**DISPERSION SIMULATION TECHNIQUES FOR
ASSESSING THE AIR POLLUTION IMPACTS OF
GROUND TRANSPORTATION SYSTEMS**

by

**L. J. Habegger, T. D. Wolsko,
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Energy and Environmental Systems Division

April 1974

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ABSTRACT

As part of the Environmental Impact of Transportation Systems Program conducted by Argonne National Laboratory, this report documents the development of air dispersion simulation techniques for assessing the air pollution resulting from roadway vehicle emissions. Various mathematical models for air dispersion are surveyed and evaluated in terms of their applicability to estimation of pollutant concentration in the vicinity of roadways. The Gaussian steady-state dispersion model is considered in detail, and extensive field studies are used to validate this model in the region within 500 feet of the edge of both an at-grade roadway and a depressed roadway. The calibrated Gaussian model is used to formulate techniques for estimating annual one-hour and eight-hour maximum concentrations resulting from roadway emissions. The estimate of the eight-hour maximum is based on a five-year statistical analysis of airport weather data. The appendices present a compilation of data from the experimental field studies and also a documentation of the computer program that was developed for the Gaussian steady-state dispersion simulation.

1.0 INTRODUCTION

In order to satisfy both the public demand for clean air, as specified by the Clean Air Act of 1970, and the intrinsic need for an efficient transportation system, a clear understanding of the cause-effect relationships between vehicle activity and ambient air quality is essential. This relationship between transportation system activity and its impact on air quality can be divided into two distinct phases: the rate of emission of pollutants and their rate of dispersion throughout the surrounding environment. (The state of the art in the estimation of emission rates from vehicles has been described in detail in the "Handbook of Air Pollutant Emissions from Transportation Systems."^{1*}) This report provides a methodology for estimating

*Numbers above the line refer to publications listed in the Reference Section in the back of the report.

dispersal of the pollutants emitted from ground transportation systems, thus providing estimates of concentration levels in the surrounding environment.

The present air quality degradation, resulting from transportation activities, is primarily associated with the use of vehicles powered by the internal combustion engine. These vehicles have been major contributors to high concentrations levels of carbon monoxide (CO), non-methane hydrocarbons (HC), nitrogen oxides (NO_x), and photochemical oxidants. Transportation systems are also minor contributors to pollution of the air by particulate matter and sulfur oxides (SO_x). The transportation contribution to the aforementioned pollutants, for the year 1969 in the United States, is given in Table 1. In most major metropolitan areas the percentages of CO, HC, and NO_x contributed by transportation systems are even higher than the values given in Table 1. For example, the transportation contributions to these three pollutants in the Chicago area for the year 1968 were, respectively, 93%, 81%, and 75%.²

Various control strategies are presently being implemented or planned, which will reduce both the number of vehicle miles traveled and the emission rate of each vehicle. The nature of control plans and expected reduction to be produced by these plans are discussed further in Ref. 3.

National Ambient Air Quality Standards (Table 2) have been promulgated for the pollutants discussed above, based on the available evidence on their health effects. The most important toxic property of carbon monoxide is its reversible reaction with hemoglobin to form carboxyhemoglobin. Research results show that a large number of susceptible individuals in our population suffer impairment of their health at carboxyhemoglobin levels as low as 3%. Depending on the level of activity, an 8-hour CO concentration at the standard levels of 10 mg/m^3 will result in 1.3 to 1.4% carboxyhemoglobin levels, and a one-hour concentration of 60 mg/m^3 (standards are 40 mg/m^3) will result in 1.3 to 2.9% carboxyhemoglobin levels.

Studies of population groups and experimental animals demonstrate that photochemical oxidants, ozone in particular, are primary irritants, causing aggravation of asthma and impairment of performance. They alter the body's defenses against infection, cause various structural changes, and can produce mutagenic effects in animals even at ambient concentrations.

TABLE 1. Transportation Contribution to the Total Air Pollution
Emissions in the United States, 1969

	CO		HC		NO _x		Particulates		SO _x		Source Total		
	10 ⁶ Tons	% of U. S. Total	10 ⁶ Tons	% of U. S. Total	10 ⁶ Tons	% of U. S. Total	10 ⁶ Tons	% of U. S. Total	10 ⁶ Tons	% of U. S. Total	10 ⁶ Tons	% of U. S. Total	% of Trans- portation Total
Motor Vehicles	97.8	54.6	17.1	45.7	8.7	36.5	0.4	1.2	0.3	0.9	124.3	44.2	86.1
Aircraft	2.9	1.9	0.4	1.1	0.4	1.7	0.1	0.3	0.1	0.3	3.9	1.4	2.7
All Other Transportation	10.8	7.1	2.3	6.1	2.1	8.8	0.3	0.8	0.7	2.1	16.2	5.8	11.2
Transportation Total	111.5	73.6	19.8	52.9	11.2	47.0	0.8	2.3	1.1	3.3	144.4	51.4	100.0
U. S. Total	151.4	---	37.4	---	23.8	---	35.2	---	33.4	---	281.2	---	----

Source: Environmental Protection Agency

TABLE 2. National Primary and Secondary Ambient Air Quality Standards⁴

Pollutant	Type of Standard	Averaging Time	Frequency Parameter	Concentration	
				$\mu\text{g}/\text{m}^3$	ppm
Carbon monoxide	Primary and secondary	1 hr	Annual maximum ^a	40,000	35
		8 hr	Annual maximum	10,000	9
Hydrocarbons (non-methane)	Primary and secondary	3 hr (6 to 9 a.m.)	Annual maximum	160 ^b	0.24 ^b
Nitrogen dioxide	Primary and secondary	1 yr	Arithmetic mean	100	0.05
Photochemical oxidants	Primary and secondary	1 yr	Annual maximum	160	0.08
Particulate matter	Primary	24 hr	Annual maximum	260	-
		24 hr	Annual geometric mean	75	-
	Secondary	24 hr	Annual maximum	150	-
		24 hr	Annual geometric mean	60 ^c	-
Sulfur dioxide	Primary	24 hr	Annual maximum	365	0.14
		1 hr	Arithmetic mean	80	0.03
	Secondary	3 hr	Annual maximum	1,300	0.50

^aNot to be exceeded more than once per year.

^bAs a guide in devising implementation plans for achieving oxidant standards.

^cAs a guide to be used in assessing implementation plans for achieving the annual maximum 24-hour standard.

Oxidants are not produced in significant amounts directly by transportation activity, but are produced by reactions between sunlight and the hydrocarbons and nitrogen oxides that are emitted by vehicles. The national standards for hydrocarbons and nitrogen dioxide (Table 2) are based largely on their role in the production of oxidants. Long-term exposure to nitrogen dioxide has also been associated with acute respiratory illness, decrease in lung function, and increased bronchitis morbidity. However, the conclusions of these studies are not complete due to the presence of other pollutants whose effect on health is not adequately understood.

The standards for particulates and sulfur dioxide (Table 2) are supported by several epidemiological studies of populations exposed to varying simultaneous concentrations of these two pollutants. As discussed above, transportation systems are not major contributors to these pollutants.

Various other pollutants, such as lead compounds and aldehydes, have also been discharged directly or indirectly into the atmosphere in minute quantities by transportation systems or as by-products of atmospheric chemical reactions of vehicle emissions. The health effects of ambient concentrations of these pollutants are still under investigation, and related air quality standards have not been promulgated.

The various public laws governing the air quality impact of transportation systems are summarized in Ref. 5. The Clean Air Act of 1970 (PL91-604) is a focal point in the legal attempts to achieve and maintain air quality standards. This act provides the Environmental Protection Agency with broad powers, including the authority to set national air quality standards, as discussed above, and to implement necessary control strategies so that standards will be met.

Of additional importance is the National Environmental Policy Act of 1969 (PL91-190), which requires that all applications for federal support be accompanied by a detailed statement on the environmental impact of the proposed action.

The remainder of this report is based on one phase of a study, conducted by Argonne National Laboratory for the Illinois Institute of Environmental Quality, whose objective was to develop techniques for assessing the environmental consequences of public ground transportation systems. Specifically, this report documents the development of air dispersion models for use in estimation of air pollutant concentrations in the vicinity of roadways.

Section 2 includes a brief discussion of the models that were considered for this study: the box model, the Gaussian-dispersion steady-state and integrated-puff models, the conservation-of-mass model, the Navier-Stokes model, the urban-canyon model, and the vehicle-wake model. In Section 3, the Gaussian-dispersion models, in particular the steady-state model, are considered in greater detail. The results of an extensive experimental validation program for the Gaussian-dispersion steady-state model are also included in Section 3. Section 4 makes use of the calibrated Gaussian steady-state

model and the urban-canyon model to derive techniques for estimating the one-hour maximum impact to be expected in the vicinity of a roadway in a one-year period. The maximum yearly values of 8-hour average concentrations in roadway vicinities presented in Section 4 are based on statistical analyses of meteorological data. Conclusions and recommendations are given in Section 5. The Appendices give a detailed description of the experimental model validation program and also a documentation of the Gaussian-dispersion steady-state model computer simulation developed in the course of this study.

2.0 DISPERSION MODELING FOR VEHICLE POLLUTANTS

Air pollutant dispersion models are the mechanism by which estimates of emission levels can be converted into estimates of pollutant concentrations in the regions surrounding the emitter. Dispersion models are thus of obvious importance to transportation planners, air pollution control agency officials, and others who are interested in estimating the impact of existing or projected transportation systems.

Dispersion models, as used in the context of this report, refer to mathematical models, as opposed to physical models that provide an understanding of the air dispersion in a region through the study of laboratory-scale models.

A large number of mathematical models for transportation pollution analysis are in existence or currently under development. However, the majority of these models are variations or combinations of the following categories. Additional surveys of transportation-related dispersion modeling can be obtained by the interested reader in Refs. 5 through 9.

2.1 BOX MODEL

The box model assumes that pollutant concentrations are homogeneous throughout a prescribed region; for example, in a "box" of height h , width w , and length ℓ . If it is assumed that the pollutants are removed from the box by a wind of velocity u that moves in a direction perpendicular to the side of the box of length ℓ , and, furthermore, that an emission source of strength Q is located within the box, then a simple mass balance will give the mathematical description for the concentration within the box as follows:

$$Q(\text{gm/sec}) = [\chi(\text{gm/m}^3)] \times [u(\text{m/sec})] [h\ell(\text{m}^2)] \quad (1)$$

or

$$\chi = \frac{Q}{u h \ell} (\text{gm/m}^3) \quad (2)$$

The assumptions required for valid use of this model corresponds to:

- 1) A constant distribution of sources throughout the region,
- 2) A trapping of the pollutant under a constant height, such as an inversion layer,

- 3) The dispersion by turbulent diffusion within the region being very fast compared to transport by the wind, and
- 4) An average wind throughout the region.

Considerable care must be used in the application of this model because of the assumptions involved. This model has been used with limited success for obtaining preliminary estimates of regionwide pollutant concentrations.¹⁰ It may also have application in situations such as an urban canyon in which physical boundaries that approximate the boundaries of the box model actually exist (see Section 2.5). Another application of the box model (which will be discussed further in the next section) is in the estimation of pollutant concentrations in the region of a high vehicle turbulence immediately surrounding a roadway. In this region the assumption of a very fast turbulent diffusion (compared to transport by the wind) is valid. The box or constant mixing height in this model is the boundary between vehicle-induced turbulence and normal atmospheric turbulence. In this application, Eq. 2 is rewritten as:

$$x = \frac{Q' (\text{gm/m-sec})}{uh}, \quad (3)$$

where Q' is the emission rate per unit length Q/ℓ , and u is the wind velocity component perpendicular to the roadway.

The model as given in Eq. 3 has an obvious deficiency in that the solution is undefined when the wind component perpendicular to the roadway is zero. Because of these and other assumptions, this model is not recommended, except for use as a conceptual model for defining emissions near roadways in conjunction with other models, such as the Gaussian model.

Various revisions could be made to the box model, such as including time-dependence or inclusion of input into the box from upwind sources. However, because of the importance of the inherent assumptions of this model, these revisions do not appear worthy of the effort, particularly in view of the availability of the other models to be discussed next.

2.2 GAUSSIAN MODELS

Variations of Gaussian models are still the most widely used models in practical applications. A prime reason for the popularity of these models is the success obtained from their use in widespread applications. The model is, in part, empirically based, and thus its successful application encourages still further use.

In these models the solution is given in closed form, which is based on the assumption of Gaussian spatial distribution for pollutant concentration. The closed form of the model equations simplifies the computation required, and multiple sources can be considered by superposition. The requirements for meteorological data input are also considerably less than for the more complex models.

The Gaussian models have the disadvantage of being applicable primarily to flat, unobstructed terrain. Also, three-dimensional spatial uniformity in wind speed and direction must be assumed. These models are not capable of detailed simulation of secondary pollutants that appear as the result of chemical reactions.

Within these constraints, the Gaussian models provide a good compromise between theoretical completeness, computational burden, flexibility, requirements for input data and accuracy of results.

A theoretical and experimental evaluation of the applicability of Gaussian models to ground-transportation pollutant analysis is a major topic of subsequent sections of this report.

2.3 CONSERVATION-OF-MASS MODELS

Conservation-of-mass models are based on an attempt to solve the basic conservation of pollutant-mass equations using numerical techniques. These techniques typically involve division of the region in question into finite grids. The influx and outflux of the pollutant into each grid are included in a balance equation that includes the effects of wind velocity components and turbulent eddy diffusion coefficients. The details of this approach can be found in Refs. 11 through 14.

The conservation-of-mass models are potentially more flexible than the Gaussian models. A prime motivation for the development of these models

is their ability to handle and deal with photochemical reactions. Also, greater variability in wind, velocity, and direction can be accounted for in these models. One disadvantage of these models, in their present state of development, is the long computer time required for solutions when a large number of grids is used. Nor do they currently enjoy as broad a base for the necessary validation of empirical constants as do the more familiar Gaussian models. Some of these problems are expected to be overcome as the conservation-of-mass models are developed further, and their use can be expected to become more widespread in the future.

2.4 TURBULENT-DIFFUSION MODELS

Diffusion models, based on the complete Navier-Stokes equations for turbulent fluid motions, are potentially the most powerful methods for computing pollutant dispersions.¹⁵ These equations can model difficult aerodynamic problems like split flow and flow around obstacles and bridges. These approaches are still at a very early stage of development and should be considered only as a basic research tool. The numerical solution of the equations typically requires large amounts of computer time.

2.5 URBAN-CANYON MODEL

For modeling pollutant concentrations in complex flow patterns, simple empirical relations, which predict gross effects, are often adequate for practical applications. In this class of models is the urban-canyon model developed for prediction of concentrations near tall buildings bordering an urban street.

Evidence of a helical air circulation in street canyons, as illustrated in Fig. 1, has been observed.¹⁶ Receptors on the leeward side of a building (to the right side as shown in Fig. 1) are exposed to substantially higher concentrations than are those on the windward (left) side because of the reverse flow component across the street, near the surface. Thus, the concentration (χ) at a receptor may be considered as having two superimposed components. One component is the concentration (χ_b) of the air entering the street from above. (It is assumed that the concentration computed by the extraurban and intraurban diffusion models represents χ_b). The other component ($\Delta\chi$) arises from the locally generated CO emissions within the street.

Fig. 1. Schematic of Cross-street Circulation Between Buildings¹⁶

The total concentration can be written as:

$$x = x_b + \Delta x \quad (4)$$

Equations for calculating the Δx components on both the leeward side (Δx_L) and the windward side (Δx_W) were derived.^{16,17} The leeward component is calculated by:

$$\Delta x_L = \frac{K Q_s}{(u + 0.5) \left[(x^2 + z^2)^{1/2} + L_0 \right]} \quad (5)$$

In this equation, K is an empirical nondimensional constant ($K \approx 7$); L_0 is a dimension representing the vehicle size ($L_0 \approx 2\text{m}$); and x and z are the horizontal and vertical distance of the receptor relative to the center of the traffic lane (see Fig. 1). Also, u is the rooftop wind speed (ms^{-1}), generally

estimated from the airport wind speed by a regression relationship, and Q_s is the average rate of emission of CO ($\text{g m}^{-1}\text{s}^{-1}$) in the street. The windward-side component (Δx_W) is calculated by:

$$\Delta x_W = \frac{K Q_s (H - z)}{W(u + 0.5)H}, \quad (6)$$

where W is the street width, and H is the average building height. When the wind direction is such that neither a leeward nor a windward case is appropriate, an intermediate concentration (Δx_I) is calculated by combining the above two equations as follows:

$$\Delta x_I = \frac{1}{2}(\Delta x_L + \Delta x_W) \quad (7)$$

The foregoing basic model description was taken from Ref. 18.

In an attempt to test the validity of the urban-canyon model, a series of carbon monoxide concentrations were measured at the sidewalk level in Chicago in the vicinity of the corner of State Street and Jackson Boulevard. Local traffic data was also collected to obtain estimates of emissions. Wind conditions were based on measurements collected at Midway Airport in Chicago.

The urban-canyon model is intended for estimating increments that are added to concentrations occurring at roof-top levels. Since these measurements were not available, estimates were obtained from the APRAC-1A area-source computer program, as described in the user guide for the urban-canyon model.¹⁸ The area-source inputs to the program were obtained from the TREMISS computer program developed for the Chicago Area Transportation Study.¹⁹

The results of the validation study were unsatisfactory. In a least-squares linear-regression analysis (see Sec. 3.1.4), a low correlation coefficient (R^2) of 0.06 was obtained. Several possible explanations are offered to account for the discrepancy between model and data:

- 1) The model, although it has received previous validation studies in St. Louis, Missouri, and San Jose, California, may not be as generally applicable as previously thought.

- 2) The estimation of roof-top concentrations may be in error, due partially to lack of refinement in area-source input values, which for regions close to the receptor are $\frac{1}{4}$ -square-mile averages, and at farther distances are 1-square-mile averages.
- 3) The wind levels recorded at Midway Airport, approximately ten miles from the site location, may be an inaccurate indicator of local breezes, which are strongly influenced by Lake Michigan located less than one mile from the site.

Until a more intensive calibration of the urban-canyon model, or an alternate model, is available, its use, as described, is suggested. However, this model should be used only when the receptor being considered is between the roadway and a building of at least 6 stories (~ 60 ft) in height located within 50 feet of the edge of the roadway. For other configurations use of the Gaussian plume model described in Section 3.1 is advised.

2.6 MODEL FOR POLLUTANT DISPERSION IN A TURBULENT VEHICLE WAKE²⁰

Classical techniques, such as Gaussian-dispersion models, do not, in general, make provision for the mixing that occurs on and near the highway. This mixing is due to the air flows created by vehicular movements as well as the natural winds. Other techniques, such as the box model proposed in Section 2.1 of this report and by Eschenroeder,²¹ do not adequately describe the turbulent mixing from the diversities of moving traffic and from the complexities of winds.

The model proposed in this section is a new model in the sense that it does take into account the wake turbulence produced by a stream of vehicles on the highway. It is necessary to take this turbulence into account in order to obtain meaningful results on or near the highway.

As a single vehicle moves along a highway, its interaction with the air creates an axially symmetric wake. At some point x along the axis, the pollution concentration χ can be approximated, using Prandtl's theory of turbulence, by:

$$\chi(x,y) = \frac{Q}{2\pi\epsilon x^{2/3} U} \exp\left[-\frac{y^2}{2\epsilon x^{2/3}}\right], \quad (8)$$

where Q is emission source strength, U is the external wind velocity relative to the moving vehicle, and ϵ is an empirical constant.

The pollution concentration measured at a receptor located a radial distance d from a highway, which has a steady stream of vehicles moving along it, can be obtained from Eq. 8 by assuming the principle of superposition to be valid. The result for a roadway of effective length L with an emission source strength per unit length Q_L (see Fig. 2) is:

$$x_{d,\theta} = \frac{Q_L}{\pi \epsilon U (\cos \theta)^{2/3}} \cdot \left(\int_0^L \frac{\exp \left[- \left(z \sin \theta - \frac{d}{\cos \theta} \right)^2 / 2 \epsilon (\cos \theta)^{2/3} z^{2/3} \right] dz}{z^{2/3}} \right), \quad (9)$$

where θ is the angle between the relative wind vector U and the roadway, and z is a distance along the roadway. Equation 9 has been multiplied by a factor of 2 to account for perfect reflection of the pollutant from the surface of the road.

Fig. 2. Schematic Representation for Obtaining Pollutant Concentration in Turbulent Wake of Vehicle

The normalized solution for Eq. 9 for various values $\sin(\theta)$ is shown in Fig. 3. Field testing of this model has not taken place as of this writing, so no values are suggested for most of the empirical constants.

The solution of Eq. 9 for several special cases is presented below.

Case I: Pollution concentration measured on the roadway when the speed of the wind is negligible compared to the speed of traffic. If the wind speed is much less than the traffic speed ($U \approx U_t$, $z \approx x$, $\theta \approx 0$) and if the receptor is placed on the roadway ($d = 0$), then Eq. 9 becomes:

$$x_{d=0, \theta=0} = \frac{3 Q_L L^{1/3}}{\pi \epsilon U_t}, \quad (10)$$

where L is an effective roadlength beyond which there is no significant pollution concentration contribution.

Case II: Pollution concentration measured off the roadway when the speed of the wind is negligible compared to the speed of the traffic. Then with $\theta \approx 0$, Eq. 9 becomes:

$$x_{d, \theta=0} = \frac{3 Q_L L^{1/3}}{\pi \epsilon U_t} \exp \left[\frac{-k}{L^{2/3}} \right] + \frac{6 Q_L \sqrt{k}}{\sqrt{\pi} \epsilon U_t} \left[-\frac{1}{2} + \int_0^{\frac{\sqrt{2k}}{L^{1/3}}} \frac{dx}{\sqrt{2\pi}} \exp \left(-\frac{x^2}{2} \right) \right], \quad (11)$$

where $k = \frac{d^2}{2\epsilon}$.

Note that the integral is the error function and its value can be obtained from tables.

Case III: Pollution concentration measured on the roadway when the speed of the wind is significant when compared to the speed of the traffic. For a finite road length, Eq. 9 becomes:

Fig. 3. Normalized Pollutant Concentration in Turbulent Wake of Vehicle for Various Relative Wind Angles

$$x_{d=0,\theta} = \frac{3 Q_L}{4U \pi \epsilon (\cos \theta)^{2/3} a^{1/4}} \int_0^{aL^{4/3}} e^{-y} y^{(1/4 - 1)} dy, \quad (12)$$

where $a = \sin^2 \theta / 2\epsilon (\cos \theta)^{2/3}$.

Note that the integral in Eq. 12 is an incomplete gamma function and is accessible from tables.

Before practical applications can be made of the wake model, field studies are required to set bounds on its validity. Values for the empirical constant ϵ must also be established.

2.7 OTHER DISPERSION MODELS

Various other models have also been developed for special applications or as simplifications of complex situations in which presently developed models, such as Gaussian and conservation-of-mass models, are not applicable. Statistical regression models have been used to relate pollution levels to emissions.²³ These regression models have been implemented in regionwide analyses to estimate the rollback in emissions required for the region to meet National Air Quality Standards.

A form of regression model is the simplified model, such as the urban-canyon model, which is based on physical principles in combination with empirical determination of proportionality constants in the model. One such model, based on a study in New York, assumes exponential decay of concentration with respect to distance from the pollutant source, as shown in the following equation:²⁴

$$x = \frac{MN}{aW (D + \frac{u}{a})} e^{-az}, \quad (13)$$

where

$$M = \frac{\text{Mass}}{\text{Vehicle mile}}$$

N = Traffic flow rate (vehicles/hr)

a = Decay constant

W = Width of cut

D = Eddy diffusion coefficient

u = Wind velocity

z = Radial distance from vehicle exhaust

χ = Concentration

Regression analysis of this model resulted in a decay constant a of 0.015 to 0.025 feet⁻¹. The primary difficulty with this approach is the limited applicability to situations other than those used in the model validation. The model given in Eq. 13 is intended for use close to a roadway where vehicular-induced turbulence predominates as opposed to wind-induced turbulence.

3.0 DESCRIPTION AND APPLICATION OF GAUSSIAN MODELS FOR VEHICLE POLLUTANTS

3.1 GAUSSIAN DISPERSION - STEADY-STATE PLUME MODEL

3.1.1 Basic Model Description

The assumption of a steady-state Gaussian distribution in the plume of a continuous emission source is one of the most widely used techniques for estimation of pollutant concentration levels. In its simplest form the equation for concentration χ at point (x,y,z) in a Cartesian coordinate system with a continuous point source of strength $Q(\text{gm/sec})$ at the origin is given by

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y(x)\sigma_z(x)u} \exp \left[- \left(\frac{y^2}{2\sigma_y(x)^2} + \frac{z^2}{2\sigma_z(x)^2} \right) \right] \quad (14)$$

In this equation, u is the wind speed. The x -axis corresponds to the axis of the plume and is thus parallel to the wind direction, and the y and z axes are in horizontal and vertical directions, respectively (see Figure 4). The

Fig. 4. Steady-State Gaussian Dispersion of Pollutant from Point Source

quantities $\sigma_y(x)$ and $\sigma_z(x)$ are dispersion coefficients which serve to define the plume spread in the horizontal and vertical direction in a crosswind plane at distance x from the point source. Zero concentration is assumed at upwind locations ($x < 0$).

The justification for the form of Equation 14 has been approached from various viewpoints. The dispersion of air pollutants has many of the physical characteristics of processes which are described by Fick's law of diffusion, which in the simplest one-dimension case is expressed as

$$\frac{\partial \chi}{\partial t} = K \frac{\partial^2 \chi}{\partial x^2}$$

The fundamental solution of this equation for dispersion from a point source in an infinite medium is known to be a Gaussian function. Refinements of this approach have been the basis for many attempts to establish theoretical relations for the dispersion coefficients, σ_y and σ_z . The form for the plume concentration distribution has also been based on the consideration of the random nature of air movements, which, by analogy with the central limit theorem of statistics, result in Gaussian distributions. With this approach, estimates of the dispersion coefficients are obtained from theoretical expressions developed for mean-square particle diffusion. Perhaps the most meaningful justification for use of models of this form (from the viewpoint of individuals involved with air resources management) is the success obtained from their use in wide-spread past applications. The closed form of the equation simplifies the computation required, and multiple sources can be considered by superposition. The requirements for meteorological data are also considerably less than for the more complex conservation-of-mass models.

As with all mathematical models of physical problems, the Gaussian model is based on assumptions which must restrict its application. First of all, the dispersion coefficients which have been most successful are primarily empirical, and as a result the model must be used only with caution in situations which have not received prior validation studies. Flat, unobstructed terrain has been the subject of the more commonly used empirical studies. Dispersion coefficients are discussed in greater detail in Section 3.1.3.

The need for empirically obtained parameters is also a restriction for most other models such as the conservation-of-mass model.

The Gaussian steady-state model is intended for use with temporally constant emission sources, wind speed and wind direction. As a practical guideline, these models can be used if the wind or source strength does not vary significantly over time periods comparable to the source-receptor distance divided by the wind speed. (This limitation is removed by the puff model described in Section 3.2.) Three-dimensional spatial uniformity in wind speed and direction is also assumed by the Gaussian models. It is known that the wind generally increases with height in the lower several hundred meters of the atmosphere, hence the use of a single mean wind will tend to result in a slight underestimate of concentrations at lower levels and an overestimate at higher levels. The horizontal spatial variations in meteorology may be significant in the region of major geographical influences such as mountains or large bodies of water. The appearance of the wind speed, u , in the denominator of Equation 5 requires careful consideration in the case of low wind speeds. This consideration is particularly important when the models are used to predict maximum concentrations which occur at low wind speed. The Gaussian models are not capable of detailed simulation of secondary pollutants such as ozone and aldehydes, which appear as the result of chemical reactions. This restriction is a prime motivation for development of conservation-of-mass models. Within these constraints, the Gaussian models provide a good balance of theoretical completeness, computational efficiency, flexibility, input requirements and accuracy.

3.1.2 Extension of the Gaussian Plume Model

Surface Reflection

The basic Gaussian model in Equation 14 predicts symmetry about the vertical and horizontal planes through the plume axis. The presence of the ground surface, however, prohibits symmetry about the horizontal axis. At the surface the pollutant is assumed to be reflected, which is characteristic of gaseous pollutants, and the above-ground concentration is easily obtained by the method of images.⁷ In this method, if a source is located at height h above the ground, an image source of equal strength is assumed to be located a distance h below the surface and the contributions of the two sources

are added together (see Figure 5). If the origin of the coordinate system is placed at ground level below the source ($z \rightarrow z-h$ in Equation 14), the sum of the actual and image sources is

$$x = \frac{Q}{2\pi\sigma_y(x)\sigma_z(x)u} \exp \left[\frac{-y^2}{2\sigma_y(x)^2} \right] \cdot \left\{ \exp \left[\frac{-(z-h)^2}{2\sigma_z(x)^2} \right] + \exp \left[\frac{-(z+h)^2}{2\sigma_z(x)^2} \right] \right\} \quad (15)$$

Non-perfect reflection can be roughly accounted for by multiplying the image source contribution (second exponential term in braces in Equation 15) by a factor P .²⁵ The reverse of perfect reflection, i.e., perfect absorption, can be approximated by using $P = -1$ to give zero ground-level concentration.

Fig. 5. Downwind Pollutant Concentration Synthesis for an Elevated Source Using a Source Image

Mixing Height Restrictions

A stable layer, or inversion layer, existing above an unstable layer (see Section 3.1.3) will have the effect of restricting the vertical diffusion.⁸ This "lid" on mixing depth can be treated as a reflector similar to treatment of the ground as a reflector. For more exact computations, multiple reflections between the lid and ground can be included.⁷

An alternate approach to modeling the effects of the lid height is to assume that beyond a properly chosen distance the concentration will be uniformly distributed in the vertical direction, and additional dispersion will occur only in the horizontal direction. One criterion for selecting the distance after which uniform vertical mixing can be assumed is based on the following arguments.^{26,27} A critical downwind distance x_c is defined such that $H = 2.15 \sigma_z(x_c)$ where H is the lid height. For $x < x_c$ the concentration at the height of the lid from ground level sources, as given by Equation 15, will be less than 10% of the maximum value. Therefore the effect of the lid is ignored for distances $x \leq x_c$. For distances $x \geq 2x_c$ uniform vertical dispersion is assumed below the lid height:

$$x = \frac{Q}{\sqrt{2\pi}\sigma_y(x)Hu} \exp \left[\frac{-y^2}{2\sigma_y(x)^2} \right] \quad (16)$$

For $x_c \leq x \leq 2x_c$ a linear interpolation is used between the value as given by Equation 15 for $x = x_c$ and the value as given by Equation 16 for $x = 2x_c$.

This second method is less precise mathematically than the method using multiple reflections, but is less burdensome computationally, and becomes a good approximation of the multiple-reflection method for sources and receptors close to ground level. Since the primary emphasis of this study is related to ground transportation, this second method has been adopted.

Line Source Model

The application of the Gaussian plume model to transportation systems makes necessary the extension of the mathematical model to dispersion about line sources. Conceptually this extension is a straightforward superposition of a series of point sources. Assume that a continuous stream of vehicles travel on a path of length L and the rate of emissions at a point λ on the path is

Fig. 6. Schematic Representation for Obtaining Pollutant Concentration from a Line Source

$Q'(\lambda)$ gm/m-sec (see Figure 6). The contribution to the pollutant concentration from the increment $(\lambda, \lambda + d\lambda)$ is given by the quantity following the integral symbol in Equation 17. This quantity is directly obtained

$$\begin{aligned}
 x(L) = & \int_{\lambda=0}^L \frac{Q'(\lambda)}{2\pi\sigma_y(\lambda)\sigma_z(\lambda)u} \exp \left[\frac{-y(\lambda)^2}{2\sigma_y(\lambda)^2} \right] \\
 & \cdot \left\{ \exp \left[\frac{-(z(\lambda)-h(\lambda))^2}{2\sigma_z(\lambda)^2} \right] + \exp \left[\frac{-(z(\lambda)+h(\lambda))^2}{2\sigma_z(\lambda)^2} \right] \right\} d\lambda
 \end{aligned} \tag{17}$$

from Equation 15 for point sources with the addition that the coordinates (x, y, z) and source height h are explicitly dependent on the parameter λ which indicates location on the line source. The parameters σ_y and σ_z which are dependent on x are thus also implicitly dependent on λ . All line segment contributions are summed by the integration. The techniques for including the effect of lid height in computation of line source dispersion is a similar direct extension of the methods used for point sources.

Initial Dispersion Near Roadways

The dimensions of the openings for the pollutant discharge from transportation vehicles are generally small enough to justify description as a line source. However, the initial dispersion resulting from vehicle-induced

turbulence is very rapid in the vicinity of the vehicle. This rapid dispersion cannot realistically be predicted using dispersion coefficients obtained from experiments in naturally occurring atmospheric conditions (see Section 3.1.3). The usual procedure for modeling this phenomena is to replace the true line source with a finite volume source, i.e., a source with an initial lateral dispersion.

The initial dispersion approximation can be based on a box model, as described in Section 2.1, with dimensions determined by the boundaries of the vehicle-induced air turbulence. The pollutant concentration is assumed constant within the box, and the pollutant is discharged on the downwind side of the box at a rate equal to the rate of source emission.

An alternate method for modeling an initial dispersion is through revision of the dispersion coefficients, $\sigma_y(x)$ and $\sigma_z(x)$. Various methods have been used for revising these coefficients so that $\sigma \neq 0$ for $x = 0$. The "virtual point" procedure is used in the present study, in which virtual distances x_y and x_z are added to the coefficient arguments in the form $\sigma_y(x+x_y)$ and $\sigma_z(x+x_z)$. For a source of width w , a suggested procedure for establishing the virtual distance x_y is to solve the relation

$$\sigma_y(x_y) = w/2.4 \quad (18)$$

This choice produces a smooth blending of many adjacent area sources.²⁸ Similarly if the source has a finite dimension h in the vertical direction, the virtual distance x_z is obtained from

$$\sigma_z(x_z) = h/2.4. \quad (19)$$

For a source which can be assumed uniform to a height h , a satisfactory approximation can be obtained by placement of the source at height $h/2$ and an equal image source at $-h/2$, both with initial dispersion given by Equation 19. The approximate initial vertical dispersion will be as shown in Figure 7.

For dispersion of vehicle pollutants in the immediate vicinity of a roadway (less than 500 feet from the road edge), the initial dispersion model which was found to give most satisfactory agreement with experimental data (see Section 3.1.4) is a combination of the box and the virtual point models

Fig. 7. Initial Plume Synthesis for a Source Uniform to a Height h Using Source Images

as shown in Figure 8. The concentration in a box over the roadway with a width equal to the roadway and a height of approximately 20 feet is assumed uniform and after leaving the downwind side of the box, the pollutant disperses according to the Gaussian plume model. Upon leaving the box the Gaussian plume is given an initial height and width of 20 feet, using the virtual point values from Equations 18 and 19. (A similar conceptual model for initial dispersion also resulted from a study of highway air pollutants conducted by the State of California for the Federal Highway Administration,²⁹ however somewhat different computational procedures used to model the initial Gaussian plume.)

Fig. 8. Schematic of Gaussian Dispersion Model for an At-grade Roadway with the Initial Plume Leaving the Downwind Edge of the Mixing Cell over the Roadway

This model avoids the use of Gaussian dispersion coefficients based on normal atmospheric turbulence in a region where vehicle-induced turbulence dominates. Previous models (for example, HIWAY³⁰) have assumed Gaussian plumes of finite initial dimensions originating from each roadway lane or from arbitrarily chosen strips into which the roadway has been divided. This assumes atmospheric turbulence as the plume moves through the vehicle-induced turbulence. As a result the pollutant moves toward the roadway edge more slowly, and vertical dispersion becomes important during this slower migration and the road-side concentration is underestimated. The box model assumes no vertical dispersion. Assuming a single plume with an initial width equal to the entire roadway and plume center at the roadway centerline similarly results in underestimation of the downwind concentrations because of the unrealistic plume width.

Computationally the model requires only consideration of the Gaussian dispersion of the pollutant as it emanates from the box. A finite dimensional source is assumed to originate from the downwind edge of the roadway with strength equal to the roadway emission rate (see Section 2.1). Since the plume originates at the road's edge, the model does not require consideration of road width. Further development of the model may indicate changing the dimensions of the initial plume based on road width or on the basis of vehicle density and velocity which affects the boundaries of the vehicle-induced turbulence. The expected importance of these factors is considered in Section 3.1.4, where the experimental validation of the proposed model is discussed in detail.

The use of a box model on the roadway should be viewed only as a conceptual aid for consideration of concentration levels off the roadway, and should not be used for computation of concentrations on the roadway. (The box model, for example, predicts infinite roadway concentrations for wind parallel to the roadway.) A suggested procedure for estimating roadway concentrations is to use the value predicted for the center of the initial Gaussian plume, although this has not been validated experimentally. The initial development of a technique for estimating concentrations in the regions of vehicle turbulence was given previously in Section 2.6.

Gaussian Plume Area Source Models

For the dispersion modeling of transportation-generated pollutants in large regions such as an entire metropolitan area, the consideration of each roadway as a separate line source is an unreasonably difficult problem. A more realistic approach is to treat as individual line sources only roadways within, say, a 100-meter radius of the receptor. The pollutant contributions from roadways at greater distances can be assumed to be uniformly distributed area sources in a preselected grid system. Estimates of transportation pollutant emissions on a region grid system have been developed for the Chicago metropolitan region by the Chicago Area Transportation Study.¹⁹ Similar emission grids have also been prepared for other metropolitan regions for use in transportation control plans³ required by the Clean Air Act of 1970. A need for consideration of area sources is also required in modeling of stationary sources in cases where there exist small residential, commercial, and industrial sources too numerous to model as individual sources.

A frequently used technique for modeling such area sources in Gaussian plume models is through the use of virtual distances x_y and x_z , which give an initial dispersion to the plume as described in the previous section. In the AQDM computer program for modeling of stationary sources, the virtual distances are dependent not only on the area source width but also on the source-receptor configuration. An "effective source strength" is also computed dependent on the source-receptor configuration.²⁷

The APRAC-1A computer model was developed specifically for computation of pollutant concentrations from transportation emissions given as area sources.¹⁸ In this model, the area-source contribution is based on an integration of the basic Gaussian plume model (Equation 14) in the x and y directions. By assuming ground-level sources, ground-level receptors, and a uniform source distribution, a closed form of solution is obtained. The area-source strength is based on emission densities within a 22.5° sector with the centerline in the upwind direction and the vertex at the receptor. The APRAC-1A model can be considered as adequate for area sources and can be expected to give good estimates of regional background concentrations. However, the overall model suffers in accuracy for receptors strongly influenced by nearby roadways which are not very well approximated as area sources. This deficiency has been partially corrected by the empirical urban canyon model which

predicts concentration levels for receptors in streets bounded by tall buildings (see Section 2.4).

3.1.3 Dispersion Coefficients for the Gaussian Plume Model

One of the most important aspects in determining roadside CO concentrations using Gaussian diffusion models is the determination of atmospheric dispersion coefficients, σ_y and σ_z . Pasquill's diffusion curves provide a convenient way to determine the coefficients σ_y and σ_z , based on only the distance of the receptor from the source and an atmospheric stability class.^{6,31} (An introduction to the concept of atmospheric stability is given in Reference 8.) From the graph of Pasquill's curves it is quite evident that the values one determines for σ_y and σ_z are quite dependent on the stability class of the atmosphere that one chooses. Though this is especially apparent at greater distances, it should be observed that at a distance of 100 meters a difference of one stability class implies a difference of 30% in the values of σ_y and σ_z . This makes the choosing of atmospheric stability classes essential in determining the diffusion coefficients and getting accurate estimates of roadway concentrations of a particular pollutant. One available method for determining the stability class is based on prevailing insolation strength and wind speed for daytime conditions, and cloud cover and wind speed for night conditions (Appendix A).³² The insolation strength is determined from the fraction of sky obscured by cloud, day of the year, and hour of the day. This method is quite convenient to use because it requires only routine meteorological parameters as input. One of the problems with this method is that the daytime insolation is divided into rather arbitrary categories of strong, moderate, and slight insolation. Picking one insolation class instead of another can result in a difference of one stability class for a given wind speed.

Pasquill's stability classes were developed as an alternative to a classification based on the standard deviation of wind direction fluctuation, σ_θ . Measured values of σ_θ should thus be related to Pasquill's stability categories and provide a check for the method used to compute stability. A straightforward method for estimating σ_θ is to divide the range or spread in wind angles by 6.0.⁶ However, taking the range of wind fluctuations over an entire hour period is not satisfactory since one extreme fluctuation that

lasts only briefly will change the range significantly but have little effect on the actual σ_θ . A preferable method to use is to divide each hour into 10- or 15-minute intervals, average the range of these intervals, and divide this average range by 6.0.

The Pasquill stability categories for σ_θ are listed below.

Pasquill stability categories	σ_θ
A extremely unstable	25.0°
B moderately unstable	20.0°
C slightly unstable	15.0°
D neutral	10.0°
E slightly stable	5.0°
F moderately stable	2.5°

A comparison of 84 hours of data compiled in the vicinity of I-55 in Chicago reveals a slight difference in the results of the two methods of computing stability. The first method, which uses insolation strength and wind speed, yields the following number of hours in each stability class: A-4, B-37, C-31, D-13. The second method, which employs analysis of the wind traces, yields the following: A-7, B-23, C-34, D-20. Though in general the number of hours in each stability class for the two methods are in general agreement, it is evident that the wind trace method will predict slightly higher stability classes in some cases. This is in part due to the fact that, according to Pasquill, the neutral category D should be used regardless of wind speed for overcast conditions during day or night, and for any sky conditions during the hour preceding or following the night.

Since the dispersion coefficients, σ_y and σ_z , are based on experimental field studies, the conditions under which these field studies were performed must be compared to conditions existing in the experimental validation of the Gaussian model described in this report. Pasquill's curves are founded on theoretical expectations as well as the use of available data, including that from the Prairie Grass experiments carried out in Nebraska in 1956.⁶ During the Prairie Grass experiments sulfur dioxide gas was released at 46 cm and the horizontal plume spread measured along semi-circular arcs

located 50 m to 800 m from the source. In comparison, the CO measurements at the I-55 site were obtained in the range of 20 m to 76 m from the downwind road edge (Appendix A) and thus the Pasquill horizontal dispersion estimates from the Prairie Grass experiments should be generally applicable.

On the other hand, Pasquill's vertical dispersion coefficients are primarily based on data collected at distances greater than 100 m from the source. This suggests the possibility of error in directly extrapolating Pasquill's curves for application to the receptors in the I-55 experiment which were less than 100 m from the source. This can be further shown by the following considerations.

The vertical dispersion coefficient σ_z describes both the effect of buoyant forces and the effect of vertical turbulence effects in dispersing the plume in the vertical. For a neutral atmosphere the "mixing length hypothesis" states that a mixing length l characterizes the local intensity of turbulent mixing. Mixing length is unique at any height, z , and is solely a function of height. For a more unstable atmosphere the mixing length will increase faster in the vertical direction, perhaps as some power of z . It is evident from this that farther downwind as a plume increases in height, more intense turbulence will work to disperse it. Although the mixing length hypothesis does not specifically indicate the size of eddies, it implies that larger eddies are generally in effect at greater heights. In application to the gathering of roadway air samples and a physical description of the dispersion of pollutants from automobile exhaust, the following may be considered. As exhaust emissions first are transported downwind, the smaller eddies are most important in diffusion, while the larger eddies tend to merely displace the plume downwind. However, as the plume disperses and increases in vertical extent downwind, larger eddies have an effect in dispersing it.

The Richardson number $R_i = \left[\frac{g\Delta T}{T(\Delta u)^2} \ln \frac{z^2}{z_1^2} \right] z$ where the bracketed quantity is fairly constant, is the ratio of mechanical energy for turbulent motion versus the buoyant effects.⁶ It is apparent from this that buoyant effects which are related to stability class are replaced in importance by mechanical effects close to the ground. In relation to the past discussion, it is evident that buoyant effects, and thus stability class, are less important in plume dispersion closer to the source where the plume does not extend

great heights. Hence, the effects of stability or instability would be much less felt the closer to the source one is sampling and vertical dispersion curves would tend to converge. Specifying virtual distances x_y and x_z such that Equations 18 and 19 are satisfied for all stability classes has the effect of converging the dispersion coefficient curves to a single value near the source as suggested by the above discussion. Additional credibility is thus given to the use of the virtual distances in describing initial dispersion.

3.1.4 Experimental Validation of Gaussian Plume Line-source Model

At-Grade Roadway

An experimental program was conducted to determine the validity of the Gaussian steady-state plume model for the prediction of pollutant concentrations in the vicinity of roadways. The initial objective was validation of the model near a single at-grade roadway located in an open region where pollutant dispersion is not influenced by hills, trees, buildings, etc. Validation for this simple configuration was considered essential for initial studies since the dispersion coefficients in the Gaussian model are based on this configuration.

The roadway chosen for the studies was Interstate 55 in Chicago, Illinois, near Cicero Avenue. Obtained in experimental program were (1) one-hour carbon monoxide concentrations at distances of 65, 155, and 250 feet from the downwind edge of the roadway, (2) background measurements from the upwind side of the roadway, (3) wind speed and velocity measurements, (4) emission estimates based on traffic volume, speed, and type, and (5) stability estimates based on wind speed, cloud cover, and sun inclination. After editing, 133 receptor-hours of data were available for comparison with model predictions. A full description of the experimental program is included in Appendix A.

The Gaussian plume line-source model described in Section 3.1.1 and 3.1.2 was used to obtain estimates of carbon monoxide levels at the experimental receptor locations using the estimates of emissions, wind speed and direction, and stability class. A lid height of 3000 feet was assumed, although lid height is not an important factor at these distances from the road edge. The Pasquill-Gifford dispersion coefficients, discussed in the previous

section, were used.³¹ A description of the computer program developed for the computations is included in Appendix B.

The computed and measured CO concentrations were compared using a linear least-squares regression analysis. That is, the computed and measured values were assumed to be related by the equation

$$Y_i = \alpha + \beta X_i \quad (20)$$

where Y_i is the i 'th measured value, and X_i is the corresponding i 'th computed value. This linear form of regression analysis only tests the validity of the Gaussian model being tested and does not indicate basic changes in the mathematical description of the model. To determine alternate expressions for the dependence of concentration on physical parameters such as wind speed, a multiple or nonlinear regression analysis should be employed. Investigations of such possible basic model reformulations were beyond the scope of this study.

Using the combination of a box model over the roadway and a line source at the downwind edge of the roadway with initial dispersion of 20 feet height and width as described in Section 3.1.2, the regression line shown in Figure 9 is obtained. Also shown in Figure 9 is the 90% confidence band. Assuming a normal distribution for the errors, for a computed value X , the statistical mean of Y , i.e., $E(Y|X)$, can be said to lie within this band with 90% confidence.³³

To determine the validity of the model for initial dispersion from the roadway described above, a comparison with other possible models is required. The results of such a comparison are summarized in Table 3. In addition to changes in initial dispersion assumptions, Table 3 lists various parameters whose numerical value can be used as criteria for model comparison. For complete agreement between model and measured values, the Y -axis intercept, α , is zero and the regression line slope, β , is unity.

The correlation coefficient, R^2 , in Table 3, is the fraction of the sum of the square of the difference between the individual measured values, Y_i , and average measured values, $\bar{Y}$, which has been explained by the regression model, Equation 12, i.e.,

TABLE 3. Experimental Validation of Initial Dispersion Models for Steady-State Gaussian Plumes in the Vicinity of an At-Grade Roadway

Model No.	No. Lines in Model	Initial Source Dimensions			Linear Regression Analysis ^b				Model Ave. ^e (ppm)
		Location ^c	Height (ft)	Width (ft)	α (ppm)	β	R^2 ^c	ΔR Signif. ^d	
1	1	Edge	20	20	.490	.994	.6526	--	1.34
2	1	Edge	20	0	.495	.987	.6529	33.2%	1.34
3	1	Edge	0	0	.659	.611	.693	77.8%	1.91
4	1	Edge	10	0	.568	.780	.684	95.0%	1.61
5	1	Edge + 10'	10	0	.596	.713	.685	93.6%	1.72
6 ^f	1	Edge	10	0	.528	.573	.596	100.0%	2.26
7	1	Center	20	139.5	.442	1.35	.619	93.6%	1.02
8	2	Edge	10	0	.544	1.01	.645	26.6%	1.27
9	2	Edge	20	0	.483	1.22	.624	88.4%	1.10
10	2	Edge	20	20	.479	1.22	.623	89.0%	1.10
11	2	Edge + 10'	10	0	.566	.939	.647	19.8%	1.34
12	2	Center	10	40	.514	1.12	.635	52.0%	1.16
13 ^f	2	Center	10	40	.554	.725	.537	100.0%	1.75
14	2	Center	0	40	.576	.953	.645	19.8%	1.31
15	2	Center	10	0	.518	1.13	.636	51.0%	1.16
16	2	Center	20	40	.463	1.33	.616	93.2%	1.02
17	2	Center	10	50	.513	1.13	.636	52.0%	1.16

^aWith a single line source, Center refers to placement of the line source at the center of the median strip, and Edge refers to placement at the downwind edge of the total roadway. For two lines, Center refers to placement at the centerlines of the inbound and outbound traffic lanes, and Edge is placement at the downwind edge of each of the two lanes. Edge + 10' indicates placement of the line sources 10 feet downwind of the Edge.

^bResults of least-squares fit to model $Y_i = \alpha + \beta X_i$ where Y_i , X_i (ppm) are experimental and computed concentrations, respectively.

^cCorrelation coefficient.

^dAssuming a normal distribution for differences between experimental values and the linear regression line, ΔR Significance is the probability that the difference in R^2 between the given model and Model 1 is not due to chance alone.

^eAverage of the computed values, X_i . The average of the experimental values, Y_i , is 1.83 ppm.

^fA neutral stability class (D) was assumed for all cases in these models.

Fig. 9. Linear Regression Line (solid line) with 90% Confidence Bounds (dashed line) for Observed and Computed CO Concentrations near the At-grade Roadway

$$R^2 = \frac{\sum (\alpha + \beta X_i - \bar{Y})^2}{\sum (Y_i - \bar{Y})^2} \quad (21)$$

The correlation coefficient reaches its maximum value of unity if all experimental values lie on the regression line. In general, an increase in R^2 indicates an improved model. However, the increase in R^2 may be the result of random errors in the particular experiment. The parameter "ΔR significance" in Table 3 is the probability, assuming a normal distribution for the errors, that the difference in R^2 for the particular model and Model 1, the reference model, is not due to chance alone and would not tend to disappear if additional data points were used.³³

An additional criteria in the selection of a model is its behavior in extensions to cases not considered in the experimental validation. For example, the regression analysis showed no significant differences between the

first two models. However, the second model would exhibit unreasonably high values near the road edge because of the zero initial dispersion width. Similarly, the third model, in addition to having a slope considerably less than unity, has an undefined concentration at the roadway edge due to zero initial dispersion. The importance of stability classification in the extension of the model to various meteorological conditions is illustrated by the poor performance of the sixth model which uses only the single neutral (D) stability class in the computation.

Models 8-17, which treated the roadway as separate inbound and outbound lanes, did not provide significantly improved results. The treatment of highways as multiple line sources, as is done for example in the EPA's HIWAY program,³⁰ thus appears to be an unnecessary computational burden. On the other hand, treatment of the roadway as a single line source placed at the median center line with initial horizontal dispersion equal to the total road width (Model 7) is shown to be inadequate.

In conclusion, the proposed model, which places a single line source at the downwind edge of the roadway with finite initial horizontal and vertical dispersion, was found to give satisfactory agreement with experimental results in the range of 65 to 250 feet from the road edge. Other models performed equally well but caused an increased computation burden or provided unsatisfactory results when projected to distances nearer the roadway. At distances greater than 250 feet the initial dispersion becomes less important and the models would tend to converge. More intense and lengthy field studies may indicate improved performance of other models, but the additional effort appears unjustified for this roadway and receptor configuration.

A further analysis of the proposed model (Model 1, Table 3) according to classes of wind speed and direction is summarized in Table 4. This disaggregate analysis shows that the model performs best at low wind speeds where the highest concentration, and thus the highest desired accuracy, occurs.

Depressed Roadway

An additional experimental program was conducted to test the applicability of the Gaussian plume line-source model in an urban environment somewhat more complex than the unobstructed configuration represented by the Interstate 55 site described above. The roadway chosen as the subject for

TABLE 4. Experimental Validation of Reference Model (Model 1, Table 3) for Various Classes of Wind Speed and Direction

Wind Speed (mph)	Wind ^a Direction	Linear Regression ^b Analysis			Data Ave. (ppm)	Model Ave. (ppm)	No. Data Points
		α (ppm)	β	R^2 ^c			
0-4	0-59	1.13	.814	.703	3.24	2.59	15
0-4	60-90	-.604	1.51	.880	2.13	1.81	17
4.5-8	0-59	.580	.910	.571	1.65	1.18	60
4.5-8	60-90	-.099	1.48	.488	1.44	1.04	18
> 8	0-59	.777	.797	.156	1.44	.83	21
> 8	60-90	--	--	--	1.40	1.15	2

^aThe angle between the wind direction and roadway.

^bResults of least-squares fit to model $Y_i = \alpha + \beta X_i$ where Y_i and X_i (ppm) are experimental and computed concentrations, respectively.

^cCorrelation coefficient.

this study was Interstate 90 in Oak Park, Illinois, near the Lombard Avenue overpass. At this location the roadway is depressed 15 to 24 feet below the level of the surrounding terrain and is bordered primarily by single-family residential units. The surrounding terrain is flat but contains numerous trees. Using procedures similar to those described for the I-55 site, estimates were obtained for (1) one-hour carbon-monoxide concentrations at distances between 48 feet and 314 feet from the downwind road edge, (2) upwind background concentrations, (3) wind speed and direction, (4) emission rates from traffic characteristics, and (5) stability class. After editing, 96 receptor hours were available for model validation. The detailed field program for this site is described in Appendix A.

Computed and measured CO concentrations were again compared using a linear least-squares regression analysis with results as summarized in Table 5. As shown in Table 5, the treatment of initial dispersion was approached by using various assumptions similar to those described in applications to the at-grade roadway. An additional variable to be considered for

TABLE 5. Experimental Validation of Initial Dispersion Models for Steady-State Gaussian Plumes in the Vicinity of a Depressed Roadway

Model No.	No. Lines in Model	Initial Source Dimensions				Linear Regression Analysis ^c			
		Location ^a	Elev. (ft.) ^b	Height (ft.)	Width (ft.)	α (ppm)	β	R^2 ^d	Model ^e Ave.
1	1	Edge	0	20	20	1.04	.875	.602	1.47
2	1	Edge	0	20	0	1.04	.872	.602	1.47
3	1	Edge	0	0	0	1.25	.474	.656	2.27
4	1	Edge	0	10	0	1.15	.640	.646	1.84
5	1	Edge + 10'	0	10	0	1.19	.575	.646	1.99
6	1	Center	0	20	140	.733	1.40	.583	1.13
7	2	Edge	0	10	0	1.05	.845	.626	1.51
8	2	Edge	0	20	0	.825	1.17	.610	1.28
9	2	Edge	0	20	20	.820	1.18	.612	1.28
10	2	Edge + 10'	0	10	0	1.09	.770	.630	1.61
11	2	Center	0	10	40	.967	.999	.621	1.36
12	2	Center	0	0	40	1.09	.783	.638	1.58
13	2	Center	0	10	0	.976	.994	.616	1.35
14	2	Center	0	20	40	.778	1.32	.601	1.17
15	2	Center	0	10	50	.965	.999	.622	1.36
16	1	Edge	-15	20	20	1.07	1.13	.403	1.12
117	2	Center	-15	10	40	.823	1.50	.394	1.00

^aFor one line, Center refers to placement of the line source at the center of the median strip, and Edge refers to placement at the downwind edge of the total roadway. For two lines, Center refers to placement at the centerlines of the inbound and outbound traffic lanes, and Edge is placement at the downwind edge of each of the two lanes. Edge + 10' indicates placement of the line sources 10 feet on the downwind side of the Edge.

^bElevation with respect to surrounding terrain.

^cResults of least-squares fit to model $Y_i = \alpha + \beta X_i$ where Y_i , X_i (ppm) are experimental and computed concentrations, respectively.

^dCorrelation coefficient.

^eAverage of the computed values, X_i . The average of the experimental values, Y_i , is 2.33 ppm.

this type of roadway is the assumed initial elevation of the source. Use of the actual physical elevation of 15 feet below the level of the surrounding terrain where the receptors are located is obviously inferior, as illustrated by the linear regression parameters in Models 16 and 17 in Table 5. The deficiency of this model was expected because of the barrier to dispersion created by the bordering walls of the depressed roadway.

In Models 1-15 in Table 5 the roadway is mathematically described as being at the level of the surrounding terrain. This approach is based on the conjecture that in the depression or cut where the roadway is located, vehicle-induced turbulence results in uniformly dispersed pollutants. The turbulence region is thus best described by a box model in a manner similar to that used for the at-grade roadway, with output from the box model determining the initial dispersion characteristics in the Gaussian plume model. Two conceptually distinct methods for proceeding with this box-plus-Gaussian-plume model for depressed roadways are illustrated in Figure 10. In Figure 10a the box enclosing the rapid dispersion from vehicle turbulence is assumed to extend above the surrounding terrain. The initial Gaussian dispersion is in the form of a single line source with finite dimensions emanating from the downwind side of the box in a manner very similar to that for the at-grade roadway (Figure 8). The vertical atmospheric dispersion above the cut is neglected. Models 1-6 in Table 5 are based on this approach.

In the second approach, illustrated by Figure 10b, the box enclosing the vehicle turbulence has an assumed upper limit at the height of the surrounding terrain. The pollutant in this configuration leaves from the top of the box and a finite dimensional plume originates at this point and disperses according to the Gaussian plume model. In Table 5, Model 6 is based on description of this initial plume by a single line source with initial width dimension equal to the road width, whereas Models 11-15 use multiple line sources to describe the initial plume. Based on the linear regression analysis values given in Table 5, the latter procedure (Figure 10b), using multiple lines, gives somewhat better agreement between model and experiment. For example, Model 15 has a combination of a slope, β , of nearly unity and a high correlation coefficient, R^2 , of .622.

On the other hand, the first approach (Figure 10a), in particular as demonstrated by Models 1 and 2 in Table 5, gave only slightly lower values

(a) The Initial Plume Leaving the Downwind Edge of the Mixing Cell.

(b) The Initial Plume Leaving the Top of the Mixing Cell.

Fig. 10. Schematic of Gaussian Dispersion Model for a Depressed Roadway.

of slope and correlation. This small degradation in performance may be acceptable in most applications because of the reduced computing requirements associated with using a single instead of multiple sources. In Figure 11 is shown the linear regression line and 90% confidence band for the experimental measurements and computed values from Model 1 for the depressed roadway. Models 3-5, although having the highest correlation coefficient, resulted in unacceptably low values of β , the slope.

Fig. 11. Linear Regression Line (solid line) with 90% Confidence Bounds (dashed line) for Observed and Computed CO Concentrations near the Depressed Roadway

3.2 GAUSSIAN DISPERSION - INTEGRATED PUFF MODEL

The Gaussian plume model discussed in Section 3.1 gives an estimate of the concentrations downwind from a source if it can be assumed that the emission rate and meteorological conditions have been constant sufficiently long to permit the concentrations to reach a steady-state value. For the analysis of concentrations from short-term releases or during periods with significant changes in meteorological variables, a transient model is required. The conservation-of-mass and integrated Gaussian puff models have this capability. The advantages and disadvantages of the conservation-of-mass models are given in Section 2.3 and will not be considered further in this report.

In the integrated Gaussian puff model,³⁴ the three-dimensional dispersion from an instantaneous emission (puff) is modeled as the puff travels downwind. As the result of an emission released over the short interval dt' at time t' with total strength $Q(t')dt'$ (gm), the concentration at time t in this model is given by the quantity following the integral symbol in Equation 22. The integral sums the individual puffs to model the effect of continuous, but not necessarily constant, emissions over the period t_0 to t .

$$x(x,y,z,t) = \int_{t_0}^t Q(t') \frac{\exp\left(-\left\{\frac{[x - u(t - t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2}\right\}\right)}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} dt' \quad (22)$$

As in Equation 14 for the Gaussian plume model, the x-axis is parallel to the wind direction and the y- and z-axis are in the vertical and horizontal directions, respectively. By permitting an implicit time dependence for the x-axis, this model takes into account changes in wind direction (see Figure 12). The dispersion coefficients, σ_y and σ_z , in this model are dependent on the age, or time since emission, for the puff, $(t-t')$. These coefficients in practice are based on experimental values dependent on atmospheric stability as in the plume model. The model formulation also has the flexibility of changing stability class.

Fig. 12. Spreading Pollutant Puff During Changing Wind Directions

The extensions of the Gaussian plume model to account for ground reflection, line sources, and sources with finite initial dispersion can also be applied to this model. This model has been implemented and successfully validated in a study of sulfur dioxide concentration resulting from stationary sources in the Chicago, Illinois, metropolitan area.³⁴ In this study the integrated puff model was shown to have an obvious and distinct advantage in versatility over the plume model and can be expected to give more accurate results in many cases. However, this increase in flexibility and accuracy is obtained at the expense of significantly greater computing running times to obtain a solution.

A simplification of the integrated puff model can be obtained by assuming that the diffusion along the x-axis can be neglected by comparison with the gross transport along the x-axis by the mean wind. The resulting equation is equivalent to the plume model with the exception that the dispersion coefficients are the time-dependent coefficients in Equation 22, with the time argument given by $T = x/u$. This is essentially the approach used by Wang and Rote³⁵ in the development of their line source model.

An apparent advantage of the puff model given by Equation 22 is the finite value obtained at zero wind speeds.²⁸ As will be discussed further in Section 4, dispersion modeling at low wind speeds is essential for estimation of maximum concentrations which result from given emission levels. Because of the wind speed factor in the denominator, the plume model, Equation 14, unrealistically predicts unlimited concentrations as the wind speed goes to zero and a lower limit must be established. It has been determined, however, that using the plume model with a minimum wind speed of 2 mph gives better agreement with experimental data at low wind speed than does the integrated puff model. The comparison of the two methods with experimental data is presented in Section 4.

4.0 MAXIMUM AIR QUALITY IMPACT OF ROADWAYS

A primary motivation for development of models which estimate pollutant concentration resulting from ground transportation systems is for comparison of predicted air quality impact of new or modified roadways with existing National Ambient Air Quality Standards (NAAQS). NAAQS have been promulgated for CO in terms of one-hour and eight-hour averages which can be exceeded not more than once per year. (The one-hour and eight-hour maximums are 9 ppm and 35 ppm, respectively.) Since ground transportation is a major emitter of CO (Table 1), the dispersion models discussed previously in this report have been used to develop computational techniques to estimate one-hour and eight-hour maximum concentrations. These maximum concentrations are, however, applicable to other pollutants, such as nitrogen oxides, particulates, hydrocarbons, and sulfur oxides, emitted directly by vehicles.

4.1 ANNUAL MAXIMUM ONE-HOUR AVERAGE CONCENTRATIONS

Two models were considered for the computation of maximum one-hour concentration: the Gaussian steady-state plume model using a minimum wind speed of 2 miles per hour and the Gaussian integrated puff model using a zero wind speed. The results of this computation for a road extending one mile in each direction from the receptor are shown in Figure 13. An initial plume located at the edge of the road with height and width of 20 feet were assumed on the basis of the validation studies described in Section 3.1.4. A neutral stability class (D) was used in these computations of maximum values in Figure 13 since this is the most stable class which can occur at low wind speeds and during the day when the experimental measurements were obtained. No lid height restriction was included. The time duration for the integrated puff model was one hour as no significant increase in concentration occurred after this length of time. The emission rate for both models was 0.01726 gm/m-sec. The wind angle used in the plume model was varied so as to give the maximum concentration for each receptor point. These wind angles were less than 10° from the road direction.

As shown in Figure 13, the value predicted by the plume model was significantly higher than the value obtained from the integrated puff model.

Fig. 13. Maximum One-hour Concentrations from a Line Source Computed by Gaussian Steady-State Plume and Integrated Puff Models (0.01726 g/m-sec emissions, stability class D)

Also shown in Figure 13 are experimental values obtained at the I-55 at-grade roadway under conditions which most nearly correspond to the conditions assumed for the computations. These conditions, occurring on July 18, 1973, at 7 am, were neutral stability, 4-mile-per-hour wind speed, and an angle of 50° between the roadway and wind direction (see Appendix A). The measured concentrations as shown in Figure 13 were normalized to an emission rate of 0.0172 gm/m-sec after subtracting the background level. The values with an additional normalization to a 2 mph wind speed are also shown. The close agreement of the normalized experimental values with the plume model suggest use of this model for maximum concentration computation.

In the computation of maximum concentration, the steady-state Gaussian plume model is sensitive to the value used for wind speed. A doubling in concentration as the wind goes from 2 to 1 mph illustrates the importance of this parameter. A 2-mph lower limit was selected as a conservative lower limit since a wind speed of less than 3.0 mph was not observed in the experimental studies. The maximum concentrations can, however, be easily adjusted for other wind speeds since concentration is directly

proportional to the inverse of wind speed. The slightly stable stability class E should be used to determine annual one-hour maximums since this class can occur at low wind speeds at night and rush-hour traffic peaks occur during night hours during winter months. The extremely stable class F, which predicts higher concentrations, can occur in a rural environment during nighttime with low wind speed, but in an urban area where major transportation-related pollutant problems occur this stability class is so rarely seen that its existence can be neglected.³⁶

Because of the trapping of pollutants under the lid height (Section 3.1.2), the line-source model predicts unlimited pollutant concentration from an unlimited road length. However, an upper limit of 5 miles was used in the computation of the maximum concentrations. This 5-mile limitation was based on the assumption that a calm wind of 2 mph will not persist in the same direction more than 2 1/2 hours, the travel time from one end of the road to the other.

In summary, one-hour maximum concentrations are based on (1) the Gaussian steady-state plume model, (2) a wind speed of 2 mph, (3) a wind direction which maximizes receptor concentration, (4) Pasquill-Gifford dispersion coefficients for stability class E (slightly stable), (5) a six-foot receptor height, (6) emissions of 0.01726 gm/m/sec (2000 vehicles/hour emitting 50 gm/mile/vehicle), and (7) a lid height of 3,000 feet. These assumptions resulted in the graphs for maximum 1-hour concentrations shown in Figure 14. The meteorological conditions for maximum 1-hour concentrations occur frequently enough to justify assuming that second highest concentrations will be equivalent to the highest. The computed values include the regression coefficients $\alpha = 0.490$ and $\beta = 0.994$ obtained using the experimental data from the at-grade roadway. Using varying receptor heights, the correction factors shown in Figure 15 were obtained for heights other than 6 feet for stability class E.

Fig. 14. Computed One-hour Maximum Concentration from a Line Source (0.01726 g/m-sec emissions, stability class E)

Fig. 15. Correction Factor for Receptor Height for One-hour Maximum Concentration

4.2 ANNUAL MAXIMUM EIGHT-HOUR AVERAGES

NAAQS for carbon monoxide specify an eight-hour concentration of 9 ppm which must not be exceeded more than once per year and thus a roadway environmental impact analysis must attempt to determine the second highest eight-hour average for a one-year period. Use of the conditions assumed to obtain the one-hour maximum in the previous section simply results in eight-hour estimates equal to the one-hour estimates. However, this assumption is not justified without further consideration since the severe meteorological conditions of less than 2 mph wind speed, constant wind direction, and constant stability class E would be implied to exist for eight hours. Rather than accept this assumption, a statistical analysis has been conducted of meteorological conditions during periods when high concentration levels can be expected.

The maximum eight-hour concentrations were assumed to occur during an eight-hour period when the following conditions are all satisfied:

- (1) The entire eight-hour period occurs during the time frame of 5 a.m. to 9 p.m. when traffic levels are at a maximum.
- (2) The average wind speed is less than or equal to 5 knots.
- (3) The cloud cover is 100%, which in combination with low wind speed gives a stability class of D or E.

(Class F was not considered for reasons discussed in Section 4.1.)

Severely restricting the class of meteorological conditions by this approach significantly simplified the required statistical analysis when compared to a statistical analysis of all the possible meteorological combinations during eight-hour periods in an entire year.

To determine the frequency of occurrence of the eight-hour periods satisfying these conditions, 53 months of airport weather data were scanned (Midway Airport, Chicago, Illinois: Jan., 1966-July, 1967, Jan., 1968-Dec., 1969; O'Hare Airport, Chicago, Illinois: Jan.-Oct., 1971). During these months, the defined eight-hour periods occurred 22 times, i.e., at an average rate of approximately 5 times per year. However, it was assumed for purposes of a conservative analysis that 7 such eight-hour periods, non-overlapping, can be expected to occur each year. This number was chosen on

the basis of the maximum annual frequency found (Midway Airport, Jan.-Dec., 1966).

Having defined the eight-hour period during which maximum concentration can occur, the probability distribution for wind speed and direction must be determined to obtain the expected concentration values. The statistics for wind direction were based on the assumption that for each hour during the eight-hour period, the difference between the wind direction and the average direction for the eight-hour period is a random variable which is independent of this difference during other hours in that period. This assumption would not be valid during long periods, say 24 or 48 hours, in which the mean wind direction may vary significantly.

This distribution of wind direction about the mean was compiled using the 53 months of weather data described above. However, to increase the sample on which to base these statistics, the wind fluctuation was assumed independent of cloud cover, that is, the third condition above was removed. Dependence on wind speed was assumed unimportant within the class of periods when the average speed was less than 5 knots. The hour periods with wind speeds below the instrument threshold have undefined wind directions and were thus not included in the directional frequency compilation. With these conditions, 1,076 hours of wind direction were compiled with the resultant fluctuation distribution shown in Figure 16.

Using a similar argument, the wind speed distribution during the defined eight-hour period can be assumed to be randomly varying, with the speed at each hour independent of the speed at other hours within the eight-hour period. This is justified because of the small range of velocities which will result in less than a 5-knot average. The eight-hour periods without the restriction on cloud cover as discussed in the previous paragraph were used for compilation of the wind speed statistics with results, based on 1315 hours of data, as shown in Figure 17.

Assuming now that wind velocity and wind direction fluctuations are independent for the eight-hour periods, the joint probability that a particular wind velocity and wind angle (about a given mean value) will occur simultaneously can easily be computed as the product of the probability of each from Figures 16 and 17. For example the probability of a 3-knot wind speed and a wind angle about the mean of $+ 30^\circ$ is $(.0753) * (.0632) = .00476$.

Fig. 16. Frequency Distribution for the Deviation from Average Wind Direction During 8-hour Periods with Average Wind Speed Less Than 5 Knots

Fig. 17. Frequency Distribution for Wind Speeds During 8-hour Periods with Average Wind Speed Less Than 5 Knots

This joint probability that a given wind speed and direction will occur is also the probability that the pollutant concentration associated with those wind conditions will occur. (This concentration is also dependent on the mean wind direction.) Thus a pollutant concentration probability distribution has been obtained for each hour within the eight-hour period.

The nighttime stability class for overcast skies and low wind speed, E (slightly stable), has been used to compute the concentrations during the eight-hour periods. A more exact analysis would consider the use of the neutral stability class (D) for the part of the eight-hour period occurring during the daytime. However, this would add considerably to the complexity of the following analysis, while resulting in only minor numerical changes. This will be demonstrated in the subsequent discussion.

Having computed the probability distribution for the concentrations at each hour, the probability distribution for the average eight-hour concentration can be obtained from the joint probability distribution for the concentration at each of the 8 hours. The rather lengthy computation of this joint probability can conveniently be avoided by use of the central limit theorem of statistics. This theorem states that if $C_1, C_2, \dots, C_n$ are random samples from any distribution having a finite variance σ^2 and mean μ , then the average, $\bar{C} = \sum_{i=1}^n C_i/n$, for large n is approximately normally distributed with mean μ and variance σ^2/n .³⁷ Applied to the problem of obtaining the probability distribution for the eight-hour average, x_8 , the central limit implies the average can be approximated as a normal distribution with mean

$$\bar{x}_8 = \sum_{i=1}^n \sum_{j=1}^m p_i p_j x_{ij} / mn \quad (23)$$

where p_i is the probability of having wind speed i , p_j is the probability of having wind direction j , and x_{ij} is the concentration level associated with these wind characteristics. The variance of the approximate normal distribution is

$$\text{Var } (x_8) = \frac{\sum_{i=1}^n \sum_{j=1}^m p_i p_j (x_{ij} - \bar{x}_8)^2}{8mn} \quad (24)$$

As discussed previously in this section it has been assumed that the 2 maximum annual eight-hour concentrations will be among 7 eight-hour periods which occur annually satisfying the described conditions. For purposes of comparison with NAAQS (which can be exceeded only once), an estimate must be obtained for the second largest eight-hour average. Having obtained the probability distribution for the eight-hour averages, this estimate can be obtained by using order statistics.³⁷ Let χ_8^2 be the second largest of the 7 eight-hour averages considered. From the theory of order statistics the probability that χ_8^2 is less than ξ_p is

$$\text{Prob} \{ \chi_8^2 < \xi_p \} = \sum_{i=6}^7 \frac{7!}{(7-i)!i!} (1-p)^{7-i} p^i \quad (25)$$

where p is the probability that χ_8 , the concentration for a single eight-hour period, is less than ξ_p , i.e.,

$$\text{Prob} \{ \chi_8 < \xi_p \} = p. \quad (26)$$

Using the normality of χ_8 with parameters given by Equations 23 and 24, Equations 25 and 26 give the result,

$$\text{Prob} \left\{ \chi_8^2 < \bar{\chi}_8 + 1.45 \sqrt{\text{Var}(\chi_8)} \right\} = 0.90, \quad (27)$$

or, in other words, we are 90% confident that the second highest eight-hour average will be less than $\chi_{8,90}^2 \equiv \bar{\chi}_8 + 1.45 \sqrt{\text{Var}(\chi_8)}$.

Still to be determined is the value used for the mean wind direction. For a receptor located equidistant from the end points of a ten-mile roadway and 250 from the edge,* the values of $\chi_{8,90}^2$ as a function of angle between the mean wind direction and the roadway in the range of 0-90° is shown in Figure 18. The values of $\chi_{8,90}^2$ for angles greater than 90° are obtained from Figure 16 using symmetry about the crosswind direction, 90°,

*Other conditions (emission rate, lid height, and initial source description) are as described in Section 4.1.

Fig. 18. Eight-hour Maximum Concentration as a Function of Angle Between Roadway and Mean Wind Direction

and angles less than 0° need not be considered since receptors on the opposite side of the road would see these mean winds as being in the range of 0 - 90° . The values in Figure 18 for $x_{8,90}^2$ show approximately a 10% difference between maximum and minimum values. Because of this small difference it is not overly conservative to use the mean wind angle that gives the maximum eight-hour concentration.

The final result of this discussion is the curve in Figure 19 for the ratio of second highest annual eight-hour average to the maximum one-hour average (Figure 14) for a receptor located equidistant from the ends of a ten-mile road.* Also shown in Figure 19 are equivalent values obtained using the neutral stability class D. The small differences between the two curves justifies the use of the more conservative E class and ignoring the possibility that during part of the maximum eight-hour period the stability class may be D. The conservatism in the results is somewhat offset by the assumption that the prescribed eight-hour periods are nonoverlapping and that 100% cloud cover is required for the maximum to occur. (Stability E can occur during the nighttime hours without 100% cloud cover.)

*Other conditions (emission rate, lid height, and initial source description) are as described in Section 4.1.

As with the one-hour maximum, the eight-hour estimate can be adjusted for varying emission density. The maximum eight-hour average traffic density is typically 50% of the one-hour maximum.³⁸

Fig. 19. Ratio of Second Highest Annual 8-hour and Maximum 1-hour Concentration for Equal Emissions and Stability Class D or E

5.0 CONCLUSIONS AND RECOMMENDATIONS

On the basis of experimental and analytical studies documented in this report, the Gaussian steady-state plume model appears to be an effective tool for the prediction of the air quality impact of highway vehicle pollutant emissions. In particular, this model has been validated in the region less than 500 feet from the downwind edge of both an at-grade roadway and a depressed roadway.

The Gaussian model was found to be sensitive to the assumptions for initial dispersion in the vicinity of the roadway. Assuming uniform dispersion over the roadway (box model) and a Gaussian plume with finite initial dimensions originating from the downwind edge of the roadway provided satisfactory agreement between measured and computed estimates of roadside CO concentrations.

For comparison with NAAQS, estimates of the one-hour and eight-hour maximum annual concentrations in the vicinity of roadways have been obtained. The eight-hour maximum, which is in the range of 25-45% of the one-hour maximum, is based on a 5-year statistical analysis of meteorological data.

Although the Gaussian steady state plume model gives satisfactory predictions of roadside pollutant concentration for the at-grade and depressed roadways considered in this report, additional validation of this model or other models is required in more complex configurations. For example, a detailed description of concentration directly above the roadway requires development of models such as the turbulent wake model introduced in Sec. 2.6. Methods for accurate prediction of concentration in the vicinity of tall buildings, non-flat terrain, overpasses, etc., must still be considered in the early stages of development. Techniques for prediction of maximum one-hour and multi-hour concentrations, as presented in this report for single roadways, would be useful if extended to prediction of total impact in regions impacted by numerous roadways.

APPENDIX A - Roadway Air Monitoring Program

A.1 DESCRIPTION OF SITE LOCATIONS

The first site chosen for the validation of the roadway air dispersion model was in the vicinity of Interstate 55 in the southwest outlying suburbs of Chicago. Data was collected during June and July, 1973. The monitoring site is in an area with flat topography between the exits of Central and Cicero Avenues. A plan view of the site, including placement of monitoring equipment as shown in Fig. A.1 and Fig. A.2, is a photograph taken from the north side of the roadway site. The development of the surrounding land includes railroad tracks just to the north of receptor R3. Trains passed at the maximum rate of one every two hours, and thus had no noticeable effects on carbon monoxide levels in the area. Petroleum product distributors and a private plant road are immediately north of the tracks, both also considered to have little or no effect on receptor CO levels. An empty field, approximately 400 feet in width, extends in both directions for a considerable length along the north side of the interstate (see Fig. A.1). The area to the south of receptors R6 and R7 is primarily residential with some commercial development, however the nearest building is more than 1000 feet from these receptors. A large park without trees lies between the two groups of receptors, R6 and R7 and R8, R4, and R5. Receptors R4 and R5 reside on the outer perimeter of a trucking terminal. By comparison of data from receptors R4 and R5 and receptors R6 and R7 located over 1000 feet from the trucking terminal, the terminal was found to have little effect on concentration except during infrequent periods of high activity with the wind blowing directly from the terminal activity to the receptors. Table A.2 located at the end of this appendix summarizes the data obtained at the I-55 site and also the computed estimates of concentration using Model 1 in Table 3 of Sec. 3.1.

For the depressed roadway monitoring, Interstate 90 at the Lombard Avenue overpass was selected. Measurements at this site were taken in August, 1973. Site topography and equipment placement are shown in Figs. A.3 and A.4. Both sides of the expressway are residential with numerous large trees. Traffic on side streets was light. Table A.3 contains the data obtained at this site and the computed estimates of concentration using Model 1 of Table 5.

Fig. A.1. Plan View of At-grade Roadway Air Monitoring Site, I-55 at Cicero Avenue, Chicago, Illinois

Fig. A.2. I-55 At-grade Roadway Air Monitoring Site.
ANL Neg. No. 190-913-2.

Fig. A.3. Plan View of Depressed Roadway Air Monitoring Site, I-90 at Lombard Avenue, Oak Park, Illinois

Fig. A.4. I-90 Depressed Roadway Air
Monitoring Site.
ANL Neg. No. 190-1368-17.

A.2 AIR SAMPLING TECHNIQUE

The air monitoring stations consisted of a stand supporting a small pump at a height of 6 feet and a container capable of holding numerous sample bags (Fig. A.2). The pump, measured by Environmental Measurements, Inc., is pulsed once every 15 seconds, having an average flow rate of 6 liters per hour. A flexible plastic tubing connects the pump and sample bag. The sample bags are made of aluminized polyester, manufactured by 3M Company. Typically, three receptors were located downwind of the roadway and in addition, receptors were located on the upwind side to obtain background values.

The air samples were laboratory analyzed with a Model 2600 Ecolyzer, manufactured by Energetic Sciences, Inc. The Ecolyzer has the following design specifications:

Sensor -----	Electrochemical
Zero Drift -----	0.5% of Full Scale in 24 hrs
Span Drift -----	1.0% of Full Scale in 24 hrs
Linearity -----	$\pm 1\%$ of Full Scale
Minimum Detectable Sensitivity-----	1 ppm
Analytic Reproducibility -----	$\pm 1\%$ of Full Scale

The manufacturer's specifications also indicate less than 1.0 ppm interference from levels of other pollutants that could reasonably be expected to occur in ambient air. The instrument was calibrated daily using a CO calibrating gas from Scott Research Laboratory, Inc., with a specified concentration of 10.3 ppm, $\pm 5\%$. (Field samples were generally between 3 and 15 ppm.) Additional periodic calibration was performed using a 47-51 ppm CO gas prepared by Energetic Sciences, Inc. A calibration was also made with measurements from a gas chromatograph. A charcoal filter was used to dry scrub the field samples.

A.3 METEOROLOGY

Wind speed and direction and ambient air temperature were obtained by using a Meteorological Research, Inc., Model 1071 mechanical weather station (Fig. A.2) at both expressway locations. A sample of the recordings is given in Fig. A.5. Cloud cover was visually estimated hourly.

N = number of days since January 1.

The solar elevation is then used in conjunction with the fractional cloud cover to determine a quantity I called insolation strength:

$$I = (1 - rf)\sin \alpha \quad (\text{A.3})$$

where:

r = average reflectance of clouds (an estimate of 0.5 was used)

f = fraction of sky with cloud cover

The quantity I will have values between 0 and 1. Intervals are defined as follows:

$.0 \leq I \leq .33$	slight insolation
$.33 < I \leq .67$	moderate insolation
$I > .67$	strong insolation.

This information is used in Table A.1 to determine the stability class.

TABLE A.1. Stability Categories*

Wind Speed (Knots)	Daytime Insolation			Night Clouds	
	Strong	Moderate	Slight	$\geq .5$	$\leq .4$
≤ 3	A	B	B	E	E
3-6	A	B	C	D	E
6-10	B	C	C	D	D
10-12	C	C	D	D	D
> 12	C	D	D	D	D

The neutral class D is assumed for overcast conditions.

*A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable.

A.4 TRAFFIC DATA AND EMISSIONS

Data on traffic volume, speed, and mix are required for the emission computation. A short study was undertaken to establish the most suitable method of obtaining the traffic volume. Traffic was counted continuously.

during a number of hour periods with running totals divided into 1-, 2-, 5-, 10-, and 15-minute intervals. Traffic counts were also compared to data from the Illinois Department of Transportation Expressway Surveillance Project for expressways surrounding the Chicago area. Two five-minute counts, evenly spaced within an hour, were selected to calculate a value for the hourly traffic volume. This procedure fit well within the hourly time period and had an average error under 10%, which was deemed acceptable.

Vehicles were classified and counted in three categories: (1) cars and light-duty vehicles, (2) heavy-duty gasoline vehicles, and (3) diesel-powered vehicles. This breakdown is needed because of the different emission factors these classes of vehicles have. Counts were obtained for each direction of travel and speeds were determined by clocking vehicles over a pre-determined distance.

The emission calculation is illustrated simply as:

$$\left(\begin{array}{c} \text{Emission} \\ \text{Rate} \end{array} \right) = \left(\begin{array}{c} \text{Emission} \\ \text{Factor} \end{array} \right) \times \left(\begin{array}{c} \text{Speed} \\ \text{Factor} \end{array} \right) \times \left(\begin{array}{c} \text{Vehicle} \\ \text{Flow Rate} \end{array} \right) \quad (\text{A.4})$$

All values on the right of the equation are dependent on vehicle class and the total emission rate of a roadway is the sum of the separate vehicle class emission rates. The following emission factors, using a base vehicle speed of 19.6 mph, were used to compute emission rates.

Auto	43.88 gm/veh-mi
Heavy duty vehicle	133.85 gm/veh-mi
Diesels	38.93 gm/veh-mi

The emission factors are for hot operation of the vehicles, and are calculated on the basis of Cook County vehicle registration data for mid-year 1973. These values were generated from the vehicle emission factor computation program, TREFACT.¹

Speed correction factors for both classes of gasoline-powered vehicles are calculated by the following equation:¹

$$\text{S.C.F} = av^b \quad (\text{A.5})$$

where:

$$a = 12.5 \frac{\text{hr}}{\text{mi}}$$

v = average speed of vehicle class

$$b = -.845$$

The speed correction factor given by this equation is equal to 1.0 at the base speed of 19.6 mph. Since diesels run at a fairly constant rpm rate at most road speeds, due to gearing, a constant speed correction factor of 1.0 is used. The computed emissions from the experimental field studies are included in Tables A.2 and A.3.

TABLE A.2. Roadway Air Monitoring Data, I-55 at Cicero Ave., Chicago

Hour	Wind Speed ^a (mph)		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a					
	Wind Dir. Stab. Class	Emissions (gm/m-s)				Vehicle Speed (mph)			Emissions (gm/m-s)		
						Northbound			Southbound		
						Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
<u>6/18/73</u>											
0700	3.5		1	10.1	2.82	4320	60	360	2742	168	210
	90°		2	8.1	1.79	26	25	25	52	47	47
	B		3	7.3		.0265	.0011	.0024	.0092	.0019	.0014
			7 ^b	6.1							
0800	4.5		1	8.1	2.28	3618	186	642	1230	414	510
	110°		2	7.7	1.42	25	24	24	50	44	51
	B		3	5.4	1.01	.0225	.0037	.0043	.0042	.0029	.0034
			6 ^b	4.3							
0900	5.0		1	6.3	1.15	2262	306	534	1044	246	270
	120°		2	5.6	0.70	47	46	45	55	44	47
	A		3	5.6	0.49	.0082	.0035	.0036	.0033	.0029	.0018
			7 ^b	3.9							
<u>6/19/73</u>											
1500	6.5		1	5.5	1.17	2190	156	456	4356	132	450
	180°		2	5.3	0.49	54	59	41	46	45	39
	B		3	4.0	0.29	.0072	.0017	.0031	.0163	.0015	.0030
			7 ^b	3.9							
1700	4.5		1	7.2	3.55	2340	162	372	4584	78	444
	160°		2	6.6	1.98	56	54	49	47	46	45
	B		3	5.1	1.37	.0074	.0016	.0025	.0167	.0009	.0030
			6 ^b	4.3							
<u>6/25/73</u>											
700	4.0		2	8.9	1.91	3120	80	684	1836	300	1224
	60°		3	8.1	1.44	36	36	33	53	48	49
	C		5 ^b	5.8		.0144	.0011	.0046	.0061	.0033	.0082
1400	7.5		1	7.7	0.84	1926	126	270	2430	252	384
	100°		2	7.3	0.60	50	42	42	52	42	44
			4 ^b	6.5		.0067	.0015	.0018	.0082	.0031	.0026
1600	8.5		1	7.8	1.28	3072	120	300	4920	192	348
	90°		2	6.4	1.03	47	42	39	42	46	39
	C		4 ^b	5.7		.0112	.0015	.0020	.0197	.0022	.0023
1700	1.43		1	7.4	1.43	2286	114	414	4956	294	228
	90°		2	6.5	1.04	49	44	41	40	37	29
	C		4 ^b	5.7		.0081	.0014	.0028	.0207	.0040	.0015
<u>7/9/73</u>											
1500	10.0		1	6.9	1.23	2274	240	282	3978	378	294
	150°		2	5.5	0.75	56	52	46	56	52	46
	C		3	4.4	0.53	.0072	.0025	.0019	.0125	.0039	.0020
			5 ^b	4.2							
1600	10.5		1	6.4	1.70	2466	246	306	4650	312	372
	160°		2	5.5	0.95	48	41	41	53	54	46
	C		3	5.5	0.66	.0089	.0031	.0021	.0154	.0031	.0025
			4 ^b	3.8							

TABLE A.2. (Contd.)

Hour	Wind Speed ^a (mph)		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a					
	Wind Dir. Stab. Class	Vehicle Speed (mph)				Emissions (gm/m-s)			Emissions (gm/m-s)		
						Northbound			Southbound		
						Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
<u>7/10/73</u>											
0700	9.5 320° C	5 _b 2 ^b	4.6 4.0	0.94	4189 21 .0302	157 18 .0038	281 19 .0019	2016 38 .0089	264 37 .0036	912 32 .0061	
0800	5.0 310° B	4 5 _b 1 ^b	4.2 4.0 2.7	1.15 0.78	2598 47 .0095	618 50 .0065	978 41 .0066	1386 44 .0054	228 38 .0031	774 43 .0052	
0900	6.0 320° B	4 5 _b 2 ^b	3.8 3.3 2.7	0.59 0.39	1818 46 .0069	234 41 .0029	570 41 .0038	840 41 .0034	96 41 .0012	468 35 .0031	
1500	7.0 300° B	4 5 _b 2 ^b	3.8 3.8 2.9	0.66 0.46	2538 60 .0075	222 52 .0023	282 55 .0019	4572 53 .0150	102 53 .0010	360 42 .0024	
1600	10.0 320° B	4 5 _b 1 ^b	5.0 4.2 2.5	0.62 0.41	2844 49 .0100	126 38 .0017	432 36 .0029	5028 44 .0193	120 48 .0013	354 44 .0024	
1700	10.0 330° C	4 5 _b 2 ^b	4.6 4.2 2.5	0.89 0.62	2472 46 .0091	108 44 .0013	420 45 .0028	4626 43 .0181	96 44 .0011	438 39 .0029	
<u>7/11/73</u>											
0800	9.0 310° C	4 5 _b 3 ^b	3.9 3.7 1.6	1.03 0.75	3900 39 .0166	228 36 .0032	492 33 .0033	2484 50 .0086	204 50 .0022	1396 42 .0094	
0900	9.0 320° C	4 5 _b 1 ^b	3.2 2.8 1.6	0.66 0.47	2016 55 .0065	204 51 .0021	720 40 .0048	1500 52 .0051	216 49 .0023	714 40 .0048	
1600	7.5 320° C	4 5 8 _b 1 ^b	4.1 3.7 5.7 1.8	1.61 1.15 2.49	3468 46 .0130	384 40 .0049	258 42 .0017	4950 31 .0260	288 28 .0050	270 28 .0018	
1700	7.0 330° C	4 5 8 _b 1 ^b	3.7 3.7 5.5 1.8	1.73 1.20 2.84	2370 47 .0086	180 40 .0023	252 40 .0017	4626 25 .0286	252 20 .0058	186 21 .0012	

TABLE A. 2. (Contd.)

Hour	Wind Speed ^a (mph)		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a Vehicle Speed (mph)					
	Wind Dir. Stab. Class	Emissions (gm/m-s)				Northbound			Southbound		
						Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
7/16/73											
0700	3.0	4	7.8	3.12	4440	264	396	2700	102	270	
	310°	5	7.3	2.12	18	14	15	54	50	46	
	B	8 _b	10.0	5.27	.0367	.0081	.0027	.0087	.0011	.0018	
		3 _b	4.6								
0800	4.0	4	6.0	1.34	3054	522	432	1404	234	582	
	310°	5	5.7	0.91	40	36	34	55	48	49	
	B	8 _b	7.8	2.26	.0128	.0073	.0029	.0045	.0025	.0039	
		3 _b	3.7								
0900	4.5	4	5.3	0.77	1854	246	456	1116	162	372	
	310°	5	4.6	0.52	42	37	35	54	48	50	
	B	8 _b	5.7	1.30	.0075	.0033	.0031	.0037	.0018	.0025	
		3 _b	3.0								
1000	5.5	4	4.1	0.42	1506	240	480	1200	246	354	
	330°	5	3.0	0.64	48	43	46	52	48	48	
	B	8 _b	3.9	1.18	.0054	.0029	.0032	.0040	.0027	.0024	
		3 _b	2.3								
1100	6.0	4	3.9	0.57	1500	204	384	1392	174	456	
	330°	5	3.0	0.37	47	40	44	52	52	50	
	A	8 _b	3.9	1.06	.0055	.0026	.0026	.0047	.0018	.0031	
		3 _b	2.3								
7/17/73											
0700	3.0	1	8.0	4.50	3996	108	192	2772	168	276	
	50°	2	6.2	2.64	18	14	16	54	50	48	
	B	3	5.3	1.84	.0331	.0034	.0013	.0091	.0018	.0019	
		4 _b	3.4								
0800	3.0	1	6.9	2.31	3000	300	540	1530	294	396	
	80°	2	5.5	1.46	45	40	42	52	47	49	
	B	3	4.6	1.04	.0113	.0039	.0036	.0051	.0033	.0027	
		5 _b	3.7								
0900	2.0	1	5.5	2.48	2100	264	408	1176	234	240	
	80°	2	4.4	1.57	50	43	47	53	50	48	
	B	3	3.9	1.12	.0074	.0032	.0027	.0039	.0025	.0016	
		4 _b	3.0								
1000	3.0	1	4.6	1.71	1698	306	342	1314	252	354	
	70°	2	3.7	1.07	49	42	45	54	49	48	
	A	3	3.2	0.76	.0060	.0038	.0023	.0043	.0027	.0024	
		4 _b	2.75								

TABLE A.2. (Contd.)

Hour	Wind Speed ^a (mph)		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a					
	Wind Dir. Stab. Class	Vehicle Speed (mph)				Emissions (gm/m-s)					
						Northbound			Southbound		
						Auto	HDVC	Diesel	Auto	HDVC	Diesel
<u>7/18/73</u>											
0700	3.5		1	8.3	3.29	4350	144	246	2376	144	264
	80°		2	6.7	2.64	28	25	26	50	44	50
	C		3	6.1	2.17	.0246	.0027	.0016	.0083	.0017	.0018
			5 ^b	3.8							
0800	6.0		1	5.9	1.71	3282	462	468	1326	384	570
	110°		2	4.4	1.36	43	37	40	53	49	48
	B		3	4.0	1.11	.0131	.0063	.0031	.0044	.0042	.0038
			4 ^b	3.6							
0900	6.5		1	4.4	1.00	1908	234	456	1158	234	300
	120°		2	3.4	0.78	50	42	44	56	52	50
	B		3	3.2	0.63	.0066	.0027	.0031	.0037	.0024	.0020
			4 ^b	3.0							
1000	6.5		1	4.2	0.91	1998	324	384	1320	168	372
	130°		2	3.2	0.54	50	42	42	51	48	49
	B		3	3.0	0.37	.0069	.0040	.0026	.0045	.0019	.0025
			4 ^b	2.6							
1100	8.5		1	4.0	0.80	1734	186	294	2028	180	450
	150°		2	3.0	0.43	51	44	44	55	48	50
	B		3	2.8	0.29	.0059	.0022	.0020	.0064	.0020	.0030
			5 ^b	2.6							
<u>7/19/73</u>											
0700	4.0		1	8.5	4.06	4356	138	306	2742	204	288
	130°		2	6.3	2.74	20	19	19	52	46	49
	C		3	5.5	2.03	.0325	.0033	.0021	.0092	.0023	.0019
			5 ^b	3.6							
0800	6.0		1	7.1	1.57	3642	468	552	1410	300	372
	140°		2	5.7	0.88	49	44	43	52	48	48
	B		3	4.2	0.67	.0129	.0055	.0037	.0047	.0033	.0025
			4 ^b	3.8							
0900	7.0		1	5.3	1.34	2256	270	390	1020	336	390
	150°		2	4.0	0.81	54	48	48	53	45	48
	C		3	3.4	0.58	.0074	.0029	.0026	.0034	.0038	.0026
			4 ^b	2.8							
1000	7.0		1	4.8	0.83	1644	198	324	1326	234	324
	150°		2	5.3	0.44	55	51	49	55	50	53
	B		3	4.0	0.30	.0053	.0021	.0022	.0042	.0025	.0022
			4 ^b	2.8							

TABLE A.2. (Contd.)

Hour	Wind Speed ^a		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a					
	Wind Dir.	Stab. Class				Vehicle Speed (mph)			Emissions (gm/m-s)		
						Northbound			Southbound		
					Auto	HDVC	Diesel	Auto	HDVC	Diesel	
<u>7/23/73</u>											
0700	5.0		2	6.7	2.74	3804	132	264	2340	96	228
	30°		3	5.7	2.09	22	20	18	57	51	53
	C		5 ^b	3.6		.0268	.0030	.0018	.0073	.0010	.0015
0800	4.0		1	7.9	2.60	2916	438	354	1194	354	456
	45°		2	6.7	1.93	51	47	42	54	49	51
	C		3	5.7	1.53	.0100	.0045	.0024	.0039	.0038	.0031
			4 ^b	3.4							
0900	5.5		1	6.9	1.59	2016	330	390	1152	282	396
	40°		2	5.9	1.16	55	50	48	55	52	50
	C		3	4.8	0.90	.0064	.0035	.0026	.0037	.0029	.0027
			4 ^b	3.6							
1000	5.5		1	6.5	2.17	1518	276	270	1356	264	408
	20°		2	5.7	1.38	54	50	50	54	51	51
	C		3	5.0	1.02	.0049	.0029	.0018	.0044	.0028	.0027
			5 ^b	3.6							
<u>7/25/73</u>											
0900	4.5		1	4.4	1.70	2040	372	510	1200	264	366
	150°		2	3.2	0.91	50	43	40	53	45	50
	B		3	2.4	0.61	.0070	.0045	.0034	.0039	.0030	.0025
			5 ^b	2.4							
1000	5.5		1	3.6	1.02	1752	306	354	1392	186	354
	130°		2	3.2	0.60	50	42	44	59	47	52
	B		3	2.6	0.42	.0060	.0038	.0024	.0092	.0021	.0024
			4 ^b	2.4							
1100	6.5		1	4.0	0.91	1434	168	318	1434	190	384
	160°		2	3.2	0.46	51	45	42	56	52	49
	B		3	2.6	0.30	.0049	.0019	.0021	.0045	.0020	.0026
			5 ^b	2.4							

TABLE A.2. (Contd.)

Hour	Wind Speed ^a	Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a					
	Wind Dir.				Vehicle Speed (mph)			Emissions (gm/m-s)		
	Stab. Class				Northbound			Southbound		
					Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
7/26/73										
0700	7.0	1	5.9	3.81	4344	96	168	2562	138	252
	160°	2	4.4	2.12	16	20	16	52	49	47
	B	3	3.6	1.47	.0399	.0022	.0011	.0086	.0015	.0017
		5 ^b	2.4							
0800	7.5	1	5.7	2.31	3372	420	504	1458	420	372
	160°	2	3.8	1.29	38	38	36	52	47	46
	B	3	3.2	0.89	.0147	.0056	.0034	.0049	.0047	.0025
		4 ^b	2.6							
0900	9.5	1	3.6	1.91	2190	180	432	1080	210	366
	170°	2	2.8	1.07	42	40	41	53	46	48
	B	3	2.4	0.74	.0088	.0023	.0029	.0036	.0024	.0025
		4 ^b	2.2							

^aVertical list of headings corresponds to vertical placement of data.

^bUpwind receptor is used to obtain a value for the background concentration of CO.

^cHeavy Duty Vehicles (greater than 6000 lb GVW).

TABLE A.3. Roadway Air Monitoring Data, I-90 at Lombard Ave., Oak Park, Illinois

Hour	Wind Speed ^a (mph)		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Traffic Volume (veh/hr) ^a					
	Wind Dir. Stab. Class	Vehicle Speed (mph)				Emissions (gm/m-s)					
						Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
<u>8/8/73</u>											
0900	3.0	1	6.0	2.64	3840	324	246	2262	354	192	
	70°	2	4.5	1.43	54	51	50	55	48	48	
	B	3	4.25	1.09	.0125	.0034	.0017	.0072	.0039	.0013	
		5 ^b	2.5								
1000	3.5	1	5.5	2.04	3282	288	270	2346	330	198	
	80°	2	4.25	1.13	54	51	49	55	50	47	
	B	3	4.0	0.86	.0107	.0030	.0018	.0075	.0035	.0013	
		6 ^b	2.5								
1100	5.5	1	5.75	1.34	3108	288	228	3210	246	240	
	90°	2	4.25	0.75	55	52	49	53	51	48	
	B	3	4.0	0.57	.0100	.0029	.0015	.0106	.0026	.0016	
		6 ^b	2.25								
1200	7.5	1	5.25	1.06	2916	252	150	3084	336	168	
	100°	2	4.0	0.70	54	53	49	51	49	48	
	C	3	3.75	0.57	.0095	.0026	.0010	.0105	.0036	.0011	
		6 ^b	2.25								
1300	8.0	1	5.5	1.21	3204	306	288	3084	336	210	
	100°	2	4.5	0.80	40	39	37	53	49	50	
	C	3	3.75	0.65	.0134	.0040	.0019	.0102	.0036	.0152	
		6 ^b	2.25								
<u>8/9/73</u>											
0900	3.5	1	7.0	2.20	3864	216	222	2298	270	228	
	100°	2	5.5	1.22	49	43	44	52	46	51	
	B	3	5.0	0.93	.0138	.0026	.0015	.0077	.0030	.0015	
		6 ^b	3.0								
1000	4.0	1	6.0	1.92	3678	240	270	2442	300	258	
	80°	2	4.5	1.06	51	48	48	54	49	50	
	B	3	4.25	0.81	.0125	.0026	.0018	.0079	.0032	.0017	
		6 ^b	2.75								
1100	5.0	1	6.0	1.62	3462	156	318	3078	336	162	
	110°	2	4.5	0.88	51	46.8	46	53	48	52	
	B	3	4.0	0.67	.0118	.0018	.0021	.0101	.0037	.0011	
		6 ^b	2.5								
1200	6.0	1	5.5	1.59	3258	180	258	2988	264	162	
	140°	2	4.0	0.75	52	52	50	53	47	49	
	B	3	3.75	0.55	.0110	.0019	.0017	.0099	.0029	.0011	
		6 ^b	2.25								
<u>8/13/73</u>											
0900	3.0	1	9.75	2.68	3822	186	246	1950	306	276	
	60°	2	8.25	1.40	50	47	50	52	50	52	
	B	3	7.75	1.06	.0133	.0021	.0017	.0065	.0033	.0019	
		5 ^b	5.75								
1000	2.5	1	8.0	3.01	3300	210	228	2412	342	198	
	70°	2	6.75	1.64	48	48	48	54	51	47	
	B	3	6.0	1.24	.0118	.0023	.0015	.0078	.0036	.0013	
		5 ^b	4.0								
1100	3.0	1	6.75	2.94	3516	342	282	2724	336	168	
	60°	2	5.75	1.54	51	48	48	53	50	50	
	B	3	5.5	1.16	.0121	.0038	.0019	.0090	.0036	.0011	
		5 ^b	4.0								

TABLE A.3. (Contd.)

					Traffic Volume (veh/hr) ^a					
Wind Speed ^a (mph)		Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Vehicle Speed (mph) ^a					
Wind Dir. Stab. Class	Emissions (gm/m-s)									
	Eastbound				Westbound					
					Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
8/13/73										
(Contd.)										
1200	2.5 30° B	1	7.5	3.96	3018	216	174	2850	216	180
		2	6.0	1.72	51	47	47	54	49	51
		3	5.75	1.25	.0104	.0024	.0012	.0092	.0023	.0012
		5 ^b	4.25							
1300	4.0 10° B	1	7.5	2.92	3462	262	198	3180	240	144
		2	5.5	1.04	50	50	48	51	51	50
		3	5.0	0.72	.0120	.0028	.0013	.0109	.0025	.0010
		5 ^b	3.5							
8/16/73										
0900	3.0 80° B	2	5.75	1.51	4170	300	210	2262	396	216
		3	5.5	1.15	51	50	49	53	51	49
		5 ^b	3.5		.0142	.0032	.0014	.0075	.0041	.0015
1000	3.0 70° B	1	6.75	2.78	3768	288	186	2766	366	276
		2	5.25	1.51	53	53	49	54	49	49
		3	5.0	1.15	.0125	.0030	.0012	.0090	.0090	.0019
		6 ^b	2.75							
1100	3.5 100° B	1	6.5	2.25	3474	300	222	3114	288	216
		2	4.75	1.25	53	52	49	55	48	50
		3	4.25	0.95	.0115	.0030	.0015	.0100	.0032	.0015
		6 ^b	2.25							
1200	3.0 80° B	1	5.75	2.73	3294	312	252	3180	384	270
		2	4.75	1.51	53	51	50	55	50	49
		3	4.25	1.15	.0109	.0033	.0017	.0102	.0041	.0018
		6 ^b	2.0							
8/17/73										
0900	3.3 75° B	1	7.0	2.36	3852	252	210	2208	354	192
		2	5.0	1.30	50	47	46	54	48	51
		3	4.0	0.99	.0135	.0028	.0014	.0072	.0038	.0013
		5 ^b	4.0							
1000	3.0 90° B	1	6.75	2.59	3492	210	252	2772	342	352
		2	4.5	1.44	49	47	49	55	49	49
		3	4.25	1.11	.0123	.0024	.0017	.0089	.0037	.0017
		6 ^b	2.5							
1100	2.5 90° B	1	6.5	3.16	3720	234	204	2922	306	162
		2	4.0	1.76	48	44	43	55	52	48
		3	4.0	1.35	.0135	.0027	.0014	.0094	.0031	.0011
		6 ^b	2.75							
1200	3.0 80° B	1	6.5	2.67	3516	198	216	3414	318	174
		2	4.0	1.48	53	46	45	53	48	50
		3	3.5	1.13	.0117	.0022	.0015	.0113	.0035	.0012
		6 ^b	2.5							
1300	3.0 90° B	1	5.75	2.77	3474	198	258	3420	342	180
		2	4.25	1.54	49	42	45	53	46	48
		3	4.0	1.18	.0117	.0022	.0015	.0013	.0035	.0012
		6 ^b	2.75							

TABLE A.3. (Contd.)

Wind Speed ^a (mph)					Traffic Volume (veh/hr) ^a					
Hour	Wind Dir. Stab. Class	Receptor Number	Exp. CO Conc. (ppm)	Computed CO Conc. (ppm)	Vehicle Speed (mph)					
					Emissions (gm/m-s)			Emissions (gm/m-s)		
					Eastbound			Westbound		
					Auto	HDV ^c	Diesel	Auto	HDV ^c	Diesel
<u>8/22/73</u>										
0900	5.0	1	5.25	2.02	3264	312	168	2208	270	228
	10°	2	5.0	0.72	54	50	48	55	50	54
	B	3	4.0	0.50	.0105	.0033	.0011	.0071	.0028	.0015
		7 5 ^b	3.75 2.75	0.57						
1000	5.0	2	5.0	0.90	3294	306	138	2634	246	252
	30°	7	4.0	0.03	55	49	47	53	51	49
	B	6 ^b	3.5		.0106	.0033	.0009	.0087	.0026	.0017
1100	4.5	1	5.5	2.26	3462	318	168	3450	312	186
	45°	2	4.25	1.09	53	49	49	53	50	52
	B	3	4.0	0.81	.0114	.0034	.0011	.0114	.0033	.0012
		6 ^b	2.75							
1200	4.0	1	5.5	2.32	3090	336	222	3024	264	240
	45°	2	4.5	1.13	53	51	49	55	50	51
	B	3	4.0	0.84	.0102	.0035	.0015	.0097	.0028	.0016
		6 ^b	2.5							
1300	3.5	1	6.0	3.1	3084	366	234	2988	216	180
	10°	2	3.0	1.10	55	51	52	55	50	52
	B	3	3.0	0.77	.0099	.0038	.0016	.0096	.0023	.0012
		5 ^b	2.5							
<u>8/23/73</u>										
0900	3.5	1	9.0	2.48	3474	282	168	1962	306	132
	60°	3	9.0	1.53	52	48	49	55	49	48
	C	6 ^b	5.5		.0116	.0031	.0011	.0063	.0033	.0009
1000	4.0	1	8.0	3.12	3486	348	240	2352	312	198
	40°	3	7.5	1.71	54	49	49	52	49	46
	B	6 ^b	4.5		.0113	.0038	.0016	.0079	.0033	.0013
1100	3.0	1	10.0	4.63	3600	420	228	3192	264	240
	40°	2	9.0	3.09	54	51	49	54	45	46
	B	3	9.25	2.54	.0117	.0044	.0015	.0104	.0030	.0016
		6 ^b	5.0							

^aVertical list of headings corresponds to vertical placement of data.

^bUpwind receptor is used to obtain a value for the background concentration of CO.

^cHeavy Duty Vehicles (greater than 6000 lb GVW).

APPENDIX B - Computer Simulation of the Gaussian Steady-state Line-source Model

In this appendix is presented the computer program which has been developed to implement the steady-state Gaussian plume model for line sources of finite length described in Section 3.1. The computer program is in the form of a series of subroutines which compute the concentration at a single receptor point resulting from emissions from a single straight segment of roadway.

The normalized receptor concentration is obtained by including the following Fortran statement in a user-written calling program:

```
CALL ASSLM (X1,Y1,Z1,X2,Y2,Z2,XR,YR,ZR,RMH,RMW,WD,HL,JSTAB,CONC)
```

The arguments (X1,Y1,Z1) and (X2,Y2,Z2) are respectively the left and right coordinates in meters of the end points of a roadway where the positive x-axis is in the direction of defined north, the positive y-axis is in the corresponding easterly direction, and the z-axis is in the vertical direction. (The simulation assumes an average roadway or line elevation of $(Z1+Z2)/2$.) The receptor coordinates are (XR,YR,ZR).

The arguments RMH and RMW are respectively the height and width in meters of the initial dispersion of the plume at the source. These parameters are used to determine the virtual distances x_y and x_z in Eqs. 18 and 19 by setting $RMH = h$ and $RMW = w$. To simulate uniform concentration to a height RMH, the program places two sources of equal strength at distances $h/2$ above and below the specified roadway elevation as discussed in Section 3.1. To implement the combination of a box model over the roadway and a Gaussian plume model with finite initial dispersion downwind as suggested by the model validation studies presented in Section 3.1, (X1,Y1,Z1) and (X2,Y2,Z2) are the coordinates of the end points of the downwind edge of the roadway, and RMH and RMW are both set equal to 6.09 meters (20 feet). Use of zero values for RMH and RMW will be accepted by the program, however unrealistically high concentrations will be predicted for receptors located near the source.

The argument WD is wind direction in degrees (0° - 360°) measured in a clockwise direction with a wind traveling from north to south specified as zero degrees. Angles between the roadway and wind direction of zero or 90 degrees are treated as special cases by the program, however no approximations beyond those implied by the mathematical model in Section 3.1 are assumed.

HL is the inversion or lid height in meters.

The atmospheric stability is specified by the following values of JSTAB:

<u>JSTAB</u>	<u>Stability</u>
1	A - extremely unstable
2	B - moderately unstable
3	C - slightly unstable
4	D - neutral
5	E - slightly stable
6	F - moderately stable

The extremely unstable class (JSTAB=1) can be specified but will be treated as moderately unstable (JSTAB=2) because of the unrealistically low values predicted by the lower class JSTAB=1. A procedure for computing stability based on wind speed, cloud cover and sun inclination is documented in Appendix A. The dispersion coefficients, $\sigma_y(x)$ and $\sigma_z(x)$, given by Pasquill-Gifford³¹ are used in the program, however these coefficients can be revised by appropriate alteration of the subroutines SIGY and SIGZ, respectively.

On return from the subroutine ASSIM, CONC will be equal to the normalized concentration ($\chi u/Q$). To obtain the unnormalized concentration χ in units of (gm/m^3), CONC must be divided by the wind speed u (m/sec) and multiplied by the average emission rate Q ($\text{gm}/\text{m-sec}$). (The units of gram-meter-second are used throughout the program.)

The flow diagram for the program is given in Figure B.1, and a listing of the various required subroutines in IBM/360 FORTRAN language follow. The input and output arguments of the user-called subroutine ASSIM are single precision (REAL*4). The numerical integration subroutine HAVIE is based on Havie quadrature.

Fig. B.1. Flow Diagram for ASSLM Line Source Computer Subroutine

FORTTRAN Listing for Finite Line Source Gaussian
Steady-State Plume Dispersion Model

ASSLM

```

SUBROUTINE ASSLM(X1,Y1,Z1,X2,Y2,Z2,XR,YR,ZR,RMW,RMH,WD,HL,
* JSTAB,CONC)
EXTERNAL SIGGY,SIGGZ,FT
COMMON /FIRST/ X0,BETA,HLID,NS,XCRIT
COMMON /STABIL/ NSTB,SIGY0,SIGZ0
COMMON /VIRT/ SUDOY,SUDOZ,REZ,SOZ
REAL*8 XUD,XLD,EPS,FT,HAVIE,AA,BB
HLID=HL
NSTB=JSTAB
NS=NSTB
THU=WD
REZ=ZR
SOZ=(Z1+Z2+RMH)*0.5
DTR=0.01745329
THUR=THU*DTR
C*****COMPUTE LID HEIGHT DEPENDENT CRITICAL DISTANCE XCRIT.
SIGZ0=HLID*0.47
EPP=0.001
A=SIGZ0
B=A/10.
NUL=10
NP=0
N4=1
CALL GUESS2(SIGGZ,A,B,SZ,EPP,NUL,NFU,NP,N4)
XCRIT=SZ
C*****COMPUTE VIRTUAL DISTANCE XZ
SIGZ0=RMH/2.4
A=SIGZ0
B=A/10.
CALL GUESS2(SIGGZ,A,B,SZ,EPP,NUL,NFU,NP,N4)
SUDOZ=SZ
C*****COMPUTE VIRTUAL DISTANCE XY
SIGY0=RMW/2.4
A=SIGY0
B=A/10.
CALL GUESS2(SIGGY,A,B,SZ,EPP,NUL,NFU,NP,N4)
SUDOY=SZ
IF(THU.LT.0.0)THU=THU+360.
IF(THU.GT.360.)THU=THU-360.
T=THU*DTR
C*****SETUP NEW COORDINATE SYSTEM AND COMPUTE LIMITS OF INTEGRATION
TL=SQRT((X2-X1)**2+(Y2-Y1)**2)
CALL CROSS(X1,Y1,X2,Y2,XR,YR,T,XP,YP,XZERO,BETA,THEL)
IF(BETA.NE.0.0)GO TO 90
C*****SPECIAL CASE OF ZERO ANGLE BETWEEN ROADWAY AND WIND DIRECTION
THUP=THU+90.
IF(THU.GT.185.)THUP=THU-90.
T=THUP*DTR

```

ASSIM (Contd.)

```

      CALL CROSS(X1,Y1,X2,Y2,XR,YR,T,XP,YP,XZERO,BETA,THEL)
      BETA=0.0
      A=SQRT((XP-X1)**2+(YP-Y1)**2)
      B=SQRT((XP-X2)**2+(YP-Y2)**2)
      XU=0.
      XL=0.
      IF(THU.GT.0.) GO TO 20
      IF(YP.GT.Y2) GO TO 100
      XU=B
      IF(YP.GT.Y1) GO TO 100
      XL=A
      GO TO 100
20    IF(THU.GT.179.5) GO TO 30
      IF(XP.GT.X2) GO TO 100
      XU=B
      IF(XP.GT.X1) GO TO 100
      XL=A
      GO TO 100
30    IF(THU.GT.180.5) GO TO 40
      IF(YP.LT.Y1) GO TO 100
      XU=A
      IF(YP.LT.Y2) GO TO 100
      XL=B
      GO TO 100
40    IF(XP.LT.X1) GO TO 100
      XU=A
      IF(XP.LT.X2) GO TO 100
      XL=B
      GO TO 100
50    CALL LIMITS(X1,Y1,X2,Y2,XP,YP,XZERO,T,THEL,BETA,TL,XL,XU,
      * DL,UL)
100   CONTINUE
C****NUMERICAL INTEGRATION USING HAVIE QUADRATURE
      CONC=0.
      IF(XL.EQ.XU) RETURN
      IF(XL.EQ.0.0) XL=0.01
      XUD=XU
      XLD=XL
110   XB=XZERO
      DX=ABS(XB-XL)
      DX=AMAX1(DX,10.)
      BB=AMAX1(0.01,XL)
120   AA=BB
      EPS=0.0001
      M=12
      N=0
      BB=BB+DX
      IF(BB.GT.XUD) BB=XUD
      TCONC=HAVIE(AA,BB,EPS,M,N,FT)

```

ASSLM (Contd.)

```

CONC=CONC+TCONC
IF(TCONC.LE.1.E-4)DX=DX*2.
ADD=ABS(TCONC/CONC)
IF(ADD-1.E-4) 140,130,130
130 IF(BB+0.001.LT.XUD) GO TO 120
140 IF(BETA.LT.1.56) RETURN
IF(XL.GT.0.0) RETURN
BB=0.01
XUD=ABS(XL)
XL=1.
GO TO 120
END

```

GUESS2

```

SUBROUTINE GUESS2(FCTN,PGGA,PGGB,PZERO,TOL1,
1 NITMAX,NFLAG1,NFLAG3,NFLAG4)
DIMENSION PGG(50),ERR(50)
C THIS SUBROUTINE FINDS A ZERO OF THE FUNCTION FCTN(X)
C FCTN MUST BE DEFINED BY AN EXTERNAL FUNCTION STATEMENT.
C PGGA AND PGGB ARE TWO INITIAL GUESSES
C TOL1 = ALLOWABLE DEVIATION FROM ZERO IF NFLAG4=1
C = ALLOWABLE DIFFERENCE BETWEEN LAST TWO
C PZERO VALUES IF NFLAG4=-1
C NITMAX = MAX NO. OF ITERATIONS
C NFLAG3 = 1 IF WANT PRINT OUT VIA THE SUBROUTINE
C NFLAG3 = 0 IF NO PRINT OUT DESIRED
C INITIALLY CODE SETS NFLAG1=0. IF A DIVIDE
C CHECK OR EXCESS NO. OF ITERATIONS OCCURS, SETS NFLAG1=1
C CCCCC MODIFIED FOR PZERO .GT.0. ONLY
C SEE STATEMENT 16
C
DELTP=ABS(PGGA-PGGB)
NFLAG1=0
NIT=2
PGG(1)=PGGA
PGG(2)=PGGB
I=3
IA=1
IB=2
ERRA=FCTN(PGGA)
ERR(1)=ERRA
IF(NFLAG4) 2,2,4
2 GO TO 5
4 VALUE=ABS (ERRA)
IF(VALUE-TOL1)400,400,5

```

GUESS2 (Contd.)

```

400 PGGB=PGG(1)
    NIT=1
    ERRB=ERRA
    GO TO 100
5. ERRB=FCTN(PGGB)
    IF(NFLAG4) 6,6,8
6. VAL=PGG(IA)-PGG(IB)
    VALUE=ABS (VAL)
    GO TO 9
8. VALUE = ABS (ERRB)
9. IF(VALUE-TOL1) 100,100,10
10. CONTINUE
    VALUE=ABS (ERRA-ERRB)
    IF(VALUE-1.E-28) 75,75,15
15. PGG(1)=PGG(1B) - ERRB*(PGG(1A)-PGG(1B))/(ERRA-ERRB)
16. IF(PGG(1).LE.0.)PGG(1)=.001*DELTP
20. ERRA=ERRB
    ERR(1B)=ERRB
    PGGB=PGG(1)
    I=I+1
    IA=I-2
    IB=I-1
    NIT=NIT+1
    IF(NIT-NITMAX) 5,5,70
C
70. PRINT 71,NITMAX
71. FORMAT('1MAX. NO. ITER. FOR PZERO EXCEEDED,NITMAX =', 15 //)
    NFLAG1 = 1
    GO TO 100
C
75. CONTINUE
    NFLAG1=1
    GO TO 100
C
100. IF(NFLAG3) 80,80,101
    80. J=I-1
        ERR(J)=ERRB
        PZERO=PGGB
        GO TO 125
C
101. PZERO=PGGB
    J=I-1
    ERR(J)=ERRB
104. FORMAT ( // // // // )
105. FORMAT( 22H NO.OF ITERATIONS =      15      // )
115. FORMAT( 4X, 4H NIT ,9X, 6H GUESS ; 16X, 6H ERROR      // )
120. FORMAT(18,2E20.8)
125. RETURN
    END

```

SIGGY

```

FUNCTION SIGGY(X)
COMMON /STABIL/ NSTB, SIGY0, SIGZ0
SIGGY=SIGY(NSTB,X)-SIGY0
RETURN
END

```

SIGGZ

```

FUNCTION SIGGZ(X)
COMMON /STABIL/ NSTB, SIGY0, SIGZ0
SIGGZ=SIGZ(NSTB,X)-SIGZ0
RETURN
END

```

SIGY

```

FUNCTION SIGY(J,X)
C****COMPUTES HORIZONTAL
C   DISPERSION COEFFICIENTS BASED ON TURNER WORKBOOK.
C   WHERE THE SIGMAS GIVEN IN THE WORKBOOK FOR
C   TEN MINUTE SAMPLINGS ARE SCALED TO 1 HOUR
C   AVERAGES BY A FACTOR OF 1.43
C   J=1,2,3,4,5,6 ARE CLASSES A,B,C,D,E,F
C   CLASS A USES B COEFFICIENTS
C   DIMENSION C(5),D(5)
C   DATA C/155.,100.,68.,50.,34./, D/.91.,.92.,.93.,.90.,.93/
C   JJ=MAX0(J-1,1)
C   SIGY=C(JJ)*((X/1000.)*D(JJ))*1.43
RETURN
END

```

SIGZ

```

FUNCTION SIGZ(J,X)
C****COMPUTES VERTICAL
C   DISPERSION COEFFICIENTS BASED ON TURNER WORKBOOK.
C   WHERE THE SIGMAS GIVEN IN THE WORKBOOK FOR
C   TEN MINUTE SAMPLINGS ARE SCALED TO 1 HOUR
C   AVERAGES BY A FACTOR OF 1.43
C   J=1,2,3,4,5,6 ARE CLASSES A,B,C,D,E,F
C   CLASS A USES B COEFFICIENTS
C   DIMENSION C(3,5),D(3,5)

```


SIGZ (Contd.)

```

DATA C/110.,110.,110.,60.,60.,60.,33.,33.,40.,21.5,21.5,
* 36.,14.,14.,23.5/
DATA D/1.,1.09,1.09,.92,.92,.92,.60,.61,.53,.70,.56,.35,
* .78,.53,.30/
I=1
Y=X/1000.
IF(Y.GT. 1.) I=2
IF(Y.GT. 10.) I=3
JJ=MAX0(J-1,1)
SIGZ=(C(I,JJ)*(X/1000.))*D(I,JJ))*1.43
RETURN
END

```

CROSS

```

SUBROUTINE CROSS(X1,Y1,X2,Y2,XR,YR,THU,XP,YP,XZERO,BETA,THEL)
C*****DETERMINE INTERSECTION POINT OF THE LINE SOURCE AND A LINE IN
C*****THE WIND DIRECTION FROM RECEPTOR R AT (XR,YR).
C*****THE LINE SOURCE IS SPECIFIED BY (X1,Y1) AND (X2,Y2)
C*****THU IS THE WIND DIRECTION MEASURED CLOCKWISE FROM THE SOUTH
TEST=0.01
PI=3.1415927
DEN=Y2-Y1
IF(ABS(DEN).LT. TEST) GO TO 10
TAND=(X2-X1)/DEN
TANT=ABS(TAND)
IF(TANT.LT. TEST) GO TO 20
THEL=ATAN(TANT)
IF(DEN.GT.0)GO TO 30
THEL=PI-THEL
GO TO 30
10 THEL=PI/2.
COTA=0.0
GO TO 35
20 THEL=0.0
GO TO 60
30 CONTINUE
COTA=COTAN(THEL)
35 IF(THU.LT.TEST)GO TO 40
DTHU=ABS(THU-PI/2.0)
IF(DTHU.LT.TEST)GO TO 50
DTHU=ABS(THU-PI)
IF(DTHU.LT.TEST)GO TO 40
DTHU=ABS(THU-3.0*PI/2.0)
IF(DTHU.LT.TEST)GO TO 50
DTHU=ABS(THU-THEL)
IF(DTHU.LT.TEST)GO TO 999

```

CROSS (Contd.)

```

      DTHU=ABS(DTHU-PI)
      IF(DTHU.LT.TEST)GO TO 999
      XP=(YR-Y1 +X1*COTA-XR/TAN(THU))/(COTA-1.0/TAN(THU))
      YP=(XP-X1)*COTA+Y1
C
C*****CALCULATE XZERO
C
      39 XZERO=SQRT((XR-XP)*(XR-XP)+(YR-YP)*(YR-YP))
      GO TO 65
C*****THU IS 0 OR 180
      40 CONTINUE
      DTHU= ABS(THU-THEL)
      IF(DTHU.LT.TEST)GO TO 999
      DTHU=ABS(DTHU-PI)
      IF(DTHU.LT.TEST)GO TO 999
      XP=XR
      YP=Y1+(XP-X1)*COTA
      XZERO=ABS(YP-YR)
      IF(THU .LT. TEST .AND. YR .GT. YP) XZERO=-XZERO
      IF( ABS(THU-PI) .LT. TEST .AND. YR .LT. YP) XZERO=-XZERO
      BETA=THEL-THU
      GO TO 75
C*****THU IS PI/2 OR 3*PI/2
      50 CONTINUE
      DTHU=ABS(THU-THEL)
      IF(DTHU.LT.TEST)GO TO 999
      DTHU=ABS(DTHU-PI)
      IF(DTHU.LT.TEST)GO TO 999
      YP=YR
      XP=(YR-Y1+X1*COTA)/COTA
      XZERO= ABS(XP-XR)
      GO TO 65
C*****THEL IS ZERO
      60 CONTINUE
      IF(THU.LT.TEST)GO TO 999
      IF(ABS(THU-PI).LT.TEST)GO TO 999
      XP=X1
      YP= YR
      DTHU=ABS(THU-PI/2.0)
      IF(DTHU.LT.TEST)GO TO 70
      DTHU=ABS(THU-PI*3.0/2.0)
      IF(DTHU.LT.TEST)GO TO 70
      YP= YP+ (XP-XR)*COTAN(THU)
      GO TO 39
      70 XZERO=ABS(XR-X1)
      65 BETA=THEL-THU
      IF(BETA.GT.0.AND.THEL.LT.PI.AND.XR.LT.XP)GO TO 75
      IF(BETA.LT.0.AND.THU.LT.PI.AND.XR.LT.XP)GO TO 75
      IF(BETA.LT.0.AND.THU.GT.PI.AND.XR.GT.XP)GO TO 75

```

CROSS (Contd.)

```

      XZERO=-XZERO
75  CONTINUE
      BETA=ABS(BETA)
      IF(BETA.GT.PI)BETA=BETA-PI
      IF(BETA.GT.PI/2.) BETA=PI-BETA
      IF(XZERO.EQ.0.)XZERO=1.0
      RETURN
999 BETA=0.0
C  PRINT 998
998 FORMAT(1H,10X,'BETA IS TOO SMALL')
      RETURN
      END

```

LIMITS

```

      SUBROUTINE LIMITS(X1,Y1,X2,Y2,XP,YP,X0,THU,THEL,B,TL,XL,XU,
      * DL,UL)
C
C**** DETERMINES THE INTEGRATION LIMITS FOR A FINITE LINE SOURCE
C**** THE LINE SOURCE IS SPECIFIED BY (X1,Y1), (X2,Y2) WITH X1 LESS
C      THAN X2 WRT A STANDARD COORDINATE SYSTEM AND IF X1=X2, THEN Y1
C      MUST BE LESS THAN Y2
C**** THU IS WIND DIRECTION WITH RESPECT TO THE SOUTH
C**** THEL IS THE LINE SOURCE ORIENTATION WITH RESPECT TO THE SOUTH
C**** BETA IS SMALLEST POSITIVE ANGLE BETWEEN LINE SOURCE AND A LINE
C      FROM THE RECEPTOR TO THE SOURCE PARALLEL TO THE WIND DIRECTION.
C
      SAVE=X0
      BETA=B
      PI=3.1415927
      CHK1=ABS(THEL-THU)
      CHK2=ABS((THEL+PI)-THU)
      UL=SQRT((XP-X2)*(XP-X2)+(YP-Y2)*(YP-Y2))
      DL=SQRT((XP-X1)*(XP-X1)+(YP-Y1)*(YP-Y1))
      IF(BETA.GT.1.56)GO TO 20
      IF(THEL.GT.PI/2.0)GO TO 500
      IF(THEL.LT.PI/2.0)GO TO 900
      GO TO 300
900 IF(THEL.GT.0.)GO TO 901
      IF(THU.LT.PI/2.0.OR.THU.GT.3.0*PI/2.0) GO TO 200
      GO TO 450
901 IF(THU.LT.PI/2.0)GO TO 200
      IF(THU.LT.PI)GO TO 650
      IF(THU.LT.3.0*PI/2.0)GO TO 450
      GO TO 700
500 IF(THU.LT.PI/2.0)GO TO 750
501 IF(THU.LT.PI)GO TO 400

```

LIMITS (Contd.)

502 IF(THU.LT.3.0*PI/2.0)GO TO 800

503 GO TO 800

C

C**** THEL IS LESS THAN 90 AND THU IS IN FIRST QUADRANT
C OR THEL IS 0 AND THU IS IN FIRST OR FOURTH QUADRANT

C

200 IF(X0.LT.0)GO TO 10

91 IF(YP.LT.Y1)GO TO 40

92 IF(YP.GT.Y2)GO TO 41

GO TO 93

10 X0=-X0

IF(YP.GT.Y2)GO TO 25

IF(YP.LT.Y1)GO TO 43

GO TO 94

C

C**** THEL IS LESS THAN 90 AND THU IS IN SECOND QUADRANT

C

650 IF(CHK1.LT.PI/2.0)GO TO 200

GO TO 450

C

C**** THEL IS LESS THAN 90 AND THU IN THIRD QUADRANT

C

C OR THEL IS 0 AND THU IS IN SECOND OR THIRD QUADRANT

C

450 UL=SQRT((XP-X1)*(XP-X1)+(YP-Y1)*(YP-Y1))

DL=SQRT((XP-X2)*(XP-X2)+(YP-Y2)*(YP-Y2))

IF(X0.LT.0)GO TO 460

454 IF(YP.GT.Y2)GO TO 40

455 IF(YP.LT.Y1)GO TO 41

456 GO TO 93

460 X0=-X0

461 IF(YP.GT.Y2)GO TO 43

462 IF(YP.LT.Y1)GO TO 25

463 GO TO 94

C

C**** THEL IS LESS THAN 90 AND THU IN FOURTH QUADRANT

C

700 IF(CHK2.LT.PI/2.0)GO TO 450

701 GO TO 200

C

C**** THEL IS GREATER THAN 90 AND THU IN FIRST QUADRANT

C

750 IF(CHK1.LT.PI/2.0)GO TO 400

751 GO TO 600

C

C**** THEL IS GREATER THAN 90 AND THU IN SECOND QUADRANT

C

400 IF(X0.LT.0)GO TO 405

IF(YP.GT.Y1)GO TO 40

IF(YP.LT.Y2)GO TO 41

LIMITS (Contd.)

```

      GO TO 93
405  X0=-X0
      IF(YP.GT.Y1)GO TO 43
      IF(YP.LT.Y2)GO TO 25
      GO TO 94

```

C

```

C**** THEL IS GREATER THAN 90 AND THU IN THIRD QUADRANT

```

C

```

800  IF(CHK1.LT.PI/2.0)GO TO 400
801  GO TO 600

```

C

```

C**** THEL IS GREATER THAN 90 AND THU IN FOURTH QUADRANT.

```

C

```

600  UL=SQRT((XP-X1)*(XP-X1)+(YP-Y1)*(YP-Y1))
      DL=SQRT((XP-X2)*(XP-X2)+(YP-Y2)*(YP-Y2))
      IF(X0.LT.0.)GO TO 610
      IF(YP.LT.Y2)GO TO 40
      IF(YP.GT.Y1)GO TO 41
      GO TO 93
610  X0=-X0
      IF(YP.LT.Y2)GO TO 43
      IF(YP.GT.Y1)GO TO 25
      GO TO 94

```

C

```

C**** THEL EQUALS 90 AND THU LT PI

```

C

```

300  IF(THU.GT.PI)GO TO 301
      IF(X0.LT.0.)GO TO 302
      IF(XP.LT.X1)GO TO 40
      IF(XP.GT.X2)GO TO 41
      GO TO 93
302  X0=-X0
      IF(XP.GT.X2)GO TO 25
      IF(XP.LT.X1)GO TO 43
      GO TO 94

```

C

```

C**** THEL EQUALS 90 AND THU GREATER THAN PI

```

C

```

301  DL=SQRT((X2-XP)*(X2-XP)+(Y2-YP)*(Y2-YP))
      UL=SQRT((X1-XP)*(X1-XP)+(Y1-YP)*(Y1-YP))
      IF(X0.LT.0.)GO TO 304
      IF(XP.GT.X2)GO TO 40
      IF(XP.LT.X1)GO TO 41
      GO TO 93
304  X0=-X0
      IF(XP.GT.X2)GO TO 43
      IF(XP.LT.X1)GO TO 25
      GO TO 94

```

C

LIMITS (Contd.)

C**** RECEPTOR IS DOWNWIND FROM THE LINE SOURCE

C

```

93 XL=AMAX1(0.,X0-DL*COS(BETA))
   XU=X0+UL*COS(BETA)
   GO TO 21
40 XL=X0+DL*COS(BETA)
   XU=X0+UL*COS(BETA)
   GO TO 21
41 IF(X0.LT.UL*COS(BETA))GO TO 25
   XL=AMAX1(0.,X0-DL*COS(BETA))
   XU=X0-UL*COS(BETA)
   GO TO 21

```

C

C**** RECEPTOR IS UPWIND FROM THE LINE SOURCE

C

```

94 XL=0.
   XU=UL*COS(BETA)-X0
   IF(XU.LT.0.)GO TO 25
   GO TO 21
43 IF(UL*COS(BETA).LT.X0)GO TO 25
   IF(X0.LT.DL*COS(BETA))GO TO 42
   GO TO 94
42 XL=DL*COS(BETA)-X0
   XU=UL*COS(BETA)-X0
   GO TO 21

```

C

C**** BETA IS 90

C

```

20 IF(X0.LT.0.)GO TO 25
   IF(DL.GT.TL.AND.DL.GT.UL)GO TO 121
   XL=-DL
   XU=UL
   IF(UL.GT.TL.AND.UL.GT.DL)XL=DL
   GO TO 21
121 XL=UL
   XU=DL
   GO TO 21
25 XL=0.
   XU=0.
21 IF(XL.LE.XU)GO TO 22
37 ALTER=XL
   XL=XU
   XU=ALTER
22 X0=SAVE
   RETURN
   END

```

HAVIE

```

      FUNCTION HAVIE(A, B, EPS, M, N, FCN)
      CHAVIE INTEGRATION
      DIMENSION TP(20), UP(20)
      REAL*8 A, B, EPS, FCN, X, EP, SUMT, H, T, SUMU, U, TEMP, TP, UP, HAVIE
      REAL*8D, AEP, ASUMT, ASUMU, FMAX, AT, AU, DEP, DIFF, AX
      IF(N.LT.0)GO TO 200
      IF(N.GT.3)GO TO 200
      IF(M-20)99,99,98
98      M=20
99      X=A
      MM=M
      NN=N+1
      M=2
      EP=FCN(X)
      X=FCN(B)
2010  AEP=DABS(EP)
2017  AX=DABS(X)
      FMAX=AEP
      IF(FMAX.GE.AX)GO TO 2002
      FMAX=AX
2002  EP=(X+EP)*0.5D0
2018  AEP=(AX+AEP)*0.5D0
2003  SUMT=0.0D0
2011  ASUMT=0.0D0
      I=1
      NC=1
      H=B-A
100    T=H*(EP+SUMT)
      AT=H*(AEP+ASUMT)
2004  SUMU=0.0D0
2012  ASUMU=0.0D0
2005  X=A-H*0.5D0
      DO 101 J=1,NC
      X=X+H
      TEMP=FCN(X)
2013  AX=DABS(TEMP)
      SUMU=SUMU+TEMP
      ASUMU=ASUMU+AX
      IF(FMAX.GE.AX)GO TO 101
      FMAX=AX
101    M=M+1
      U=H*SUMU
      AU=H*ASUMU
      K=1
2014  DIFF=DABS(T-U)
      GO TO (2006,2015,110,111),NN
2006  DEP=DABS(T)
      GO TO 112
2015  DEP=1.0D0

```

HAVIE (Contd.)

```

      GO TO 112
110 DEP=AT
      GO TO 112
111 DEP=FMAX
112 TEMP=DIFF-EPS*DEP
      IF (TEMP)2016,2016,103
103 IF(K-I)105,2007,2007
2007 H=H*0.5D0
      SUMT=SUMT+SUMU
      ASUMT=ASUMT+ASUMU
      TP(K)=T
      UP(K)=U
      I=I+1
      NC=2*NC
      GO TO 100
105 J=2*K
      D=2**J
      TEMP=T
2008 T=(D*T-TP(K))/(D-1.0D0)
      TP(K)=TEMP
      TEMP=U
2009 U=(D*U-UP(K))/(D-1.0D0)
      UP(K)=TEMP
      K=K+1
      IF(K-MM)2014,106,106
106 CONTINUE
2016 HAVIE=(T+U)*0.5D0
      EPS=DIFF/DEP
      GO TO 102
200 PRINT 2,N
      2 FORMAT(' ERROR RETURN-N= ',I2)
102 RETURN
      END

```

FT

```

      FUNCTION FT(XX)
C****COMPUTE THE INTEGRAND FOR THE NUMERICAL INTEGRATION
      REAL*8 FT,XX
      COMMON /VIRT/ SUDOY,SUDOZ,REZ,SOZ
      COMMON /FIRST/ X0,BETA,HL,NS,XCRIT
      X=XX
      PIH=SQRT(3.1415927*2.)
      COSB=1.
      IF(BETA.GT.1.56) GO TO 40
      SY=X+SUDOY
      SZ=X+SUDOZ

```


FT (Contd.)

```

      SIGH=SIGY(NS,SY)
      IF(BETA.LT.0.01) GO TO 45
      COSB=COS(BETA)
      TOP=((X-X0)*TAN(BETA)/SIGH)**2)/2.
3     IF(-TOP.GT.-20.) GO TO 5
      FT=1.D-24
      RETURN
5     E1=EXP(-TOP)/(SIGH*PIH*COSB)
      IF(SZ.LE.2.*XCRIT) GO TO 7
      FT=E1/HL
      RETURN
7     SZ2=AMIN1(SZ,XCRIT)
      SIGV=SIGZ(NS,SZ2)
      F1=0.
      IF(REZ.EQ.SOZ) GO TO 10
      TOP=((REZ-SOZ)/SIGV)**2)/2.
      IF(-TOP.GT.-20.) F1=EXP(-TOP)
      GO TO 15
10    F1=1.0
15    F2=0.
      IF(REZ.EQ.-SOZ) GO TO 20
      TOP=((REZ+SOZ)/SIGV)**2)/2.
      IF(-TOP.GT.-20.) F2=EXP(-TOP)
      GO TO 25
20    F2=1.
25    FT=1.D-24
      E2=(F1+F2)/(PIH*SIGV)
      IF(E2.EQ.0.0) RETURN
      IF(XCRIT-SZ) 35,30,30
30    FT=E1*E2
      RETURN
35    E2P=1./HL
      E2P=((SZ-XCRIT)*(E2P-E2)/XCRIT)+E2
      FT=E1*E2P
      RETURN
40    SY=X0+SUD0Y
      SZ=X0+SUD0Z
      SIGH=SIGY(NS,SY)
      TOP=((X/SIGH)**2)/2.
      GO TO 3
45    TOP=((X0/SIGH)**2)/2.
      GO TO 3
      END

```

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