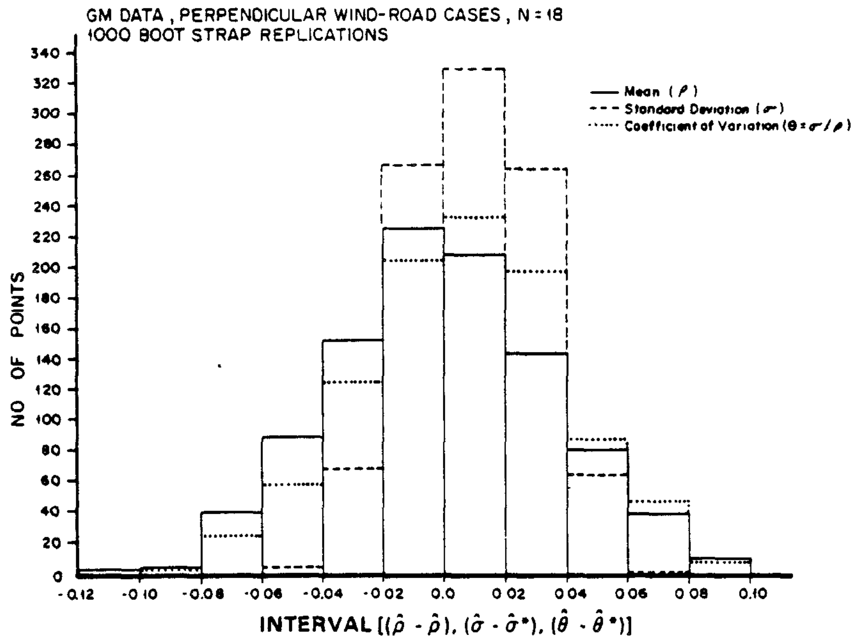

Fig. 2. Uncertainty distribution for the selected parameters using 1000 bootstrap replications.

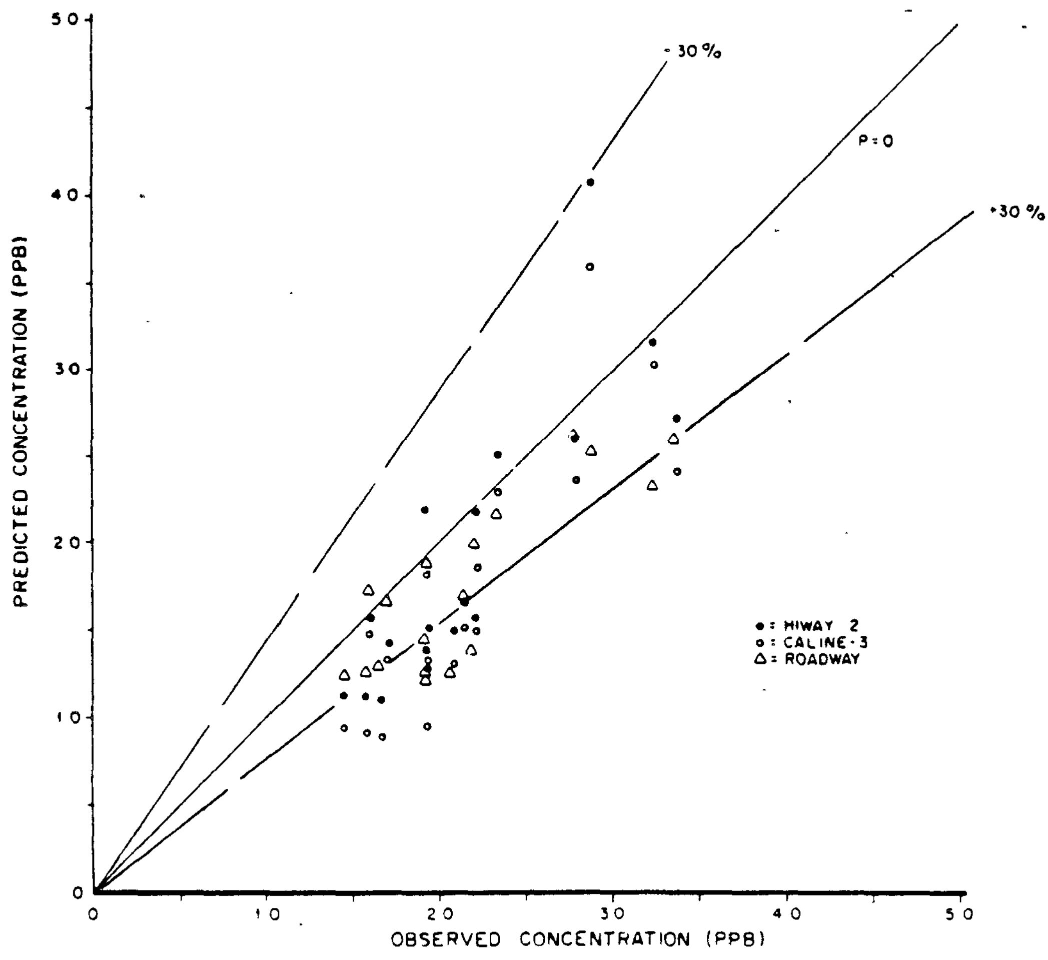

Fig. 3. Scatter plot of model predictions and measurements.

Table 2. Comparison of model predictions with GM data

Data subset	Model	Percent of predictions within ±30% of observed concentration	Percent of predictions < 30% of the observed concentrations	Percent of predictions > 30% of observed concentrations
GM data—ground level downwind receptor nearest to roadway where maximum is observed ($N = 61$)	HIWAY	40%	7%	53%
	HIWAY-2	75%	17%	8%
	CALINE3	42%	53%	5%
	ROADWAY	71%	21%	8%
All GM data from all runs	HIWAY	28%	14%	58%
	HIWAY-2	55%	10%	35%
	CALINE3	44%	29%	27%
	ROADWAY	46%	13%	41%

concentrations has not been determined. To evaluate the simulation capability of the models in predicting the maximum concentrations, asymptotic extreme value theory is used. In this method the maximum observed and predicted concentrations in each of the 18 tracer experiments are rank-ordered and the cumulative probabilities are determined by

$$\text{prob}(x \leqslant x_2) = \exp[-\exp(-y)], \quad (1)$$

where $y = (x - u)/a$ and y is called the reduced variate, x is the maximum concentration in each experiment, a is the Gumbel slope, and u is the mode of the extreme value distribution (see Gumbel, 1962).

The maxima of the observations and predictions for each of the General Motors experiments for the CALINE3, HIWAY-2, and ROADWAY models are plotted in Figs 4, 5 and 6, respectively, as a function of the reduced variate, y. The figures show the best fit to the model predicted data and the 95% confidence interval to the fit, which is determined by the method of maximum likelihood estimation. This fit has the character of a type I double exponential distribution (see Tabony, 1983).

The maximum observed concentrations are also plotted to provide a comparison between the observations and model predictions. The measured data above the mode of the distribution fall within the confidence band for the model predicted values for ROADWAY and almost for HIWAY-2, which indicates that the model simulates the physical processes leading to the maximum concentrations quite well. A large number of the observations fall outside the confidence bands for the CALINE3 model. Good agreement was found between the predictions and observations as far as the extremes of the maxima (upper tail of the extreme value distribution) are concerned for all three models

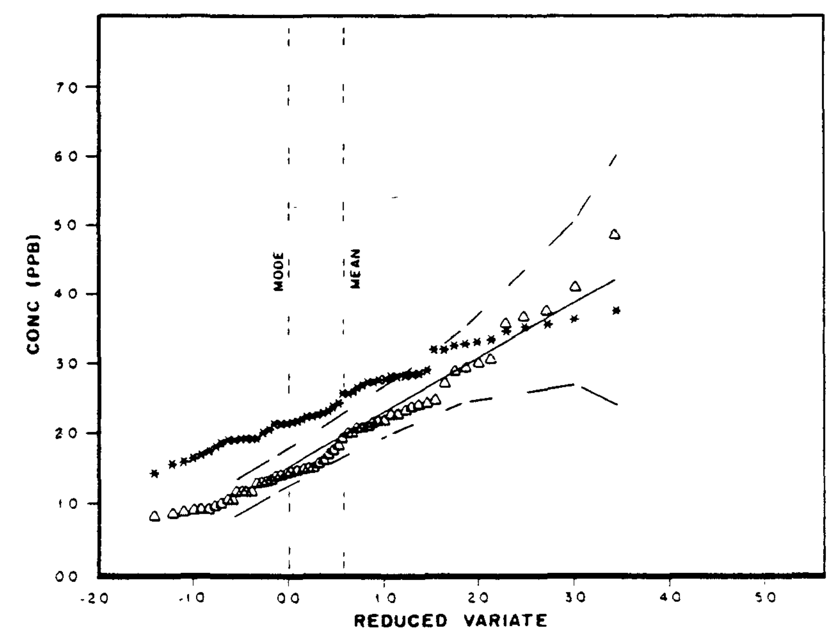

Fig. 4. Maxima of the observations (stars) and predictions (triangles) of CALINE3. Dashed lines are the 95% confidence limits for the best fit line through the predictions. The reduced variate is defined in Equation (1).

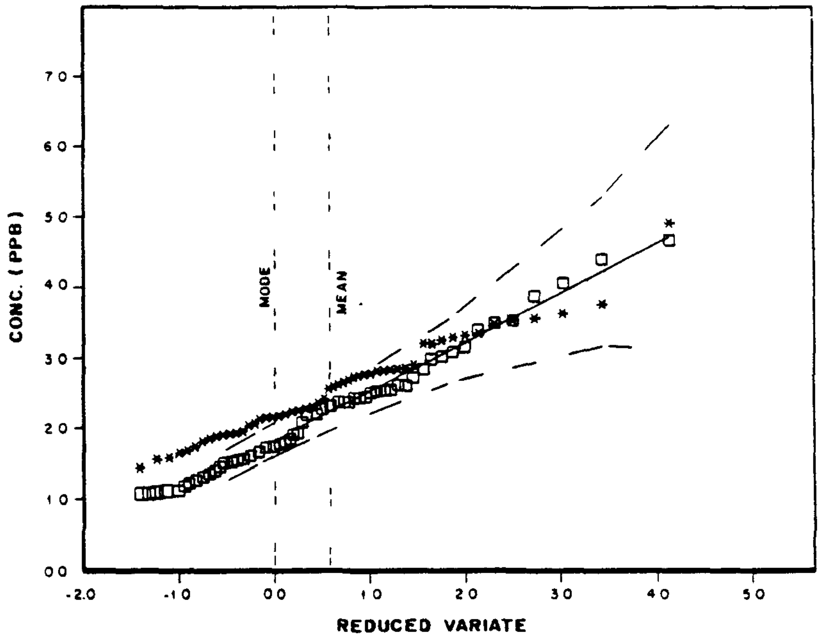

Fig. 5. Same as Fig. 4 except for HIWAY-2 and model predictions are shown using boxes.

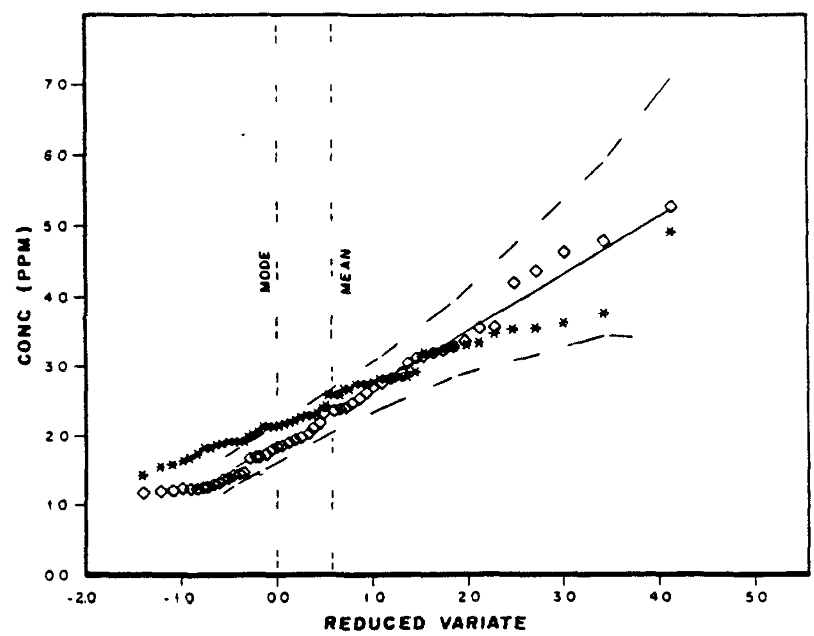

Fig. 6. Same as Fig. 4 except for ROADWAY and model predictions are shown using diamonds.

as shown in Figs 4–6. The statistical parameters for the extreme value distributions for the three models are presented in Table 3. The second highest of the observed maximum concentration is well within the predicted second highest concentrations, indicating that all these models are capable of simulating the atmospheric processes quite well.

The extreme value distribution discussed above is dependent on the distribution of the data. An alternate approach is to use the bootstrap method to evaluate each model's ability to simulate the maximum concentration. The bootstrap method is applied to the sets of second highest concentration from the General Motors data and the predictions of the three models. The cumulative distributions of these concentrations based on 1000 bootstrap replications are presented in Fig. 7. It is evident that all of the models predict somewhat larger values (within 1.0 ppb) of the concen-

Table 3. Model comparison of second highest concentration (ppb)

Model	Mode	Sample size	Predicted S	Observed	Boot strap 95% confidence interval
HIWAY-2	1.839	61	4.219 ± 1.057	3.770	3.40–4.37
CALINE3	1.525	60*	4.207 ± 1.191	3.770	3.10–4.80
ROADWAY	1.895	61	4.665 ± 1.230	3.770	3.56–4.69

95% confidence limit to the model predicted second highest concentration based on the extreme value distribution.

*One tracer run with very low wind speed is removed from this analysis.

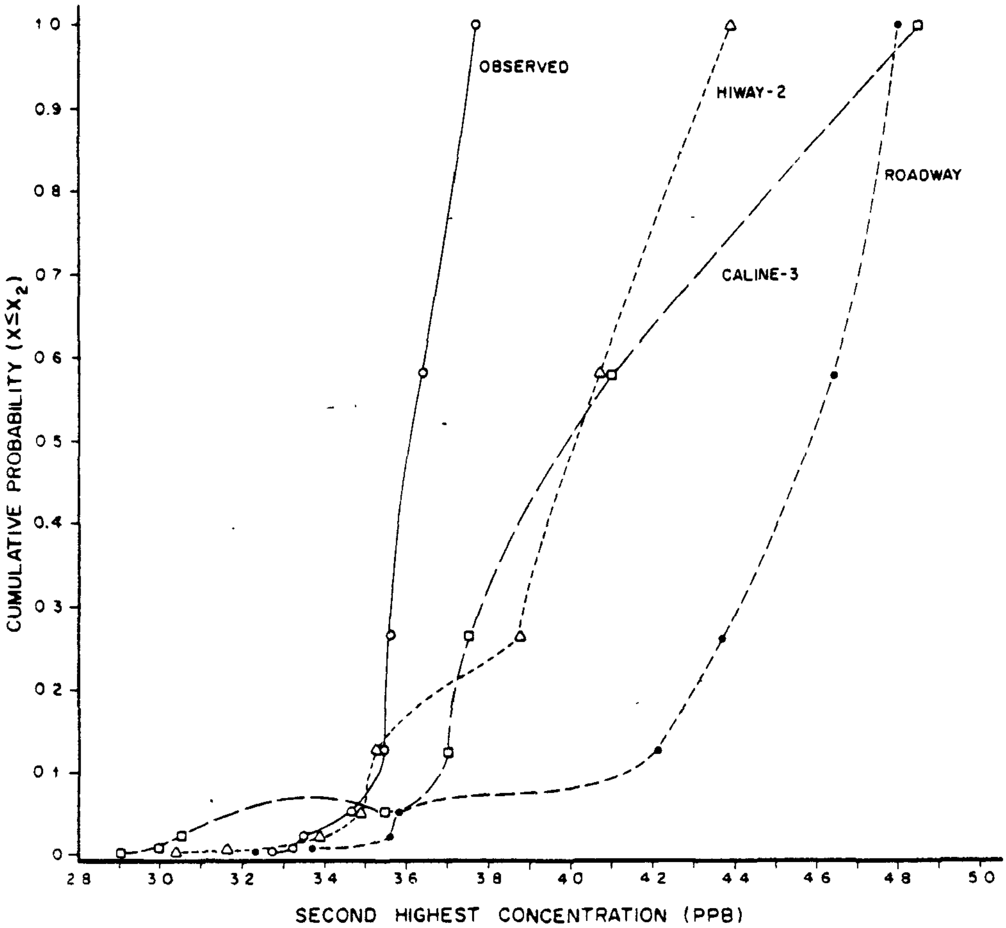

Fig. 7. Cumulative frequency distribution of model-based and the observation-based second highest concentration using 1000 bootstrap replications.

tration than that measured for a given probability. The ROADWAY model provides a more conservative estimate (i.e. higher) of the concentration than the other models. At 50% probability, the observed data indicate that the second highest of the maximum concentration is 3.62 ppb, while for the ROADWAY model it is 4.58 ppb. Given that there is no significant difference between model predictions and measurements as long as the predictions are contained within plus or minus 30% of the measured concentrations, the above result indicates that the predictions from the ROADWAY model, as well as the other two models, are in agreement with the measurements. Thus, these models are seen to provide slightly conservative and realistic estimates of the concentrations. Not only the central tendencies, but also the extreme values produced by these models (especially HIWAY-2 and ROADWAY) are observed to be in good agreement with the measured data.

4. SUMMARY

The performance of CALINE3, HIWAY-2 and ROADWAY has been assessed using the tracer data from the General Motors Sulfate Dispersion Experiment. The model predictions were first paired in time with the observations and various statistical parameters were evaluated. These tests indicate all three models perform well with the General Motors data, but HIWAY-2 and ROADWAY simulate the data better than CALINE3.

Using the bootstrap method and the normalized observations immediately downwind of the road, it was shown that there is an expected variation in the data of about $\pm 30\%$. This variability in the observed concentrations is due to measurement errors and the randomness of the atmosphere. The implication of this natural variability is that model predictions within $\pm 30\%$ of the observations can not be improved upon with this data set.

To test how well the models predict extreme values, asymptotic extreme value theory and the bootstrap method were used. The results indicate that all three models performed well in predicting the extreme concentrations.

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