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This study was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. Abstract

At the request of the Washington State Department of Highways a study was conducted to evaluate three computer models specifically designed to predict carbon monoxide (CO) concentration at receptor points along roadways. The models were evaluated on their ability to predict values obtained from a monitoring network established along various roadways in the State of Washington. Monitoring consisted of 12 ground level CO stations, 2 meteorological stations and traffic counters. Traffic speeds were sampled for conformity during peak hours. The final selected models, CALINE II and EPA's HIWAY, were given calibration factors to be used when calculating Receptor Concentrations for Impact Assessments.

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THE SELECTION AND CALIBRATION OF AIR QUALITY DIFFUSION MODELS FOR WASHINGTON STATE HIGHWAY LINE SOURCES

A Study

Prepared for the

WASHINGTON STATE HIGHWAY COMMISSION

DEPARTMENT OF HIGHWAYS

In Cooperation With

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

by

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Table of Contents

List of Figures

List of Tables

A Comparison of Three Air Quality Diffusion Models for Highway Line Sources

1.1 Background

For the past several years the Departments of Atmospheric Sciences and Civil Engineering of the University of Washington have jointly conducted studies involving mathematical atmospheric diffusion models to predict air quality in the vicinity of highways. The first phase of this research consisted of a comprehensive review of available diffusion models, and the results were reported by Lamb, Badgley and Rossano, 1973.

A second phase was initiated in October 1973, and its principal objective was to select three of the air quality models reviewed in the first phase and to test them in existing highway projects in the State of Washington.

The purpose of this report is to describe the findings from the field testing of three different models under actual highway conditions. Both phases of this research have been funded by a grant from the Washington State Department of Highways, and the Federal Highway Administration.

The importance of having an accurate technique for predicting air quality patterns resulting from future transportation systems is obvious in light of national policy and legal requirements for preventing or minimizing future degradations in air quality.

Additional benefits from having valid and relatively simple atmospheric modeling techniques are the optimization of design and operation of transportation systems to minimize adverse environmental impacts, and economics of time, manpower and costs of conducting large numbers of environmental impact studies. Gaussian plume models of the type analyzed in this study are the simplest of the dispersion models in use. Such models require a minimum of meteorological inputs which would normally be readily available to an agency utilizing a dispersion model in the preparation of an environemtnal impact statement.

1.2 Objective

The principal objective of the project is to select two or three of the diffusion models reviewed in the first phase and subject them to thorough testing on actual highway locations in the State of Washington. The testing consists of a comparison of the concentrations of carbon monoxide calculated by the computer programs incorporating the various diffusion models with the concentrations measured at several highway sites. Two of the three models were then calibrated for use by the Washington State Department of Highways.

1.3 Monitoring Sites

The sites selected for study include freeway segments with the prevailing winds parallel to or across the highway and an intersection of a major arterial with a freeway.

These test sites were located as follows:

1. West of the Intersection of SR-405 and SR-167, Renton, Washington. See Figure 3.1.
2. SR-405 at N.E. 60th and continuing 1600' south, Kirkland, Washington. See Figure 3.2.
3. Intersection of Interstate 5 and N.E. 145th, Seattle. See Figure 3.3.

4. Interstate 90 - 2,400 feet west of Park Road, Spokane, Washington. See Figure 3.5.

5. Interstate 5 - Quarnberg Road and continuing 800' south, Vancouver, Washington. See Figure 3.4.

Additional details are found in Section 3.

1.4 Emission Data

A basic requirement for making the desired comparison of measured and model predicted carbon monoxide concentrations is to have as complete information as is possible about a particular highway segment to be studied. This information must include the rate of emissions of the pollutant of interest, which for this study is carbon monoxide, the meteorological conditions, and the actual carbon monoxide concentrations in the vicinity.

The emission rate on a highway is calculated by the techniques suggested by Kircher and Armstrong, 1973. The emission factor in grams per vehicle mile for a given calender year is calculated given the Federal Test procedure emission rate for each model year, the deterioration factor for each model year, the weighted annual travel for each model year, and the weighted speed adjustment factor for exhaust emissions for each model year. Local vehicle age distributions and the national distribution of annual travel by vehicle age were used to calculate the weighted annual travel by model year for this project.

Traffic counts on an hourly basis were obtained for each highway segment modeled through the cooperation of State Department of Highways. The speed distribution for one site was measured with a radar unit. For other sites, only an average speed was available. The speed adjustment factor is based on Kircher and Armstrong's data. The total emissions for a highway segment were calculated as the product of the traffic count in vehicles per hour and the speed weighted emission factor. All traffic was assumed to be light duty passenger vehicles.

1.5 Air Monitoring Data Collection

Average hourly air samples were collected during peak traffic hours with sequential bag samplers Mfg. by Environment Resources Assoc. Inc. Twelve hourly samples were collected per unit per day. The ppm of carbon monoxide in the sample was determined with an Ecolyzer Carbon Monoxide Monitor manufactured by Energetics Science, Inc. The Ecolyzers were field calibrated with gas samples obtained from cylinders containing a known carbon monoxide concentration (10 ppm - 15 ppm) determined by the State Department of Ecology's reference method. Concentrations were reported to the nearest part per million (ppm).

At each monitoring location, one or two portable meteorological stations were used to record the wind speed and direction and ambient temperature. The stations are manufactured by Meteorology Research, Inc. Wind data were reduced to hourly averages by procedures outlined by Beaton, et. al, Volume 1, 1972. Wind direction was reported to the nearest 10° and wind velocity to the nearest mile per hour.

The stability index was determined by the procedures outlined by Turner, 1961. Observations of cloud cover, ceiling and wind velocity were obtained from the nearest recording weather station. The net radiation index was determined for each weather station by using Turner's classification method. The stability class was then determined, Pasquill, 1961.

MATHEMATICAL MODELS

2.1 DISPERSION MODELS - GENERAL

All three mathematical dispersion models chosen for analysis are based on the Gaussian plume model, that is, the concentrations of pollutants within the plum generated by the vehicles on the highway are distributed normally in both the cross wind and vertical directions. The Gaussian plum model satisfies the continuity equation if diffusion along the plume axis is neglected. In general, the form of the solution for the concentration at a receptor downwind from a point source is given by Turner (1969) as:

$$C_{(x,y,z,H)} = \frac{Q}{2\pi\sigma_y(x)\sigma_z(x)u} \{\exp [- \frac{1}{2} (\frac{y^2}{\sigma_y^2})]\} \{ \exp [- \frac{1}{2} (\frac{z-H}{\sigma_z})^2] + \exp [- \frac{1}{2} (\frac{z+H}{\sigma_z})^2]\} \qquad 2.1$$

where:

C = concentration at point x, y, z

Q = emission rate term

$\sigma_y(x)$ = standard deviation of plume concentration in horizontal direction

$\sigma_z(x)$ = standard deviation of plume concentration in vertical direction

u = mean wind speed

H = height of source

This equation assumes a uniform wind field with the x-axis extending horizontally in the direction of the mean wind. The y-axis (cross-wind) is in a horizontal plane perpendicular to the x-axis. The z-axis extends vertically upward.

2.2 CALIFORNIA DIVISION OF HIGHWAYS: HIGHWAY LINE SOURCE DISPERSION MODEL (Beaton, et al.)

Two versions of the California Highway Line Source Model were available during the study. The first version, CALINE-I, was available throughout the study period and was used for the original comparisons with the other two models. A second version, CALINE-II, was modified by the California Division of Highways and became available late (February, 1975) in the project. The description of this CALINE-II model below is constructed from analysis of the computer program supplied. The CALINE-I description is abstracted from Beaton, et al.

2.21 Description of Model, Caline I

The California Highway Line Source Model assumes that there is a mechanical mixing cell on the highway in which there is a zone of intense mixing and turbulence caused by the motion of the vehicles on the highway. This mixing cell is assumed to be as wide as the highway (from shoulder to shoulder if the median is less than 30 feet wide) and 12 feet high. In the cell the concentration of a pollutant emitted by the vehicles is assumed to be constant. Downwind of the mixing cell, a Gaussian infinite line source model is used in different forms depending on the highway design, heights of sources and receptor and whether the wind is parallel or skewed with respect to the highway.

The general CALINE-I equation for the downwind concentrations is:

$$C = \frac{4.24\ Q}{K\sigma_z(x)u\ \sin\ \phi}\left[\exp\left\{-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right\} + \exp\left\{-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right\}\right] \quad 2.2$$

where C, Q, σ_z, u, a and H were defined above, and where:

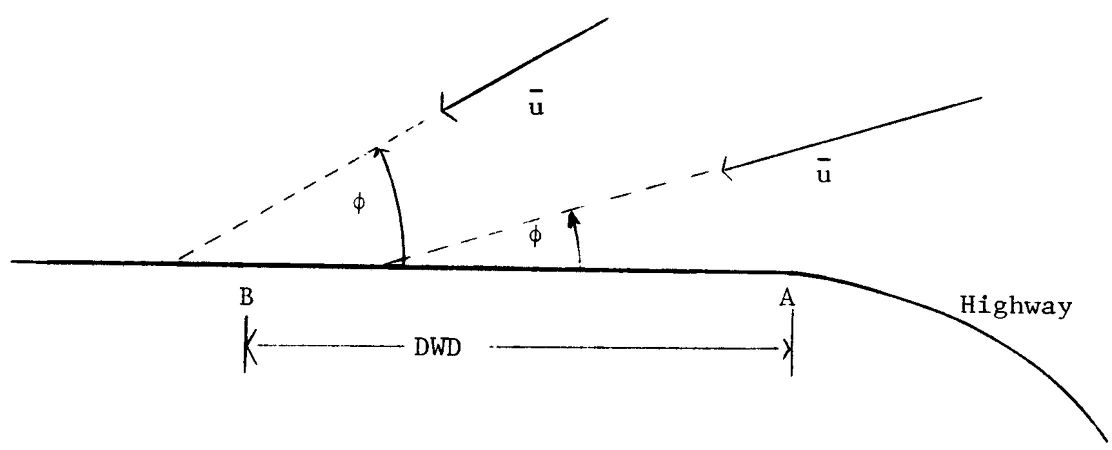
ϕ = angle of wind with respect to the highway ($\phi = 90^o$ for perpendicular winds, $\phi = 0^o$ for parallel winds)

K = empirical constant, suggested value = 4.24

Note that the horizontal dispersion parameter, σ_y and the cross-wind distance, y, do not appear in equation 2.2. Lateral dispersion from one segment of the infinite line source effectively compensates dispersion in the opposite direction from an adjacent segment. The cross-wind distance, y, does not appear since the concentration at a given downwind distance is constant. Equation 2.2 is similar to Turner's equation 5.19 for an infinite line source.

2.2.1.1 Cross-Wind Conditions

Equation 2.2 is used by CALINE-I for calculating concentrations when the angle between the wind vector and the highway is $12^o < \phi \leq 90^o$ as illustrated in Figure 2-1.



$\bar{u}$ = Wind vectors

ϕ = Angle between wind direction and highway

DWD = Distance upwind to point where highway first becomes parallel (±12°) to the wind

Figure 2-1. Diagram Showing California Highway Model Orientation

A simplified form of equation 2.2 is used to calculate the downwind concentrations at grade highways with elevated receptors and cross-wind conditions. In this case, H = 0, and the resulting equation is:

$$C = \frac{4.24\ Q}{K\sigma_z u \sin\phi} \{\exp[-\frac{1}{2}(\frac{z}{\sigma_z})^2]\} \qquad 2.3$$

The mixing cell concentration for cross-winds is given by:

$$C_{mix} = \frac{1.06\ Q}{K_1 u \sin\phi} \qquad 2.4$$

where: K_1 = empirical coefficient (suggested value is 4.24)

The source strength, Q, is calculated from the available emissions data, as discussed in Section 2.5.

2.2.1.2 Parallel Wind Conditions

A buildup of pollutants along a highway can occur if the wind is blowing parallel to the highway. The buildup will begin from the point where the wind initially becomes parallel to the highway (Point A in Figure 2-1) when ϕ in equation 2.2 is less than or equal to 12^o. CALINE-1 uses a slightly different set of equations for the mixing cell and downwind concentrations. Equation 2.5 is used to calculate the mixing cell concentrations for highways with shoulder to shoulder width of 30.5 meters (100 feet) or more:

$$C_{mix} = \frac{AQ}{Ku}(\frac{30.5}{W}) \qquad 2.5$$

where C_{mix}, Q, and u have been defined and where:

K = empirical coefficient (suggested value is 4.24)

W = width of roadway, in meters

A = downwind concentration ratio for parallel winds

For estimating concentrations with W less than 30.5 meters (100 feet) it has been found that equation 2.5 underestimated the size of the mixing cell (Beaton, et al). For W less than 100 feet, equation 2.6 is used to estimate the mixing cell concentration for parallel winds:

$$C_{mix} = \frac{AQ}{uK} \left(\frac{W}{30.5}\right) \qquad 2.6$$

In order to calculate receptor concentrations at a distance away from the highway, the mixing cell concentration is multiplied by an exponential term which depends on the highway and receptor configurations. Depending upon conditions, one or more of the exponential terms in equation 2.1 may contribute to the calculated concentration at a downwind receptor.

The factor A in equations 2.5 and 2.6 is a function of the degree of atmospheric mixing, the distance DWD illustrated in Figure 2.1, and the highway configuration (cut, elevated, at-grade section). Typical values of A are shown in Figure 2.2 for at-grade sections. Interpolation for various average cut widths between 61 and 213.5 meters (200 and 700 feet) is performed by the program.

2.2.1.3 Cut Sections

CALINE-I calculates concentrations downwind of cut sections equal to or less than 30 feet deep. The calculations are based on the inclusion

Table 2.1. California Model Parameters for the Relationship $\sigma_y = ax^b$

Class	Downwind Distance, m	Parametric Values for $\sigma_y = ax^b$	
		a	b
A	<900	242.36	0.494
	900 - 2000	247.5	0.692
	>2000	215.2	0.898
B	<900	169.0	0.442
	900 - 1500	172.0	0.707
	>1500	161.0	0.874
C	<800	120.0	0.392
	800 - 1500	128.4	0.692
	>1500	121.77	0.817
D	<600	86.96	0.346
	600 - 1500	98.65	0.588
	>1500	89.60	0.826
E	<700	65.00	0.304
	700 - 1500	70.00	0.494
	>1500	61.00	0.82
F	<600	49.00	0.263
	600 - 1500	53.50	0.435
	1500 - 3000	49.0	0.653
	>3000	38.6	0.876

Table 2.2. California Model Parameters for the Relationship $\sigma_z = cx^d$

Class	Downwind Distance, m	Parametric Values for $\sigma_z = cx^d$	
		a	b
A	<40	47.4	0.357
	40 - 100	91.0	0.562
	100 - 200	148.0	0.782
	200 - 400	300.0	1.22
	>400	485.0	1.74
B	<100	34.9	0.314
	100 - 200	62.0	0.565
	200 - 300	78.0	0.710
	400 - 1000	105.0	1.04
	>1000	105.0	1.104
C	<150	28.4	0.283
	150 - 300	45.8	0.536
	300 - 600	49.0	0.594
	600 - 1000	58.0	0.922
	>1000	58.0	0.909
D	<200	22.4	0.249
	200 - 500	26.9	0.360
	500 - 1000	31.4	0.534
	>1000	31.4	0.652
E	<300	17.44	0.213
	300 - 700	20.32	0.340
	>7000	21.98	0.561
F	<500	13.6	0.177
	500 - 1500	14.08	0.289
	>1500	13.2	0.552

of the appropriate exponential terms in an equation similar to equation 2.2 and to use of the proper value of A for parallel wind cases.

2.2.1.4 Dispersion Parameters σ_y and σ_z

The dispersion parameters used by CALINE-I are calculated from the relationships ;

$$\sigma_y = aX^b \qquad 2.7$$

$$\sigma_z = cX^d \qquad 2.8$$

where a,b,c, and d are parameters that vary with the stability class and the distance downwind.

Tables 2.1 and 2.2 list values for these parameters for σ_y and σ_z respectively.

The lower and upper values listed under downwind distance in Tables 2.1 and 2.2 are inflection points on the σ_y versus distance curves. All the curves converge at a value of $\sigma_y = 8$ at a downwind distance of 0.001 km (1 meter). The σ_z curves converge at a value of $\sigma_z = 4$m for a downwind distance of 0.001 km (1 meter). These are initial dispersion estimates. The initial vertical dispersion estimate corresponds to the height of the mixing cell.

2.2.2 Description of Model, CALINE II

CALINE-II contains major revisions of CALINE-I, in particular, the cut section and parallel wind calculations have been changed significantly.

The basic approach for cross-wind conditions remains the same as in CALINE-I. The concentration at a receptor site is calculated by adding components of "pure" parallel and cross-wind models vectorially.

2.2.2.1 Cross-wind conditions

Equation 2.9 is the general equation used to calculate the cross-wind component of the concentration. Equation 2.9 is a modification of Equation 2.2.

$$C = \frac{Q\ R \sin^2 \phi}{\sqrt{2\pi}\,\sigma_z u} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right\} \qquad 2.9$$

where R is an empirical factor for cut sections (see 2.2.2.3 below) and the other variables have been defined above.

R has a value of 1.0 for at-grade or elevated sections. The $\sin^2\phi$ term is the cross-wind vector term.

2.2.2.2 Parallel Wind Conditions

The parallel wind model is completely different in CALINE-II. The roadway is divided into a series of square area sources as wide as the roadway. The concentration downwind of the area source is calculated as if the emissions originated at a virtual source upwind of the area source. The distance from the center of the area source to the virtual source is such that σ_y at the area source coincides approximately with the edge of the highway, forcing the model to assume a uniform concentration within the mixing cell, a condition which would not exist with a virtual point source.

The equation used to calculate the concentration from each area source is:

$$C = \frac{Q_\ell LR \cos^2\phi}{\sqrt{2\pi}\sigma_y\sigma_z u} \{ \exp[-\frac{1}{2}(\frac{y}{\sigma_y})^2] \} \{ \exp[\frac{1}{2}(\frac{z-H}{\sigma_z})^2] + \exp[-\frac{1}{2}(\frac{z+H}{\sigma_z})^2] \} \qquad 2.10$$

where y is equal to the perpendicular distance from the receptor to the roadway edge plus an initial dispersion parameter. L is the segment length, which for this model is equal to the raodway width. The $\cos^2\phi$ term is the parallel wind vector, Q_ℓ is the emission rate per unit length of highways term. Other variables have been previously described for Equation 2.1, which is the basis for 2.11.

The number of areas used to calculate the parallel component is equal to one-half mile (in feet) divided by the roadway width in feet. For example, a 112 foot roadway is divided into 24 segments upwind of the receptor. The concentrations from each segment are summed to give the parallel component.

A correction is made to the total parallel component for the different stability classes. The correction increases the concentration of the parallel component by the factor listed in Table 2.3.

Table 2.3 Correction Factors for Parallel Wind Concentration Components

Stability	Factor
A	1.0
B	1.06
C	1.16
D	1.40
E	1.64
F	2.08

2.2.2.3 Cut Sections

Three empirically determined factors are used to adjust the concentrations determined by equations 2.9 and 2.10. The factor R in these equations is calculated from the equation

$$R = 10^{(a + bVPH + cH + d\phi + e^{u})} \qquad 2.11$$

where VPH = number of vehicles per hour

H = level of roadway with respect to grade

ϕ = angle of wind

u = wind speed

The values of the coefficients as a function of stability class are given in Table 2.4. Values of R are typically 0.3 to 1.0.

Table 2.4 Parametric Values of Coefficients in Equation 2.11

Class	Coefficient a	b	c	d	e
A	-0.018164	1.439×10^{-5}	0.01448	7.9×10^{-4}	0
B	0.21754	0	0.01431	7.2×10^{-4}	0.02252
C,D,E,F	0.02019	4.98×10^{-6}	0.0138	0.0	-5.73×10^{-3}

2.2.4 Dispersion Parameters σ_y and σ_z

CALINE-II uses the same vertical dispersion parameter, σ_z, as does CALINE-I, see equation 2.8 and Table 2.2. The horizontal dispersion parameter σ_y used in CALINE-II is identical to those in CALINE-I for downwind distances greater than lower inflection point distances for each stability class, Table 2.1. For values of the downwind distance smaller than the inflection point, σ_y as a function of downwind distance is found by setting the initial σ_y equal to the width of the roadway divided by 4.3 at the virtual distance. A straight line is then drawn between the inflection point σ_y and the initial σ_y. The coefficients a and b from equation 2.7 are then determined. These coefficients are subsequently used to calculate σ_y for use in equation 2.10.

2.3 ENVIRONMENTAL PROTECTION AGENCY - HIWAY AIR POLLUTION MODEL

2.3.1 Description

The EPA HIWAY model is a Gaussian plume model developed by the Environmental Protection Agency's Meteorology Laboratory, Zimmerman and Thompson (1973). The model is capable of modeling each lane of the traffic of a multiple lane highway separately, contrasted to the CALINE models which model an entire highway. The highway is placed in a Cartesian grid system to locate the endpoints of the highway and all receptors of interest. The individual lanes are placed in the grid by the program at locations corresponding to the lane width and median width. The wind direction is specified by the user in degrees from north (North = 360° = 0°). The program then relocates the highway in a grid system oriented with the wind direction for computation of the concentrations of pollutants at given receptor points.

The process of finding the pollutant concentration downwind of the highway entails simple trapezoidial integration of a series of point sources located along this line source. The integration is based on an assumption that the concentration varies linearly between two calculated points so that the integrated value between the two points is the average of the concentrations normalized for source strength from the two points multiplied by both the distance between the points and the line source emission rate. The distance between the calculated points is successively halved until the calculated concentration at a receptor point does not change appreciably by further reduction of the spacing between point sources.

The integral form of equation 2.1 used to calculate the concentrations at an at-grade receptor point downwind of an at-grade highway extending from point A to point B is (z = 0 in equation 2.1):

$$C = \frac{Q_\ell}{u} \int_A^B \frac{1}{\pi\sigma_y(x)\sigma_z(x)} \{\exp [- \frac{1}{2} (\frac{y}{\sigma_y(x)})^2]\} dL \qquad 2.12$$

where:

Q_ℓ = emission rate per unit length of highway

dL = incremental length along source from A to B

The other parameters were defined for equation 2.1. HIWAY is programmed to accept both elevated and cut highway sections as well as at-grade and elevated receptor. Equation 2.12 is the simplest form of the general equation used. The HIWAY program uses as the general equation a modification of Equation 5.8 in Turner's workbook (1969). The general equation indludes terms for reflection of a plume by an inversion condition above the ground. Knowledge of the height of the inversion layer is critical only for receptors more than a few hundred meters from the highway.

2.3.2 Cut Sections

Cut sections are modeled by HIWAY as a series of ten "pseudo" line sources at grade level above the cut. The "pseudo" line sources are spaced evenly across the top of the cut and the total emission rate for the highway is proportioned between the ten "pseudo" sources.

2.3.3 Parallel Winds

Due to the nature of equation 2.12, no special solution is required for winds nearly parallel to the highway, as is the case with equation 2.2.

2.3.4 Dispersion parameters, σ_y and σ_z

Turbulence of the air produced by the motion of automobiles results in a rapid mixing of the pollutants near and on the highway. HIWAY models this initiai dispersion by assuming that there is a virtual source upwind of the actual source. The emissions disperse from this virtual source to give an initial vertical concentration distribution at the downwind edge of the highway. Calder (1973) has shown that a value of $\sigma_z = 1.5$m is a conservative approximation of the initial vertical standard deviation of the plume.

The horizontal deviation, σ_y, was arbitrarily chosen as 3 meters at the downwind edge of the road to account for a reasonable amount of cross-highway spreading due to vehicle-generated turbulence for the parallel and near-parallel wind cases.

For cut sections, HIWAY uses initial values of σ_y and σ_z that are functions of the wind speed. These values are given in Table 2.5.

Table 2.5 CRITICAL VALUES OF σ_y AND σ_z USED IN HIWAY FOR CUT SECTIONS

u, Wind Speed, m/s	σ_{yo}	σ_{zo}
u < 1	10	5
1 < u < 3	$10 - 7(\frac{u-1}{2})$	$5 - 3.5(\frac{u-1}{2})$
u < 3	3	1.5

For all other conditions, σ_y and σ_z are calculated from equations 2.7 and 2.8 with parametric values for HIWAY listed in Tables 2.6 and 2.7.

2.4 Mathematical Sciences Northwest, Inc. Model

The Math Sciences model (MSNW) is also a Gaussian plume model. The line source is approximated by an infinite line source, or by a series of point sources when the angle between the wind and the road is less than 45^o or when calculating the concentrations at receptor points affected by the "edge effects." The "edge effects" at the ends of a finite line source are caused by the lack of compensating lateral dispersion from a adjacent segment which is normally assumed for the infinite line source model.

Equation 2.13 is used by the MSNW model for calculating concentrations from sources that meet the criteria of an infinite line source:

$$C = \frac{Q_\ell L}{\sqrt{2\pi} \sin \theta \sigma_z u} \{\exp [-\frac{1}{2}(\frac{H}{\sigma_z})^2]\} \qquad 2.13$$

and the other variables have been defined above. This equation is essentially the same as equation 2.2 with the exceptions of the numerical

Table 2.6. PARAMETRIC VALUES FOR $\sigma_z = ax^b$ for HIWAY

Stability Class	Distance, meters					
	100 to 500		500 to 5000		5000 to 50,000	
	a	b	a	b	a	b
A	0.0383	1.2812	0.2539×10^{-3}	2.0886	- -	- -
B	0.1393	0.9467	0.4936×10^{-1}	1.1137	- -	- -
C	0.1120	0.9100	0.1014	0.9260	0.1154	0.9109
D	0.0856	0.8650	0.2591	0.6869	0.7368	0.5642
E	0.0818	0.8155	0.2527	0.6341	1.2969	0.4421
F	0.0552	0.81	0.2189	0.5957	1.5151	0.3672

Table 2.7. PARAMETRIC VALUES FOR $\sigma_y = ax^b$ for HIWAY

Stability Class	a	b
A	0.4	0.903
B	0.295	0.903
C	0.2	0.903
D	0.13	0.903
E	0.098	0.903
F	0.065	0.903

constants in the equation 2.2. For cases when the line source must be treated as a series of point sources, the line is divided into segments with a length proportional to the grid spacing specified by the user. The smaller the grid-spacing, the more points calculated. For each point source, the concentrations are calculated by equation 2.1 with $z = 0$. The source strength Q for each point source is equal to the emission rate for the entire line divided by the number of segments.

2.4.1 Special Cases

The MSNW model is applicable to at-grade receptors, and at-grade or elevated sources only. As mentioned above, the parallel wind cases are modeled with a series of point sources. The model also will calculate the concentrations at each of 1600 points in the grid area in order to generate concentration isoplethes. These isoplethes can be produced graphically on a CALCOMP plotter. An example of such a plot is given in Figure 2.2. The model is written to calculate concentrations from multiple sources.

2.4.2 Dispersion Parameters σ_y and σ_z

The dispersion parameters σ_y and σ_z are calculated from polynomial equations that are functions of the log of the downwind distance x. The general form of the equation is

$$\sigma = 10^{a + b \log_{10} x + c(\log_{10} x)^2 + d(\log x)^3 + e(\log x)^4} \quad 2.14$$

Figure 2.2. Example of Plot Created by MSNW Computer Program

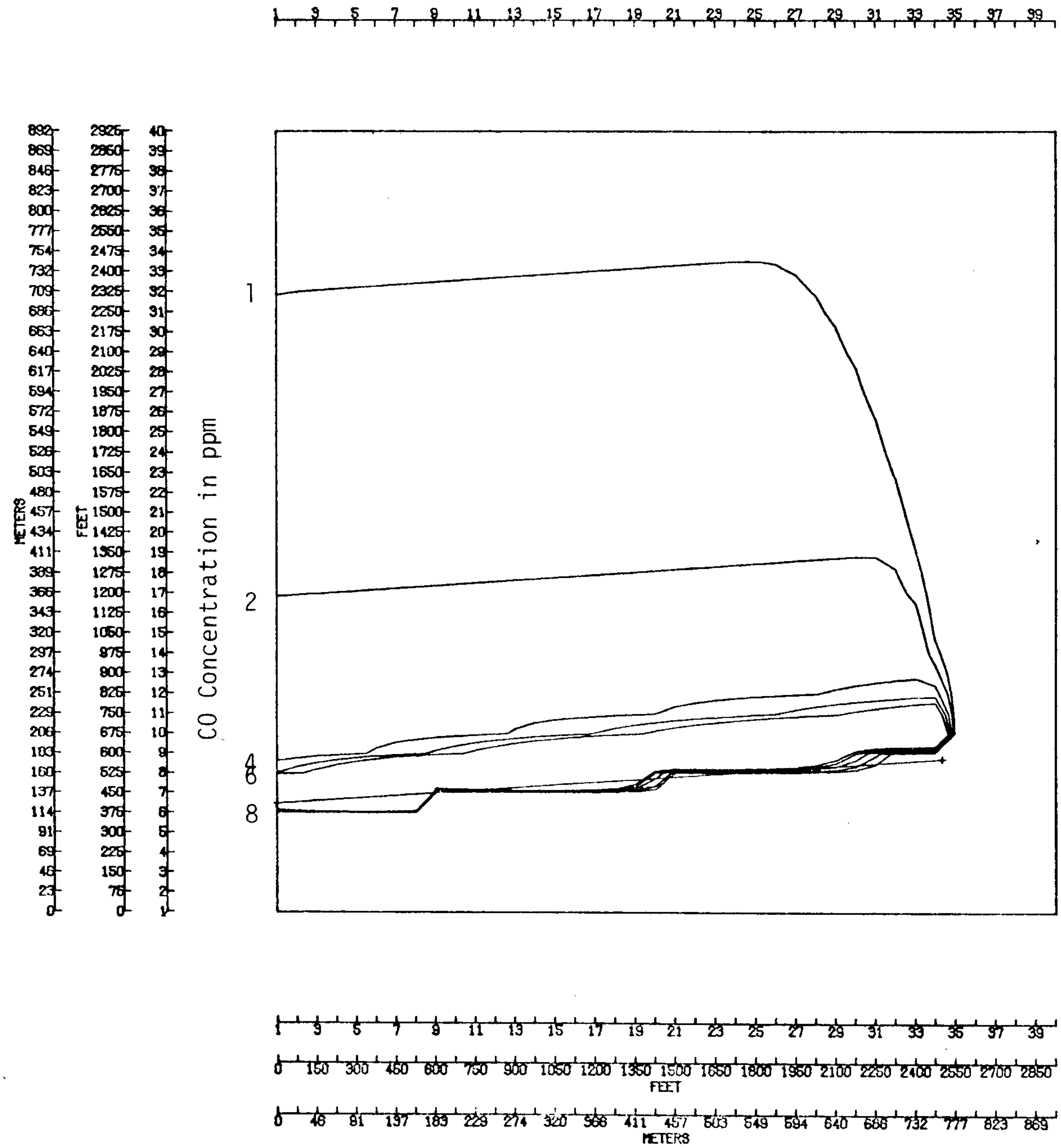


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Table 2.8 lists the coefficients for the polynomials for σ_y and σ_z. An additional factor equal to $2/\sqrt{2\pi}$ is added to σ_y and σ_z to approximate the initial mixing.

2.5 Emissions Model

The calculation of emission factors for carbon monoxide from light-duty vehicle exhaust can be expressed as the sum of individual model year emission factors for twelve years (Kircher and Armstrong, 1973):

$$e_n = \sum_{i=n-12}^{n+1} c_i d_{in} m_{in} s_i \qquad 2.15$$

where:

e_n = emission factor in grams per vehicle mile for calendar year n.

c_i = the 1975 Federal Test Procedure emission rate (grams/mile) for the i^{th} model year, at low mileage

d_{in} = the controlled vehicle emission deterioration factor for the i^{th} model year at calendar year n

m_{in} = the weighted annual travel of the i^{th} model year during calendar year n (the determination of this variable involves the use of the vehicle model year distribution)

s_i = the weighted speed adjustment factor for exhuast emission for i^{th} model year

Values for c_i, d_{in}, and s_i were taken from Kircher and Armstrong, Table 1, Table 4 and Figure 1, respectively. These data are reproduced in Appendix A for reference.

Values of m_{in}, the weighted annual travel by model year, were calculated from equation 2.16.

$$m_{in} = f_{in} \times L_i / \sum_{i=n-12}^{n+1} (f_{in} \times L_i) \qquad 2.16$$

Table 2.8. Math Sciences Model Parameters for σ_y and σ_z

$$\sigma_y = \sqrt{\frac{2}{2\pi}} + 10^{a + b \log_{10} x + c(\log_{10} x)^2 + d(\log_{10} x)^3}$$

Stability	a	b	c	d
A	2.3284	0.88051	-0.016851	0.0
B	2.1959	0.90315	-0.021478	0.0
C	2.0208	0.91633	-0.016268	0.0
D	1.8370	0.91885	-0.014852	0.0
E	1.702	0.92641	-0.0036713	-0.0061313
F	1.5304	0.92266	-0.0084951	-0.00508

$$\sigma_z = \sqrt{\frac{2}{2\pi}} + 10^{a + b \log_{10} x + c(\log_{10} x)^2 + d(\log_{10} x)^3 + e(\log_{10} x)^4}$$

Stability	a	b	c	d	e
A	2.6602	2.2217	0.96213	-1.6261	-1.014
B	2.033	1.0832	0.0495	-0.028374	0.0
C	1.7861	0.91339	0	0	0
D	1.4945	0.71622	-0.10078	0.018849	0.0
E	1.3266	0.67678	-0.10211	0	0.0
F	1.139	0.6526	-0.13087	0.005547	0.0

where:

f_{in} = the fraction of vehicles of i^{th} model year in use on December 31 of n^{th} year.

L_i = annual miles driven for i^{th} model year car.

Tables B-1, B-2, and B-3 in Appendix B show the calculated values of m_{in} for the three counties of interest for this project: King, Clark and Spokane. The fraction of vehicles in use by age in each county was estimated from motor vehicle registration data. Appendix B contains a description of the estimation procedures used to calculate the fraction of vehicles in use by age. Table 2.9 shows the results of the calculations of the weighted emission factors for January 1, 1974, based on equation 2.15. It was assumed for this project that all vehicles were light duty vehicles.

It should be noted that the calculated emission factors differed only in the third significant figure indicating that for these urban counties a single set of emission factors may be used without significant error.

Table 2.9. Emission Factors for Three Washington Counties January 1, 1974, by Vehicle Speed.

Average Speed, mph	Emission Factors, g/veh-mile Clark Co.	King Co.	Spokane Co.
15	78.31	78.23	78.47
20	62.15	62.09	62.28
25	48.48	48.43	40.58
30	42.88	42.84	42.97
35	37.29	37.25	37.37
40	34.18	34.15	34.25
45	31.08	31.04	31.14
50	29.21	29.18	29.27
55	25.48	25.46	25.54
60	24.24	24.21	29.29

MODEL EVALUATION

3.1 EVALUATION SITES

In order to evaluate the utility of the three models under diverse conditions, the project was planned to include evaluation studies at five sites in Washington. These sites were chosen as much as possible to represent certain common combinations of highway and environmental parameters.

3.1.1 Renton

The first highway section modeled was Interstate 405 near Renton, between the Green River and South Renton Interchanges. This section was chosen because it is approximately perpendicular to prevailing north-south winds. Figure 3.1 shows schematically the orientation of the site and receptor points.

3.1.2 Kirkland

The second highway section was Interstate 405 approximately one mile north of Highway 520 near Kirkland. The highway is parallel to the prevailing winds at this location. Figure 3.2 shows the site and receptor points.

3.1.3 Seattle

The third site which was modeled was the intersection of Interstate 5 and N 145th Street at the northern city limits of Seattle. This location was to be the validation site for intersections. Figure 3.3 shows schematically the orientation of this site and the receptor points modeled.

3.1.4 Vancouver

The fourth highway section was Interstate 5 north of downtown Vancouver, Washington with prevailing cross-winds. A second site was necessary to

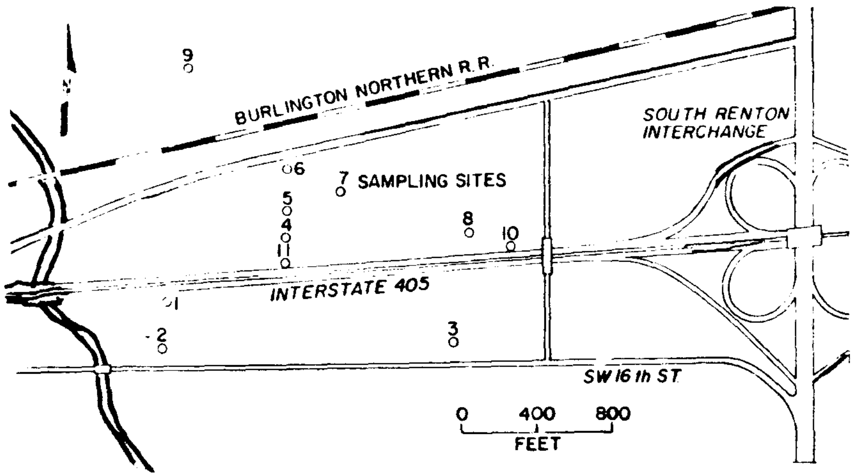

Figure 3.1
Renton Sampling Site

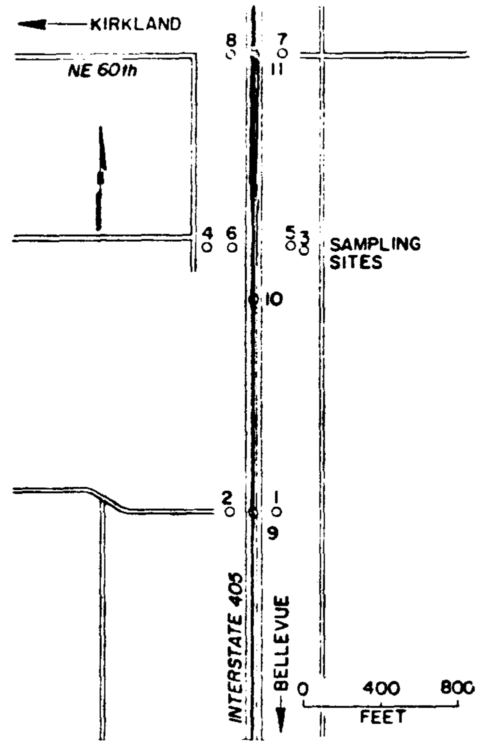

Figure 3.2
Kirkland Sampling Site

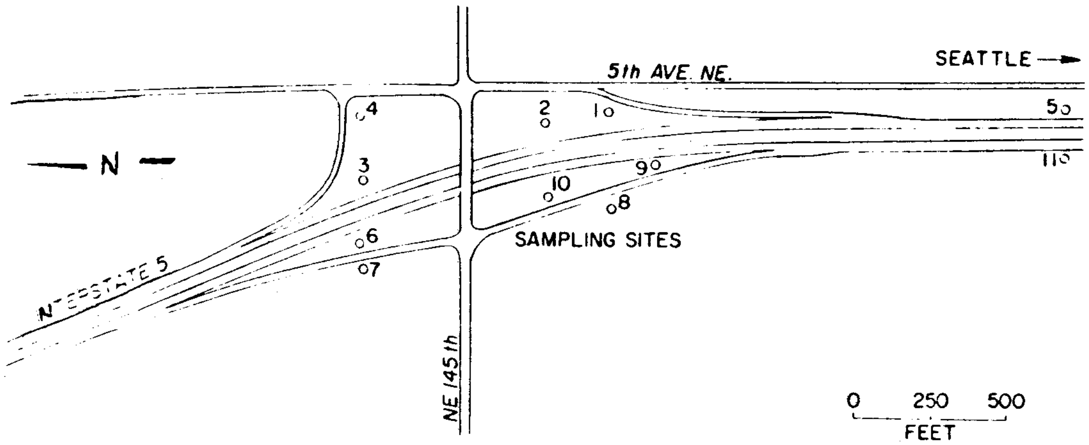

Figure 3.3
Seattle Sampling Site

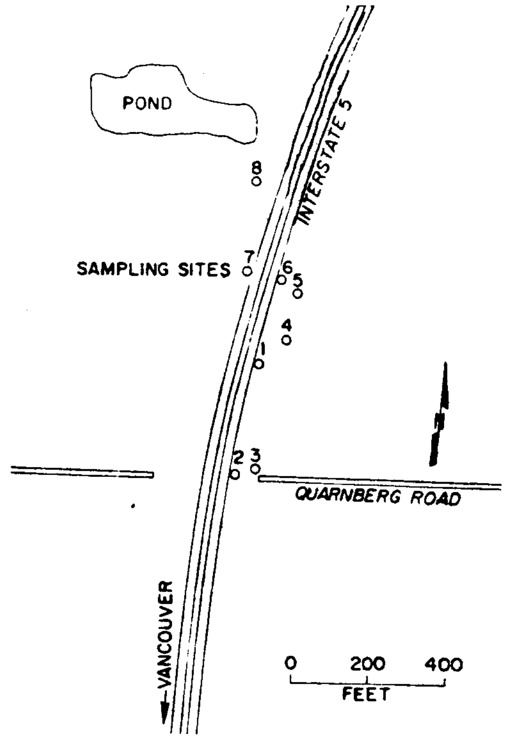

Figure 3.4
Vancouver Sampling Site

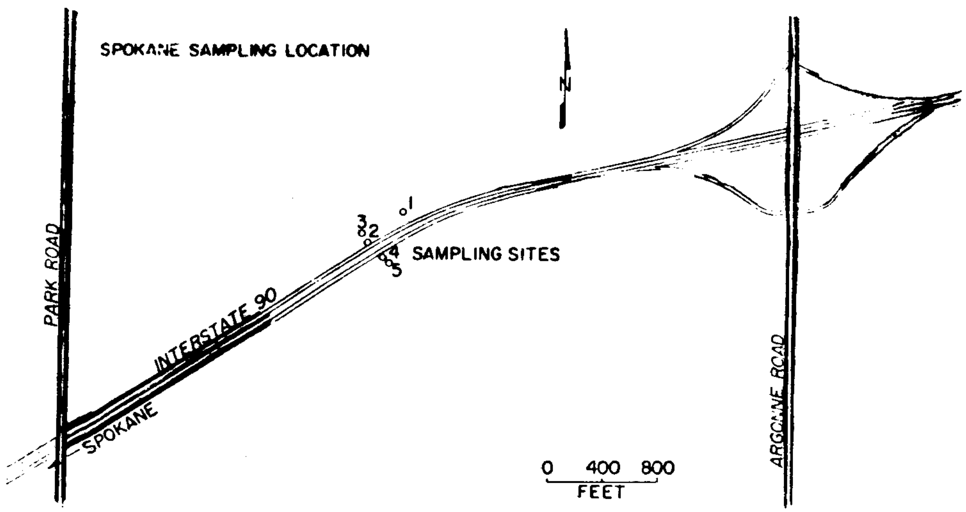

Figure 3.5
Spokane Sampling Site

test the models' general utility at different locations under approximately the same general meteorological conditions. Figure 3.4 shows the Vancouver location.

3.1.5 Spokane

The fifth highway section modeled was Interstate 90 east of Spokane, between Argonne Road and Park Road. This location was chosen to represent eastern Washington meteorological and topographical features. Figure 3.5 shows the Spokane location schematically.

3.2 EVALUATION METHODOLOGY

The general approach taken to evaluate the models was to supply the same emissions, meteorological, highway, and receptor parameters to each of the four models for each one-hour period sampled. The concentrations calculated at each of the receptor points from these inputs were then compared to the measured concentrations for that one-hour period. The resulting comparisons of measured and calculated concentrations were then analyzed to determine if any of the models evidenced a superior ability to describe the carbon monoxide concentration distributions at the various sites. Only downwind receptor sites have concentrations calculated by the models. No concentrations are obtained from the CALINE model for 0 - 2 mph wind speeds because the authors of the CALINE programs maintain that the model was not applicable for low wind speeds. HIWAY authors chose large initial values of σ_y and σ_z at low wind speeds to reduce the predicted concentrations and thus extend the HIWAY model usefulness to low wind speeds. Only those sites and time periods for which both calculated and measured values were available are included in the analysis.

The analysis was performed by stratification of the data, primarily by meteorological variables. The data subsets were determined for each site from the wind speed, wind direction with respect to the highway and the stability index. The wind speeds were grouped into three ranges, 0 - 3, 4 - 6, and 7 - 10 mph as recorded at the site. The wind direction with respect to the highway was parallel for an angle ϕ (see Figure 2-1) equal to $\pm 12^{\circ}$, oblique for ϕ equal to 33° to 57° and perpendicular for ϕ equal to 78° to 102°. The stability index was determined as described in section 1.5. A subset was considered to have statistically sufficient data for inclusion in subsequent analysis if it had at least 15 non-zero values of the calculated and measured CO concentration in each of the four models. The number of subsets for each site with sufficient data are two for Renton, three for Kirkland, seven for Seattle, fourteen for Vancouver, and six for Spokane. Parameters for the subsets are given in Table 3.1.

The general analysis scheme utilized to make the inter-model comparison is based on minimizing the difference between the measured concentration and the calculated concentration for a given receptor and line source. For each subset the linear least squares regression coefficients, a_i and b_i for the expression

$$(\text{Meas. CO})_i = a_i + b_i(\text{Calc. CO})_i \qquad \text{Eqn. 3.1}$$

are determined. The intercept, a_i, of the regression curve with the ordinate or measured concentration may be physically interpreted as the "background" concentration. The second regression coefficient, b_i, is the slope of the line relating the measured and calculated concentrations. The intercepts and slopes are listed for each subset in Table 3.1.

Table 3.1: Summary of Subset Parameters

Site	Data Subset	Stability	Wind Speed mph	Wind Direction	Number of Values EPA	CAL	MSNW	EPA Int. ai	EPA Slope bi	EPA F	EPA Signif	CALINE - 1 Int. ai	CALINE - 1 Slope bi	CALINE - 1 F	CALINE - 1 Signif.	CALINE - 2 Int. ai	CALINE - 2 Slope bi	CALINE - 2 F	CALINE - 2 Signif.	MSNW Int. ai	MSNW Slope bi	MSNW F	MSNW Signif.
Renton	1	D	4-6	⊥	26	26	26	2.97	0.42	1.21	50	2.78	0.95	0.36	<50	2.79	1.18	0.36	<50	2.55	0.86	1.95	75
	2	D	7-10	⊥	63	63	63	2.80	1.39	13.61	99	2.69	1.92	6.12	97.5	2.69	2.48	6.25	97.5	2.55	1.44	16.01	99
Kirkland	1	C	4-6	∥	52	52	52	1.67	0.22	4.97	99	1.60	0.11	5.42	97.5	1.59	0.38	5.03	95	1.63	0.44	4.14	95
	2	D	4-6	∥	216	216	216	1.80	0.16	11.18	99	1.74	0.15	11.77	99	1.67	0.31	12.80	99	1.81	0.27	6.68	97.5
	3	D	7-10	∥	131	131	131	1.17	0.24	12.43	99	1.13	0.23	17.63	99	1.08	0.49	18.61	99	1.10	0.51	15.11	99
Vancouver	1	B	0-3	∥	30	22	30	4.23	0.56	22.45	99	3.98	0.75	2.90	75	6.09	0.36	1.01	50	4.65	0.76	12.10	99
	2	B	4-6	⊥	23	23	23	2.89	1.40	5.65	95	0.32	8.34	5.51	95	0.29	10.58	5.51	95	6.14	-1.81	0.78	<50
	3	B	4-6	/	18	18	18	2.25	2.05	16.08	99	-0.43	8.24	7.30	97.5	-0.05	11.14	5.18	95	3.67	2.06	5.36	95
	4	B	4-6	∥	96	70	96	3.73	0.78	64.96	99	2.65	1.26	20.48	99	2.66	5.06	18.07	99	3.55	1.79	64.86	99
	5	C	0-3	∥	26	17	29	4.51	0.58	2.10	75	3.81	0.41	1.58	75	3.70	1.19	1.91	75	4.30	0.41	10.24	99
	6	C	4-6	/	20	20	20	3.73	1.09	4.47	95	3.59	2.82	1.86	75	3.54	3.27	2.04	75	4.77	0.86	2.58	75
	7	C	4-6	∥	133	108	158	3.88	0.63	62.73	99	2.47	1.37	23.91	99	2.40	3.78	26.66	99	3.59	1.31	100.99	99
	8	C	7-10	∥	104	92	129	2.87	1.26	86.49	99	0.94	2.92	31.20	99	0.94	7.87	33.78	99	2.60	2.57	175.49	99
	9	D	0-3	⊥	58	45	60	6.02	-0.013	0.01	<50	5.83	0.25	0.08	<50	5.80	0.32	0.10	<50	6.00	-0.01	0.03	<50
	10	D	0-3	/	67	65	67	4.30	0.46	13.09	99	4.91	0.84	3.31	90	4.61	0.82	5.78	97.5	5.78	0.11	1.68	75
	11	D	0-3	∥	73	73	101	3.86	0.36	31.82	99	4.20	0.51	9.09	99	3.96	0.96	13.32	99	4.88	0.37	28.26	99
	12	D	4-6	/	25	25	25	0.82	1.90	22.42	99	-0.18	6.20	12.97	99	0.35	4.50	15.81	99	5.41	0.27	1.19	50
	13	D	4-6	∥	92	92	111	2.90	0.78	58.59	99	3.08	1.19	17.89	99	2.85	2.19	26.17	99	3.77	0.87	40.91	99
	14	D	7-10	∥	119	119	145	3.42	0.85	23.08	99	3.07	1.69	10.11	99	2.95	3.00	14.23	99	3.27	1.45	56.54	99
Spokane	1	C	0-3	/	18	18	17	5.00	-0.14	0.11	<50	2.58	1.83	3.42	90	2.56	2.07	3.52	90	4.01	0.29	1.61	75
	2	C	4-6	∥	28	28	41	4.83	-0.35	1.64	75	4.17	-0.12	.0008	<50	4.78	-0.74	0.12	<50	4.56	-0.68	1.53	75
	3	C	4-6	/	23	23	23	1.80	0.54	2.85	75	1.20	1.98	9.76	99	1.22	2.20	9.49	99	2.47	0.14	1.52	75
	4	D	0-3	∥	18	15	18	2.81	0.16	1.55	75	4.21	-0.55	1.01	50	3.46	-0.14	0.02	<50	2.36	0.37	7.17	99
	5	D	0-3	/	23	23	26	1.86	0.38	3.18	90	1.29	1.43	1.37	50	1.24	1.30	1.63	75	2.26	0.22	4.06	90
	6	D	4-6	/	28	28	28	3.00	-0.25	0.56	50	2.56	0.02	.0003	<50	2.46	0.15	0.03	<50	2.43	0.11	1.44	75
Seattle	1	C	0-3	N-S	30	--	30	2.32	0.04	0.76	50									2.32	0.07	0.34	<50
	2	C	0-3	E-W	18	--	18	3.21	-0.02	0.02	<50									3.12	0.03	0.03	<50
	3	C	4-6	N-S	60	--	60	2.96	0.18	2.19	75									2.39	0.63	12.30	[illegible]
	4	C	7-10	N-S	36	--	88	2.82	0.32	3.58	90									2.71	0.70	3.25	90
	5	D	0-3	N-S	156	--	157	3.15	0.07	13.29	99									2.76	0.17	23.37	99
	6	D	4-6	N-S	198	--	202	3.23	0.06	5.80	97.5									2.96	0.20	17.16	99
	7	D	7-10	N-S	149	--	151	2.84	0.16	9.24	99									2.34	0.55	26.87	99

α Wind Direction Legend
∥ Parallel
⊥ Pendicular
/ Oblique

The subsets were tested to see if the correlation between the calculated and measured concentrations was real or due to chance only. The F-test was used for this analysis. The F-test compares the quotient of the mean square error due to regression divided by that due to deviation from the regression equation to the ratio predicted from the F-distribution for the proper number of degrees of freedom. If the quotient so calculated is greater than the predicted value of F at a given confidence level, then the relationship between the two variables is not likely to be due to chance.

Table 3.1 lists the F values for the various subsets as well as the significance level. Significance levels of 50% or less indicate the probability that a real relationship exists is only even or less. Based on this analysis certain subsets that had significance levels of 50% or less for all models were eliminated from subsequent analyses. These subsets were Vancouver 9 and Seattle 1 and 2.

3.2.1 Intra-model Variability

In order to quantify the degree of variability in a given model's results, an analysis of the variability in the values of b_i from Eqn. 3.1 was undertaken. The analysis consisted of the following procedure, applied to the values of b_i listed in Table 3.1:

First, the subsets of data are stratified by evaluation site, stability classification, wind-speed and wind direction (i.e., parallel, perpendicular, or oblique to the line source.)

Second, subsets with negative values of b_i are eliminated from further analysis. Seattle data are excluded for inter comparison purposes because the CALINE 1 and CALINE 2 models were not applied to the Seattle site due to the site's complexity.

Table 3.2. Summary of Calculations of Intra-Model Variability

Data Stratum	HIWAY			CALINE-1			CALINE-2			MSNW		
	b_s	$\frac{\text{Low } b_i}{b_s}$	$\frac{\text{High } b_i}{b_s}$	b_s	$\frac{\text{Low } b_i}{b_s}$	$\frac{\text{High } b_i}{b_s}$	b_s	$\frac{\text{Low } b_i}{b_s}$	$\frac{\text{High } b_i}{b_s}$	b_s	$\frac{\text{Low } b_i}{b_s}$	$\frac{\text{High } b_i}{b_s}$
1. Sites												
Renton	1.11	0.38	1.27	1.64	0.58	1.17	2.10	0.56	1.18	1.27	0.60	1.13
Kirkland	0.19	0.83	1.25	0.17	0.66	1.36	0.38	0.82	1.29	0.37	0.72	1.38
Vancouver	0.72	0.44	2.50	2.39	0.10	3.49	3.42	0.24	2.29	1.25	0.09	2.06
Spokane	0.39	0.42	1.38	1.22	0.01	1.62	1.28	0.12	1.71	0.18	0.63	2.00
2. Stability Class												
B	0.96	0.58	2.13	3.46	0.18	2.40	6.06	0.06	1.84	1.61	0.47	1.28
C	0.77	0.29	1.64	2.26	0.06	1.83	4.39	0.09	1.79	1.44	0.10	1.77
D	0.53	0.03	3.57	1.14	0.02	5.45	1.26	0.25	3.55	0.64	0.17	2.27
3. Wind Direction												
Perpendicular	1.17	0.36	1.20	2.22	0.11	3.75	2.82	0.11	3.72	1.27	0.68	1.13
Oblique	0.90	0.42	2.28	2.30	0.01	3.45	2.52	0.06	4.43	0.38	0.29	5.42
Parallel	0.48	0.33	2.64	1.37	0.08	3.03	2.31	0.13	3.40	1.02	0.26	2.52
4. Wind Speed												
0-3 mph	0.42	0.38	1.32	0.88	0.81	2.08	0.89	0.36	2.34	0.34	0.33	2.26
4-6 mph	0.61	0.13	2.46	1.14	0.02	7.32	2.50	0.06	4.44	0.84	0.13	2.46
7-10 mph	0.84	0.28	1.65	2.16	0.11	1.92	3.21	0.15	2.45	1.49	0.34	1.72

Next, the weighted mean value, $\bar{b}_s$, of the slopes for each data stratum is calculated from the equation:

$$\bar{b}_s = \frac{\Sigma b_i N_i}{\Sigma N_i} \qquad \text{Eqn. 2}$$

where N_i is the number of values in the subset.

The variability within a data stratum for each model is determined by examining the ratios of the lowest and highest values of b_i to $\bar{b}_s$. The least variable model has ratios that are closest in value to 1.0.

Table 3.2 shows the results of these calculations. The overall results indicate that the HIWAY model was slightly less variable than the MSNW model. The CALINE 1 model was more variable than any of the models. CALINE 2 was more variable than HIWAY or MSNW. Qualitatively, the analysis of variability indicates that one would be more confident in applying the HIWAY or MSNW models for different conditions than applying either of the CALINE models.

3.2.2 Inter-model Comparison

The analysis of how well the models would predict the mean measured concentrations is based on minimizing the value of the mean square difference between the mean measured concentration per subset and the mean calculated concentration per subset.

The mean calculated concentration per subset is determined in the following manner. The values (one from each model) of a_i from Eqn. 3.1 and Table 3.1 are averaged to give the best estimate of the average background concentration, $\bar{A}_i$, which is added to the mean of the values calculated for individual receptor points in each subset to give the mean calculated concentration for the subset, $(\overline{CO})_i$:

$$\overline{(CO)}_i = (\text{Calc. } \overline{CO})_i + \overline{A}_i \qquad \text{Eqn. 3}$$

The square of the difference between the mean measured and calculated values is D_i^2. The sum of the products of the square of the difference and the number of values divided by the sum of the number of values results in a statistic, D^2, which will be called the mean square difference for each model. This statistic is a measure of the model's lack of success in making a correct prediction and may be described mathematically as:

$$D_i^2 = \{\overline{(\text{Meas. CO})}_i - \overline{(CO)}_i\}^2 \qquad \text{Eqn. 4}$$

$$D^2 = \frac{\Sigma N_i D_i^2}{\Sigma N_i} \qquad \text{Eqn. 5}$$

Table 3.3 is a summary of the mean measured and calculated concentrations based on the above procedure. The Seattle data are not used in subsequent calculations because the CALHWY model was not applied to the Seattle site. Subsets with negative values of b_i previously excluded are also excluded from this analysis.

A summary of the values of $D_i N_i$ for each data subset is shown in Table 3.4, along with the values of D^2 for each model at the bottom of the table.

The results summarized in Table 3.4 show the minimum difference between the calculated and measured CO concentrations is given by the MSNW model, with a D^2 value of 1.21 The second lowest D^2 value was for the CALINE 2 model, 2.14 while the CALINE 1 and EPA models have nearly the same D^2 values, 2.39 and 2.41 respectively.

Table 3.3. Summary of Mean Measured and Mean Estimated Concentrations in PPM

Site	Case	Stab.	Wind		HIWAY		MSNW		CALINE-1		CALINE-2	
			Spd	Dir	Meas.	Est.	Meas.	Est.	Meas.	Est.	Meas.	Est.
Renton	1	D	4-6	⊥	3.23	3.37	3.23	3.56	3.23	3.24	3.23	3.14
	2	D	7-10	⊥	3.30	3.04	3.30	3.26	3.30	3.00	3.30	2.93
Kirkland	1	C	4-6	||	1.87	2.51	1.87	2.16	1.87	3.97	1.87	2.33
	2	D	4-6	||	2.09	3.57	2.09	2.81	2.09	4.19	2.09	3.14
	3	D	7-10	||	1.14	2.14	1.41	1.73	1.41	2.32	1.14	1.81
Vancouver	1	B	0-3	||	5.83	7.62	5.83	6.31	6.55	8,17	6.55	6.00
	2	B	4-6	⊥	5.09	3.98	--	--	5.09	2.92	5.09	2.99
	3	B	4-6	/	6.00	3.31	6.00	2.61	6.00	2.26	6.00	2.02
	4	B	4-6	||	4.97	4.76	4.97	3.95	5.41	4.92	5.41	3.70
	5	C	0-3	||	5.23	8.25	5.17	6.06	5.29	6.43	5.29	5.26
	6	C	4-6	/	5.75	5.76	5.75	5.05	5.75	4.68	5.75	4.59
	7	C	4-6	||	5.38	5.44	5.05	4.16	5.60	4.64	5.60	3.90
	8	C	7-10	||	5.05	3.55	4.55	2.58	5.28	2.86	5.28	2.37
	10	D	0-3	/	6.13	8.80	6.13	7.98	6.09	6.31	6.09	6.70
	11	D	0-3	||	6.59	10.39	5.98	7.12	6.26	6.55	6.26	6.53
	12	D	4-6	/	6.04	4.38	6.04	3.99	6.04	2.63	6.04	2.90
	13	D	4-6	||	5.41	6.30	5.41	4.77	5.41	4.25	5.41	4.24
	14	D	7-10	||	5.08	5.12	4.74	4.18	5.08	3.88	5.08	3.87
Spokane	1	C	0-3	/	--	--	4.67	5.32	4.67	4.18	4.67	4.06
	3	C	4-6	/	2.70	3.32	2.70	2.34	2.70	2.43	2.70	3.23
	4	D	0-3	||	3.50	6.77	3.50	5.70	--	--	--	--
	5	D	0-3	/	2.88	4.39	2.88	3.55	2.70	2.66	2.70	2.79
	6	D	4-6	/	--	--	2.57	3.73	2.57	3.13	2.57	3.22

Legend: ⊥ Wind Perpendicular to Highway Axis
|| Wind Parallel to Highway Axis
/ Wind Oblique to Highway Axis

Table 3.4. Summary of Calculations of the Mean Square Difference

Site	Case	Stab.	Wind Spd	Wind Dir	HIWAY	MSNW	CALINE-1	CALINE-2
Renton	1	D	4-6	⊥	0.51	2.83	0.00	0.21
	2	D	7-10	⊥	4.26	0.63	5.67	8.62
Kirkland	1	C	4-6	||	21.48	4.37	229.32	11.00
	2	D	4-6	||	473.13	111.98	952.56	238.14
	3	C	7-10	||	69.81	13.41	108.48	20.96
Vancouver	1	B	0-3	||	96.12	6.91	57.74	7.40
	2	B	4-6	⊥	127.02	-----	267.45	276.94
	3	B	4-6	/	130.65	206.86	251.78	285.13
	4	B	4-6	||	4.25	99.88	16.81	204.69
	5	C	0-3	||	237.13	22.97	22.09	0.02
	6	C	4-6	/	0.00	9.80	22.90	26.91
	7	C	4-6	||	0.48	125.15	99.53	210.42
	8	C	7-10	||	234.00	500.64	538.79	781.98
	10	D	0-3	/	477.63	229.31	3.15	24.19
	11	D	0-3	||	1054.12	131.26	6.14	5.32
	12	D	4-6	/	68.89	105.06	209.70	246.49
	13	D	4-6	||	72.87	24.52	123.79	125.94
	14	D	7-10	||	0.19	45.47	171.36	174.23
Spokane	1	C	0-3	/	-----	7.61	4.32	6.70
	3	C	4-6	/	8.84	7.73	1.68	2.98
	4	D	0-3	||	192.47	87.12	-----	-----
	5	D	0-3	/	59.28	72.51	0.04	0.19
	6	D	4-6	/	-----	37.68	8.73	11.83
$\Sigma D_i N_i$					3333.11	1853.73	3102.03	2770.29
ΣN_i					1381	1530	1296	1296
D^2					2.41	1.21	2.39	2.14

⊥ Winds Perpendicular to Highway Axis

|| Winds Parallel to Highway Axis

/ Winds Oblique to Highway Axis

3.2.3 Critical Subsets

Critical subsets are those with parameters describing what are expected to represent the worst and most probable combinations of meteorological conditions. Worst case conditions are D stability and 0-3 mph winds and most probable conditions are D stability and 3-6 mph winds for the State of Washington. These conditions, along with the orientation of the wind with respect to the highway to be modeled, define the critical subsets.

Analysis of the various models success in predicting the maximum concentrations in critical subsets was undertaken as suggested by Turner, et al., 1972. Such an analysis is undertaken because a consistent over-or underprediction of maxima would be an undesirable feature of a model.

The maximum measured value at any receptor for each critical case was found and compared with the calculated value at that receptor. The calculated value includes the average background, $\bar{A}_i$, described in Section 3.2.2 above. Similarly, the maximum calculated value at any receptor was compared to the maximum measured value of any receptor. Table 3.5 summarizes these comparisons for the critical subsets.

Neither the CALINE-1 or CALINE-2 models ever overpredicted the maximum concentration at the maximum receptor. In addition, the maximum calculated concentration at any receptor never exceeded the maximum measured concentration at any receptor for the CALINE-2 model, and did so only for the Kirkland case for the CALINE-1 model. The MSNW and HIWAY models overpredicted the maxima for the parallel, 0-3 mph cases and MSNW overpredicted the Spokane, 4-6 mph case. The more than 100% difference between the maximum estimated and measured values for the oblique, 0-3 mph Vancouver case with the MSNW model is noted.

Table 3.5: Summary of Analysis of Most Probable and Worst Case Categories[a]

Stab.	Wind Spd.	Wind Dir.[d]	Subset	Maximum Measured				Error at Max. Meas.[c]				Max. Estimated Value[b]			
				EPA	MS	C-1	C-2	EPA	MS	C-1	C-2	EPA	MS	C-1	C-2
D	0-3	/	Vancouver	9.0	9.0	9.0	9.0	+1.2	+1.2	-2.4	-1.8	13.5	17.7	7.4	8.1
			Spokane	7.0	7.0	7.0	7.0	-3.1	-1.1	-4.2	-4.0	9.2	10.4	3.1	3.3
D	0-3	||	Vancouver	11.0	11.0	11.0	11.0	+3.8	-0.4	-1.7	-3.7	15.6	11.5	10.5	7.9
			Spokane	7.0	7.0	-	-	+4.9	+4.9	-	-	11.9	11.4	-	-
D	4-6	⊥,/	Renton	6.0	6.0	6.0	6.0	-2.1	-2.2	-2.7	-2.8	5.4	4.5	3.7	3.5
			Spokane	-	4.0	4.0	4.0	-	+1.6	-0.7	-1.9	-	6.3	3.5	3.6
			Vancouver	9.0	9.0	9.0	9.0	-9.3	-6.8	-6.4	+6.0	5.3	7.4	2.9	3.3
D	4-6	||	Kirkland	5.0	5.0	5.0	5.0	-2.7	-3.0	-2.4	-2.7	6.3	4.4	7.4	4.7
			Vancouver	10.0	10.0	10.0	10.0	-1.0	-3.3	-4.0	-5.1	10.0	7.6	6.7	5.3

[a] All values in ppm of Carbon Monoxide

[b] Estimated Value includes average background, A_i

[c] Negative value indicates underprediction by the model

[d] Wind Direction Legend

⊥ Winds Perpendicular to Highway Axis

|| Winds Parallel to Highway Axis

/ Winds Oblique to Highway Axis

This analysis does not establish a clearly superior model with respect to successful prediction of maxima. The calibration phase of the project, see Section 6, will affect the magnitude of the errors involved in predicting maxima and may improve the models' ability in this prediction.

4. EVALUATION OF QUALITATIVE FACTORS

4.1 Model Acquisition Costs

The MSNW model is contained in a proprietary computer program developed by Mathematical Sciences Northwest, Inc. The cost of acquiring this program is several thousand dollars. In contrast, the HIWAY and CALINE programs are available without charge from the Environmental Protection Agency and California Division of Highways, respectively.

4.2 Model Operating Costs

The direct operating costs for any of the models is directly proportional to the time required to run the computer programs containing the models. The CALINE programs require the least amount of computer time to run. The MSNW program running time is dependent upon the grid size specified by the user, but for this study required approximately 6 times more computer time than CALINE for the same number of cases. EPA's program, because of the integration procedures, requires approximately 20 times more computer time than CALINE, although this might be reduced substantially by changing the integration convergence criterion so that fewer iterations would be necessary for each calculation.

4.3 Flexibility

The flexibility of the models varies with the nature of the assumptions basic to the model. The CALINE models are least flexible because they assume the line source segment being modeled is an infinite straight line source. CALINE-1 is slightly more flexible than CALINE-2 for parallel cases because the length of the parallel wind fetch can be specified. Both the MSNW and EPA models are more flexible in that line sources that do not fit the infinite length assumption may be modeled. For example, a curved section, such as the Spokane evaluation site, can be modeled as two or more straight lines.

The HIWAY model is in turn more flexible than the MSNW model due to the integration procedures incorporated in HIWAY. The MSNW model can lead to unrealistically high results if a receptor is chosen that lies immediately downwind of one of the point sources used to approximate the line source. Or alternatively, a receptor site might be chosen in-between the "plumes" emitted by two point sources and thus the MSNW model would calculate unrealistically low results. It should be possible to remedy this weakness by changing the program somewhat.

4.4 Support Level

As many other research, regulatory, and operating organizations and agencies are or will be involved in similar applications of line source dispersion models, it is worthwhile to consider the level of "support" each model evaluated in this study is likely to receive. "Support" in this context means improvements in the programs incorporating the models and improvements in the models, such as in improved dispersion coefficients and application of the models to diverse situations.

The California Department of Highways is in the process of shifting their program support from CALINE-1 to CALINE-2, and is applying CALINE-2 in California. These applications should result in new validation data.

EPA continues to support HIWAY, although in a somewhat altered form from that used in this study. Due to the status of EPA as the ultimate regulatory authority with respect to air pollution regulations, in addition to the strong in-house modeling expertise, HIWAY, in some form, will probably find the widest application of any of the models evaluated. This wide application should ultimately result in a program and model with the broadest base of actual use experience.

Mathematical Sciences Northwest, Inc. should be able to provide all the necessary program support necessary for their model. Due to its proprietary nature, applications will be limited, although any validation from studies similar to this project could, of course, be used with the MSNW model to broaden its application base. Such applications would be limited by Math Sciences internal support level.

HIWAY should receive the strongest support level, followed by CALINE-2, MSNW and CALINE-1 in that order.

5. SUMMARY AND MODEL(S) CHOICES

Quantitative and qualitative analysis of four line source dispersion models indicated that each of the models, the U.S. Environmental Protection Agency's HIWAY model, the California Highway Line Source Dispersion Models, CALINE-1 and CALINE-2, and a Mathematical Sciences Northwest, Inc. model MSNW, had certain desirable features that would recommend its use by the Department of Highways.

Table 5.1 is a matrix table summarizing the preliminary results of the evaluation study. The six parameters used to "rank" the three models are (1) the intra-model variability as analyzed in Section 3.2.1; (2) the inter-model comparison of the mean square difference between measured and calculated concentrations as analyzed in Section 3.2.2; (3) the model acquisition costs; (4) the operating costs; (5) the model flexibility; and (6) the "support" level. A rank order of 1 to 4 is assigned to each model for each of these parameters, representing the most to least desirable model.

The Department of Highways participated in the decision on which model(s) to calibrate at this point in the project because several of the qualitative factors involved could only be properly evaluated and weighted by the Department. Since none of the models was shown to be clearly superior in its ability to describe the carbon monoxide distributions at the various sites, the qualitative factors described above carried considerable weight in the model(s) choice. The Department requested that both the CALINE-2 and HIWAY models be calibrated in the final phase of the project. The CALINE-2 model was chosen because of its simplicity and low operating costs. The HIWAY model was chosen because of the need to have a model capable of handling more complex highway configurations than the CALINE-2 model and because of the support level that could be expected from EPA.

Table 5.1. Matrix of Model Desirability

	HIWAY	CALINE-1	CALINE-2	MSNW
Intra-model variability analysis	1	4	2	2
Inter-model mean square difference analysis	4	3	2	1
Cost of obtaining computer program	1	1	1	2
Operating costs for computer programs	3	1	1	2
Model flexibility	1	4	3	2
"Support" level	1	4	2	3

KEY

1	Most desirable characteristics
2,3	In-between
4	Least desirable characteristics

6. CALIBRATION OF THE CALINE-II AND HIWAY MODELS

6.1 General Methods

Calibration of the two models requested by the Department of Highways was based on the analysis begun in Section 3. In general, the subsets' regression slopes and intercepts were calculated. Then a comparison was made to determine if the various subsets could be combined into larger groupings in order to generalize the calibration.

The confidence limits (99%) for the least squares regression slopes, a_i, and intercepts, b_i, for the subsets with a significant correlation between the measured and calculated concentrations are shown along with the coefficients in Table 6.1. The grouping by stability class was suggested by these data, which show decreasing values of b_i with increasing stability. Since the Department of Highways had indicated particular interest in applying the models for conditions typical of the "most probable" and "worst case" conditions, and since the models are based on different dispersion parameters (See Section 2) for different stabilities, the stability class groups were used to determine the calibration curves for the models. Three stabilities were used, B, C and D. All data for each model were grouped by stability classes. Then the three stability groups were further divided randomly into statistical and prediction subgroups. The division was performed by a computer program using a random number generator function.

The regression coefficients for the linear least squares fit line relating measured and calculated concentrations of carbon monoxide were calculated for each statistical subgroup. The best estimate of the intercept determined in Section 3.2.2 from the average of the four original models was subtracted from the measured concentration before the regression line was calculated.

Table 6.1: Regression Analysis Results for CALINE-II and Hiway Models Including 99% Confidence Intervals for Intercept and Slope of Regression Line

					CALINE - II							EPA HIWAY						
Site	Case	Stability	Wind Spd.	Wind Dir.	Lo α	α	High α	Lo β	β	High β	n	Lo α	α	High α	Lo β	β	High β	n
Vancouver	1	B	0-3	∥	4.58	6.09	7.61	-0.539	0.357	1.25	22	3.12	4.23	5.34	0.27	0.56	0.85	30
Vancouver	4	B	4-6	∥	1.08	2.66	4.24	2.22	5.06	7.09	70	3.26	3.73	4.20	0.55	0.78	1.00	96
Vancouver	2	B	4-6	⊥	-4.91	0.287	5.48	-0.76	10.58	21.92	23	0.450	2.86	5.32	-0.083	1.40	2.88	23
Vancouver	3	B	4-6	/	-6.99	-0.053	6.89	-1.51	11.14	23.78	18	-0.281	2.25	4.79	0.73	2.05	3.37	18
Spokane	1	C	0-3	/	-0.44	2.56	5.56	-0.78	2.07	4.93	18	2.28	5.00	7.72	-1.20	-0.14	0.93	18
Vancouver	5	C	0-3	∥	0.58	3.70	6.81	-1.05	1.19	3.44	17	3.21	4.19	5.17	0.058	0.24	0.42	26
Vancouver	7	C	4-6	∥	0.88	2.90	8.91	2.04	3.77	5.51	108	3.33	3.88	4.22	0.44	0.63	0.82	133
Kirkland	1	C	4-6	∥	1.27	1.59	1.91	-0.028	0.38	0.79	52	1.42	1.67	1.92	-0.018	0.22	0.46	52
Vancouver	6	C	4-6	/	-0.503	3.54	7.50	-2.58	3.27	9.12	20	1.16	3.73	6.30	-0.23	1.09	2.41	20
Spokane	3	C	4-6	/	-0.041	1.22	2.48	0.401	2.20	3.99	23	0.392	1.80	3.20	-0.267	0.544	1.36	23
Vancouver	8	C	7-10	∥	-0.87	0.938	2.75	4.65	7.87	11.08	92	2.23	2.87	3.51	0.940	1.26	1.58	104
Vancouver	11	D	0-3	∥	2.58	3.95	5.53	0.33	0.96	1.57	73	2.77	3.86	4.96	0.21	0.36	0.52	73
Spokane	4	D	0-3	∥	-0.85	3.46	7.76	-2.49	-0.14	2.19	15	1.11	2.81	4.51	-0.178	0.165	0.506	18
Vancouver	10	D	0-3	/	3.07	4.61	6.15	0.006	0.82	1.64	65	3.01	4.30	5.59	0.16	0.46	0.76	67
Spokane	5	D	0-3	/	-1.71	1.24	4.19	-1.26	1.30	3.87	23	0.280	1.86	3.45	-0.149	0.375	0.899	26
Kirkland	2	D	4-6	∥	1.36	1.67	1.98	0.105	0.306	0.507	216	1.56	1.80	2.05	0.047	0.158	0.269	216
Vancouver	13	D	4-6	∥	1.61	2.85	4.10	1.17	2.19	3.21	92	2.05	2.90	3.75	0.54	0.78	1.02	92
Vancouver	12	D	4-6	/	-3.29	0.346	3.99	1.66	4.48	7.29	25	-2.00	0.82	3.64	0.90	1.90	2.90	25
Renton	1	D	4-6	⊥	0.924	2.79	4.66	-3.69	1.18	6.05	20	2.25	3.00	3.71	-0.53	0.427	1.38	26
Kirkland	3	D	7-10	∥	0.867	1.08	1.28	0.222	0.490	0.758	131	0.979	1.17	1.36	0.078	0.238	0.398	131
Vancouver	14	D	7-10	∥	1.58	2.95	4.32	1.12	3.00	4.87	119	2.54	3.42	4.29	0.43	0.85	1.26	119
Renton	2	D	7-10	∥	2.06	2.69	3.12	0.110	2.47	4.84	63	2.41	2.80	3.19	0.49	1.39	2.30	63
Spokane	6	D	4-6	/	0.92	2.46	4.00	-1.88	0.15	2.18	28	1.60	2.98	4.36	-1.08	-0.25	0.58	28

Wind Direction Legend
∥ **Parallel**
⊥ **Pendicular**
/ **Oblique**

The results from the statistical subgroup analysis were used to predict the concentrations for the prediction subgroup. The predicted concentrations were calculated from the equation:

$$\text{Predicted CO} = (\text{Calculated CO}) \times B \qquad \text{Eqn. 6.1}$$

where B is the regression slope determined from the statistical subgroup analyses and the calculated values are from the prediction subgroup. These predicted concentrations were then compared to the measured concentrations in the prediction subgroup. Two measures of the agreement between measured and predicted concentrations were determined. These were the standard error

$$S = \sqrt{\frac{\Sigma(\text{Pred.}-\text{Meas.})^2}{n-2}} \qquad \text{Eqn. 6.2}$$

and the average absolute error, E:

$$E = \frac{\Sigma(\text{Pred.}-\text{Meas.})}{n} \qquad \text{Eqn. 6.3}$$

The absolute error is not weighted as heavily by individual cases with large differences as is the standard error.

After these calculations were made, the statistical and prediction subgroups were reversed to determine if the results would be different. A significant difference would suggest a lower degree of confidence in the relationship between the measured and modeled concentrations.

6.2 Calibration Results

The statistical subgroups, one for each of the models, were analyzed by computing the regression coefficient, B, for the linear least squares equation relating the measured and calculated concentrations. Table 6.2 gives the computed regression coefficient and its 95% confidence limits as

Table 6.2: Statistical Subgroup Regression Analysis Results

Model	Stability Class	No. of Values	Regression Coefficient Slope	95% Confidence Interval	Standard Error of Estimate
Hiway	B	92	1.22	1.03 - 1.40	1.92
	C	186	0.97	0.87 - 1.08	1.68
	D	418	0.46	0.40 - 0.49	1.44
Caline-2	B	63	4.80	4.04 - 5.57	1.85
	C	167	2.51	2.13 - 2.88	2.04
	D	422	0.89	0.78 - 0.99	1.40

well as the standard error of the estimate for the three stability classes for the two models.

The regression equation was forced through the origin because the "background" concentration was subtracted from the measured concentrations prior to the computations. Thus the resulting measured values should be due to the modeled highway alone, as are the calculated concentrations.

Table 6.2 shows that the HIWAY model overpredicted the measured concentrations for D stability, as the slope is less than unity and underpredicted B stability. For C stability, the slope was not significantly different than unity at the 95% confidence level. Table 6.2 also indicates that CALINE-2 substantially underpredicted concentrations for B and C stability, while the upper confidence limit for the D stability slope is quite close to unity.

The slopes indicated in Tables 6.2 were used in equation 6.1 as the coefficient B in order to compute the "Predicted CO" values for the prediction group. The standard errors and average absolute errors resulting from equations 6.2 and 6.3 are shown in Table 6.3 for the different stability classes for the two models. As may be seen from this table the standard errors are all less than 2.2 ppm and are quite similar in magnitude to the standard errors of the estimate computed within the statistical subgroup, (see Table 6.2).

When the statistical and prediction subgroups are interchanged, the results in Table 6.4 indicate a significant difference in the calculated slopes for the HIWAY model for B and C stability between the statistical and prediction subgroups at the 95% confidence level. For the CALINE-2 model, the B stability slopes were different between the subgroups but the C and D stability slopes were not statistically different at the 95% confidence level. The HIWAY D stability slopes were not significantly

Table 6.3: Prediction Subgroup Standard and Average Absolute Errors

Model	Stability	No. of Values	Standard Error, ppm	Avg. Abs. Error, ppm
Hiway	B	75	2.11	1.63
	C	172	2.13	1.56
	D	438	1.45	1.04
Caline-2	B	70	2.17	1.71
	C	163	1.98	1.61
	D	439	1.66	1.21

Table 6.4: Prediction Subgroup Regression Analysis Results

Model	Stability Class	No. of Values	Regression Coefficient Slope	95% Confidence Interval		Standard Error of Estimate
Hiway	B	75	0.82	0.64	1.00	1.87
	C	172	0.71	0.60	0.81	1.97
	D	438	0.40	0.36	0.45	1.44
Caline-2	B	70	3.80	2.97	4.63	2.07
	C	163	2.62	2.23	3.01	1.57
	D	439	0.84	0.73	0.95	1.65

different at the 98% confidence level.

Applying the results of Table 6.4 to the statistical subgroup results in the standard and average absolute errors tabulated in Table 6.5. No significant trends or anomalous results are indicated from comparing Tables 6.3 and 6.5

It is believed that because of the anticipated use of these results, a conservative approach should be taken. This approach would use the slope giving the highest predicted concentrations. Thus the statistical subgroup, with its largest slopes, is to be used as the statistical base.

6.3 Application of Calibration Results

The desired products of this project are calibrated models for application to different highway line sources. The following Table 6.6 indicates the calibration equation to be applied to the model-calculated concentrations of carbon monoxide due to such a line source. The use of these equations is as follows:

1. Highway, meteorological, emissions, and receptor parameters are input into the models.

2. The models calculate concentrations for each receptor for each combination of input parameters.

3. The calculated concentrations are multiplied by the calibration factor from Table 6.6.

The above steps are integral parts of the computer program. The steps below are optional input the model may use. Of course, focal background concentrations may vary.

4. A value of 2 times the standard errors in Table 6.6 is added to the product from 3 above. This allows for "worst case" deviations from the expected concentrations.

Table 6.5: Statistical Subgroup Standard and Average Absolute Errors

Model	Stability	No. of Values	Standard Error, ppm	Avg. Abs. Error
Hiway	B	92	2.11	1.60
	C	186	1.79	1.35
	D	418	1.45	1.05
Caline-2	B	63	1.97	1.55
	C	167	2.05	1.69
	D	422	1.47	1.09

5. The result is the upper limit of carbon monoxide concentrations that would be expected from the highway sources. Added to the background concentration, the total is the predicted concentration, which would be used, for example, for comparison with ambient air quality standards or measured air quality concentrations.

The calibration equations have not been incorporated directly into the applicable computer programs. If the background concentration is supplied as computer input along with the input parameters, these equations could be incorporated into the programs.

It should be realized that the final result computed as above is not the best, unbiased estimate of the concentration, but rather a deliberately high estimate chosen so that in only approximately 2% of cases chosen at random would the measured value exceed the estimate. Thus it serves as a conservative basis for prediction and design.

Table 6.6: Calibration Equations for HIWAY and CALINE-2 Models

Model	Stability	Calibration Equation
HIWAY	B	Predicted CO = 1.40(Calc.CO) + 2(2.11) + Background CO
	C	Predicted CO = 1.08(Calc.CO) + 2(2.13) + Background CO
	D.	Predicted CO = 0.49(Calc.CO) + 2(1.45) + Background CO
CALINE-2	B	Predicted CO = 5.57(Calc.CO) + 2(2.17) + Background CO
	C	Predicted CO = 2.88(Calc.CO) + 2(1.98) + Background CO
	D	Predicted CO = 0.99(Calc.CO) + 2(1.66) + Background CO

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APPENDIX A

Calculation of Fraction of Vehicles in Use

The vehicle registrations by model year for King, Clark, and Spokane Counties, Washington, were obtained early in the project from the Department of Motor Vehicles. The registrations were for the period ending 9/30/73. Since the procedures outlined in Section 2.5 call for December 31 distributions, the available data had to be adjusted for 1973 and 1974 registration. The following data were available:

Model Year	Number of Vehicles Registered		
	King Co.	Clark Co.	Spokane Co.
1973	37572	3575	8544
1972	49651	5580	11052
1971	38417	4974	9034
1970	37214	5046	9596
1909	46197	5916	11075
1968	44852	5443	10924
1967	44136	5430	10082
1966	44834	5464	10772
1965	41663	5663	11110
1964	33201	4854	9139
1963	29077	3876	8004
1962 & older	77130	11305	25670

In addition, it was known that on December 31, 1973, a total of 52445 new (1973 and 1974) vehicles had been registered in 1973 and 12620 new cars were registered after 9/30/73 in King County. It was then assumed that 80% of all new cars registered after 9/30/73 were 1974 models. Thus, the estimated total 1974 model registrations on 12/31/74 were 0.80 (12620) + (52445 - 12620 - 35752) = 12349 and 1973 model registrations were (52445 - 12349) = 40094.

For Spokane and Clark Counties, only total registrations for 12/31/73 were known. It was assumed that all vehicles registered after 9/30/73 were either 1973 or 1974 models. It was further assumed that 80% of those registered after 9/30/73 were 1974 models, and 20% were 1973 models. Thus, the total 1974 models were 80% of the difference between the 9/30 and 12/31 registration totals and the 1973 models were the remiander, plus the 1973 total as of 9/30/73. For all three counties, 1962 registrations were assumed to be 30% of the 1962 and older registrations.

Table A-1 WEIGHTED ANNUAL TRAVEL BY LIGHT DUTY VEHICLES, KING COUNTY

AGE	FRACTION OF VEHICLES IN USE ON DEC. 31[a]	AVG. MILES DRIVEN[b]	WEIGHTED TRAVEL FRACTION
0	.023	3600	.008
1	.074	11900	.087
2	.092	16100	.146
3	.071	13200	.093
4	.063	11400	.071
5	.086	11700	.099
6	.083	10000	.082
7	.082	10300	.083
8	.083	8600	.071
9	.077	10900	.083
10	.062	8000	.049
11	.054	6500	.035
12	.043	6500	.028
13 AND OLDER	.100	6500	.064

[a]Appendix A

[b]Kircher and Armstrong, p. 14

Table A-2 WEIGHTED ANNUAL TRAVEL BY LIGHT DUTY VEHICLES, CLARK CO.

AGE	FRACTION OF VEHICLES IN USE ON DEC. 31[a]	AVG. MILES DRIVEN[b]	WEIGHTED TRAVEL FRACTION
0	.079	3600	.030
1	.068	11900	.083
2	.075	16100	.125
3	.067	13200	.091
4	.068	11400	.080
5	.079	11700	.096
6	.073	10000	.076
7	.073	10300	.078
8	.073	8600	.065
9	.076	10900	.086
10	.065	8000	.054
11	.052	6500	.035
12	.046	6500	.031
13 AND OLDER	.106	6500	.071

[a]Appendix A

[b]Kircher and Armstrong, p. 14

Table A-3 WEIGHTED ANNUAL TRAVEL BY LIGHT DUTY VEHICLES, SPOKANE COUNTY

AGE	FRACTION OF VEHICLES IN USE ON DEC. 31[a]	AVG. MILES DRIVEN[b]	WEIGHTED TRAVEL FRACTION
0	.070	3600	.026
1	.075	11900	.093
2	.075	16100	.125
3	.061	13200	.084
4	.065	11400	.077
5	.075	11700	.091
6	.074	10000	.077
7	.068	10300	.073
8	.073	8600	.065
9	.075	10900	.085
10	.062	8000	.051
11	.054	6500	.037
12	.052	6500	.035
13 AND OLDER	.122	6500	.082

[a]Appendix A

[b]Kircher and Armstrong, p. 14

APPENDIX B

I. Site Descriptions in Grid Format

A. General

All sites were placed in a Cartesian coordinate system oriented along north-east axes. That is, the ordinate runs along a north-south line and the abscissa runs east-west. The origin was located so that the line source and all receptors lay in the first quadrant of the Cartesian system. The size of the grid was dependent upon the maximum extent of the receptors, or upon the orientation of the highway line sources. The accompanying maps show the sites as modeled. The maps are produced using the Mathematical Sciences Northwest, Inc. program. Some maps are plotted with one axis exaggerated relative to the other.

B. Sites

Table B-1 shows a summary of the various sites, including the extent in feet of the grid system as well as the locations of the line sources in the grid system. For the Renton, Kirkland and Vancouver sites, a single line source was sufficient to describe the highway segment. The Spokane source was divided into two segments in order to more closely approximate the curve near the receptors. The Seattle site consisted of ten segments, three for the main freeway, one for the main cross street, four on-off ramps and two segments of an arterial. Included in Table B-1 are the width of the segments, the heights, the width of any center medians and the number of lanes for each segment.

Table B-1

Table B-1

Site	Source Number	Length of East-West Axis (x), feet	Length of North-South Axis (y), feet	Source Coordinates, feet x_1	y_1	x_2	y_2	Source Parameters: Number of Lanes Modeled	Width feet	Height feet	Median feet	Source Identification
Renton	1	3000	3000	0	410	2500	580	2	75	8	10	SR-405, freeway
Kirkland	1	1000	14000	500	200	500	13800	2	115	0	40	SR-405, freeway
Vancouver	1	2000	3000	735	0	1410	3000	2	64	0	0	Interstate 5, freeway
Spokane	1	6000	4000	0	67.8	2740	1783	2	83	0	27	Interstate 90, freeway, west of curve
	2			2740	1783	6000	2450	2	83	0	27	Interstate 90, freeway, east of curve
Seattle	1	1200	4000	150	4000	680	2630	2	145	0	20	Interstate 5, north segment
	2			680	2630	880	1660	2	120	0	20	Interstate 5, middle segment
	3			880	1660	880	0	2	145	0	20	Interstate 5, south segment
	4			0	2370	1200	2340	2	50	20	0	NE 145th Street, arterial
	5			365	3450	560	2355	1	20	10	0	Southbound off-ramp
	6			540	2355	880	1155	1	20	10	0	Southbound on-ramp
	7			1055	1915	880	1455	1	25	0	0	Northbound off-ramp
	8			1065	2340	1060	1915	1	55	50	0	N.E. 5th Ave., South of N.E. 145th
	9			1070	2780	1060	2340	1	50	50	0	N.E. 5th Ave., North of N.E. 145th
	10			1065	2780	620	2780	1	30	0	0	Northbound on-ramp

II. Receptor Locations in Grid Coordinates

Table B-2 shows the receptor grid coordinates for each site. The receptor number is the identifier of each receptor in all data lists. For the Renton and Kirkland sites the MR series receptors were located on the north highway shoulder for Renton and on the median for the Kirkland sites. Receptors are plotted on the site maps.

III. Hourly Data for Each Site

The general input data for each site are available through A.T. Rossano, Department of Civil Engineering, University of Washington, Seattle, Washington 98195. The data are stored on two card images per case. The information on each card image is listed in the accompanying Table B-3 along with the format of the data. The table explains what each variable is and any applicable units (mph, degrees, etc.). The five files, one for each site, containing these data, have two lead cards identifying the site and are ended with an end of file marker.

Table B-2 Receptor Grid Coordinates

Site	Receptor Number	Grid Coordinates, feet x	y	z
Renton	1	520	110	0
	2	550	350	0
	3	2030	140	0
	4	1170	680	0
	5	1170	820	0
	6	1170	1040	0
	7	1450	920	0
	8	2110	710	0
	9	660	1230	0
	MR1	2330	570	0
	MR2	1170	485	0
Kirkland	1	615	8200	0
	2	380	8200	0
	3	760	9595	0
	4	255	9575	0
	5	690	9645	0
	6	380	9560	0
	7	620	10200	0
	8	350	10270	0
	MR1	500	8200	0
	MR2	500	8820	0
	MR3	500	10200	0
Vancouver	1	1070	1300	0
	2	1000	1100	0
	3	1140	1375	0
	4	1060	1030	0
	5	1170	1480	0
	6	1120	1520	0
	7	1050	1770	0
	8	1035	1545	0
Spokane	1	2350	1650	0
	2	2095	1440	0
	3	2070	1480	0
	4	2200	1395	0
	5	2235	1360	0
	6	2600	1575	0
Seattle	1	970	1820	0
	2	935	2090	0
	3	800	2650	0
	4	990	2670	0
	5	950	200	0
	6	560	2610	10
	7	460	2610	10
	8	640	1805	10
	9	750	1695	0
	10	710	2070	0
	11	790	290	0

Table B-3

Card	Columns	Format	Variable
1	1-8	A8	Date sample was obtained MO/DA/YR
1	9-10	I2	Day of the week, Monday = 1
1	11-14	I4	Time of day sample was taken, midnight = 0000
1	15-18	I4.1	Wind velocity, mph
1	19-22	F4.0	Wind direction, degrees from north
1	23-26	F4.0	Ambient temperature[b], ^{o}F
1	28	I2	Stability Class, A to F = 1 to 6
1	29-80	13F4.0	Measured receptor Carbon Monoxide concentration, ppm by volume
2	1-70	14F5.0	Vehicles per hour for each lane of traffic, beginning with the north or west lane of the first source, followed by the south or east lane, and then followed by each source in order.

[a]Pacific daylight time except for dates prior to 2/24/74, which were Pacific Standard time

[b]Some temperatures are missing

IV. Emission Rate

The procedures outlined in Chapter 2 to calculate the emission rates for the various line sources are based on Kircher and Armstrong's 1973 procedures for calculating the emission factors. Recent modifications to the original procedures are indicated in Supplement No. 5, October, 1974 to EPA-450/2-73-003. These modifications may change the estimates of emission rates to be used for the period of this project. For this reason, the basic data are included in this report rather than the calculated emission rates.

The emission factors (Chapter 2) and Weighted Annual Travel (Appendix A) have previously been presented. The speed distributions for the various segments were measured or estimated based on in-traffic speed checks. The speed distribution for the Renton site was determined on 2/13/74 and 2/14/74 for the north and south lanes of SR405 by using a radar unit and observers who counted the number of vehicles traveling within given speed range. Table B-4 shows the resulting distribution of the fraction of vehicles traveling at a given speed for each hour period from 0600 - 2000.

At the other sites, no measurements of the speed distributions were made with the radar unit. In-traffic speed checks were used to estimate the average traffic speed. The relative fractional distribution as a function of speed from Renton was then used as a guide to generate a distribution for the other sites. Thus, if plotted as the fraction travelling a given speed versus the speed, the distributions under analogous traffic conditions would have similar shapes but might be shifted to different speeds.

Table B-4 Renton Speed Distribution

North Lanes

Hour	mph	25	30	35	40	45	50	55	60
		Fraction travelling given speed							
0600		.00	.00	.00	.01	.06	.58	.29	.08
0700		.05	.11	.06	.15	.23	.30	.07	.00
0800		.00	.00	.00	.01	.07	.04	.34	.18
0900		.00	.00	.00	.01	.07	.04	.34	.18
1000		.00	.00	.00	.03	.10	.40	.34	.14
1100		.00	.00	.00	.01	.12	.41	.32	.15
1200		.00	.00	.00	.04	.07	.42	.28	.15
1300		.00	.00	.00	.03	.13	.47	.24	.12
1400		.00	.00	.00	.03	.12	.49	.26	.08
1500		.00	.00	.01	.14	.26	.41	.15	.03
1600		.02	.01	.01	.20	.32	.31	.08	.01
1700		.00	.00	.04	.10	.22	.47	.14	.06
1800		.00	.00	.00	.02	.24	.45	.18	.06
1900		.00	.00	.00	.02	.10	.40	.33	.15

South Lanes

Hour	mph	25	30	35	40	45	50	55	60
		Fraction travelling given speed							
0600		.00	.00	.00	.06	.20	.52	.18	.03
0700		.00	.01	.01	.10	.23	.54	.10	.01
0800		.00	.00	.00	.07	.18	.36	.17	.04
0900		.00	.00	.00	.01	.07	.47	.31	.15
1000		.00	.00	.00	.03	.08	.44	.34	.11
1100		.00	.00	.00	.04	.09	.45	.30	.11
1200		.00	.00	.00	.04	.09	.45	.30	.11
1300		.00	.00	.00	.04	.09	.45	.30	.11
1400		.00	.00	.00	.04	.09	.45	.30	.11
1500		.00	.00	.00	.04	.11	.47	.27	.11
1600		.03	.02	.04	.20	.31	.32	.06	.02
1700		.00	.00	.00	.08	.19	.46	.19	.08
1800		.00	.00	.00	.04	.09	.45	.30	.11
1900		.00	.00	.00	.04	.09	.45	.30	.11

Table B-5 lists the speed distributions so generated. There distributions are numbered and keyed to the list of sources and peak hours in Table B-6. The peak traffic periods are 0700,0800, 1600, and 1700 hours. All other hours are off-peak. The lanes of traffic are listed in the same order as the traffic count data appears in the hourly data, i.e., north or west lanes first, then south or east lanes. The Seattle sources for which a single speed was assumed to be applicable are noted in Table B-7.

Table B-5. Average Speed Distributions for Sites Other than Renton

Distribution Number	Fraction Travelling Given Speed mph 30	35	40	45	50	55	60
1	0	0	0.04	0.06	0.30	0.50	0.15
2	0	0.02	0.15	0.25	0.40	0.15	0.03
3	0.05	0.25	0.40	0.15	0	0	0

Table B-6. Speed Distributions at Various Sites

Hours	Applicable Speed Distribution: Kirkland West[a]	Kirkland East[a]	Vancouver West	Vancouver East	Spokane[b] North[a]	Spokane[b] South[a]	Seattle Freeway[c] North	Seattle Freeway[c] South
0700, 0800	2	1	2	1	2	1	2	1
1600, 1700	1	2	1	2	1	2	1	3
all other	1	1	1	1	1	1	1	1

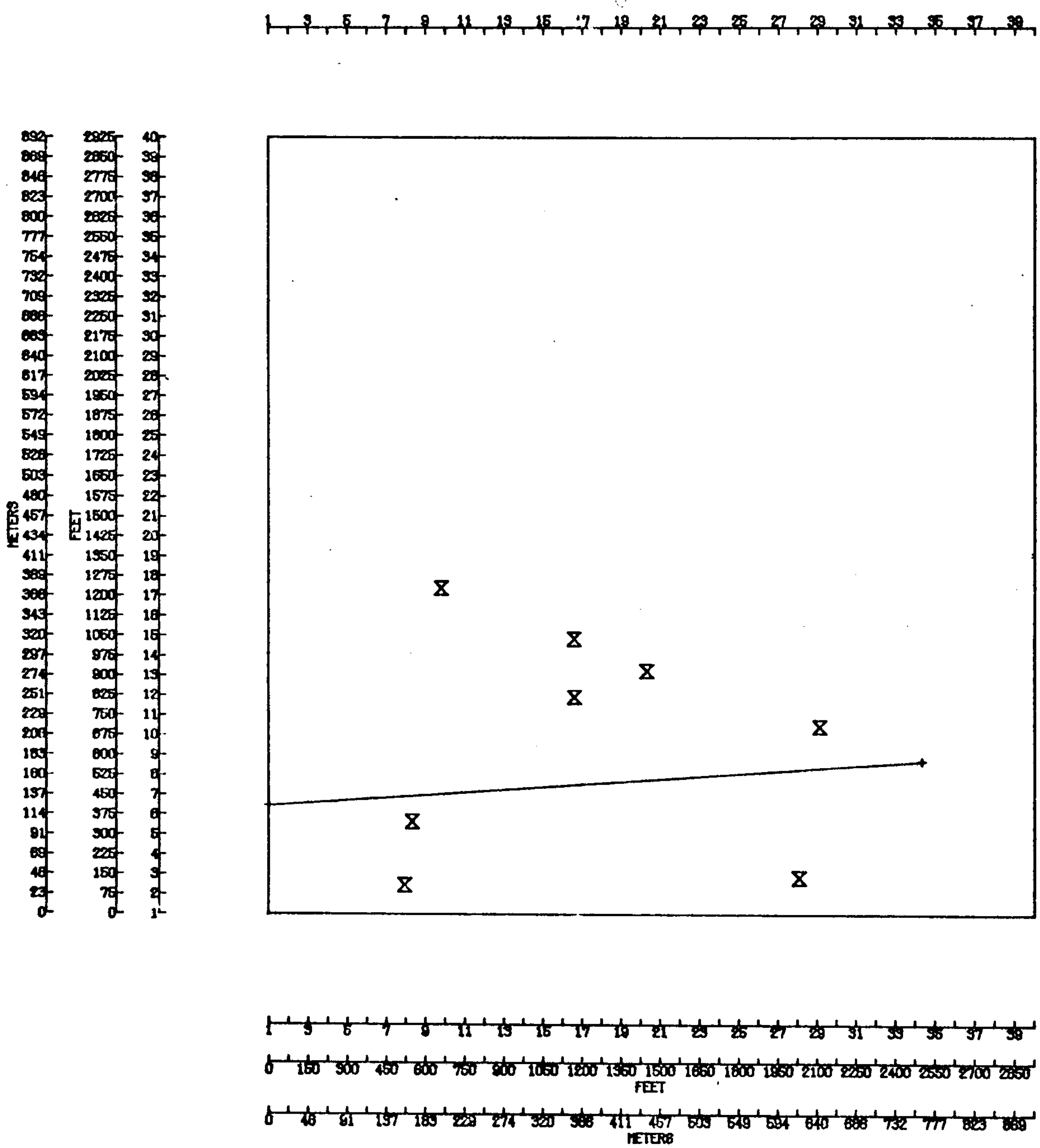
[a] Lanes [b] Sources 1 and 2 from Table C-1

[c] Sources 1,2,3 from Table C-1

Table B-7. Speeds for Seattle Sources Other Than I-5

Source		Speed, mph
4	NE 145th	25
5	SB off ramp	25
6	SB on ramp	30
7	NB off ramp	30
8	5th Ave. N.E., South Segment	20
9	5th Ave. N.E., North Segment	20
10	NB on ramp	20

Figure B-1. Renton Site Map



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4545 FIFTEENTH AVENUE NE
SEATTLE, WASHINGTON 98105

Figure B-2. Kirkland Site Map

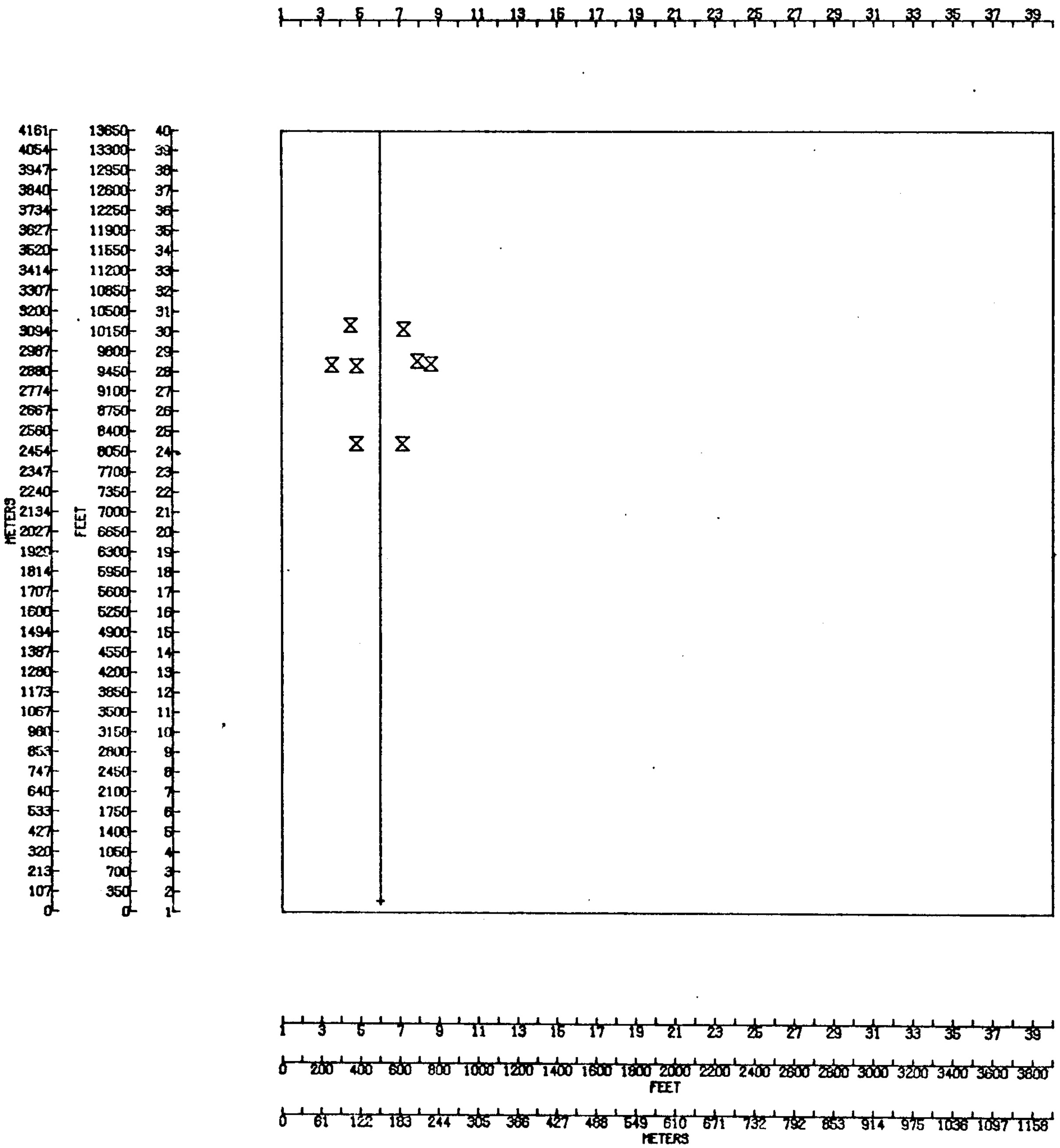

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Figure B-3. Vancouver Site Map

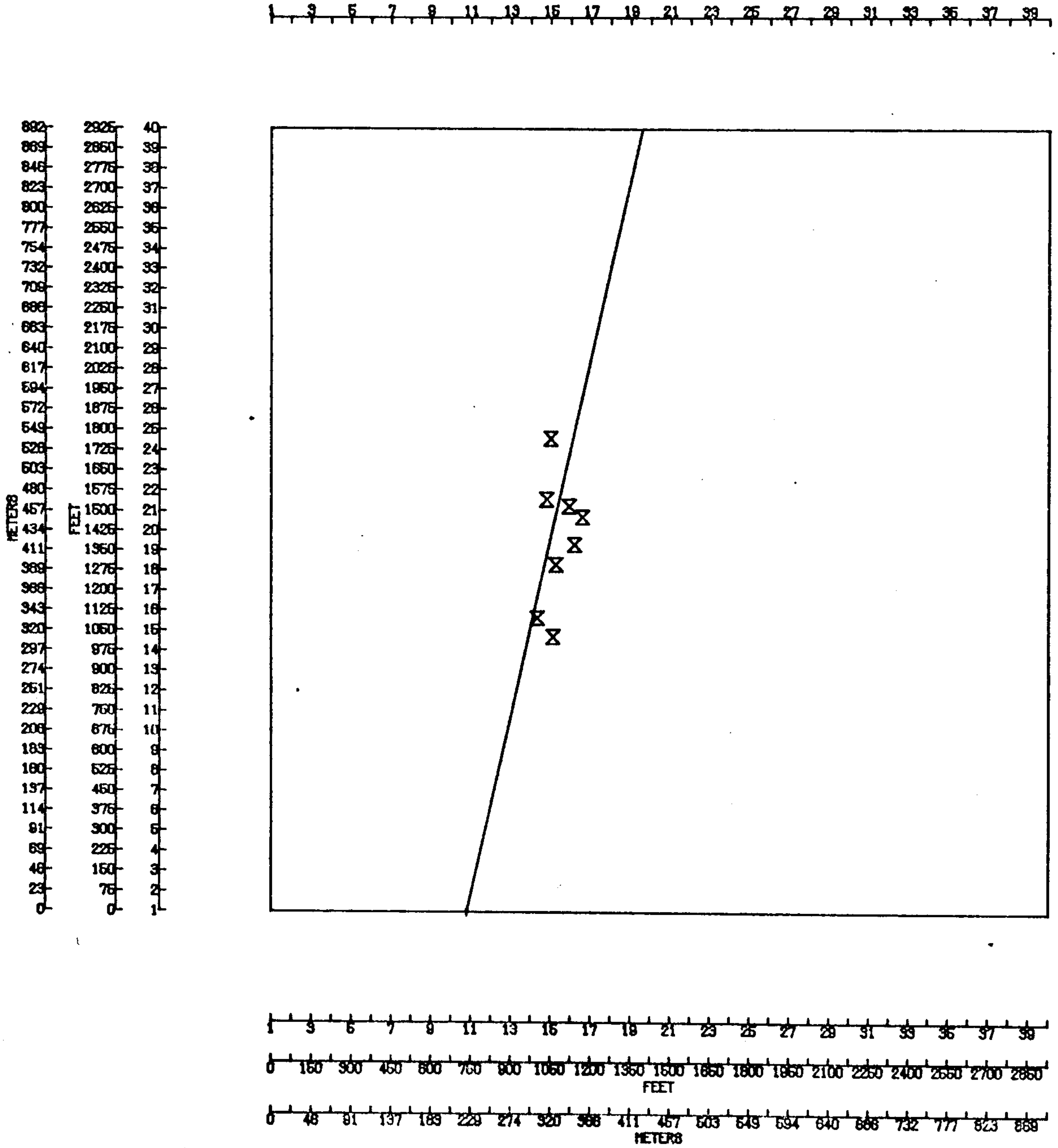

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Figure B-4. Spokane Site Map

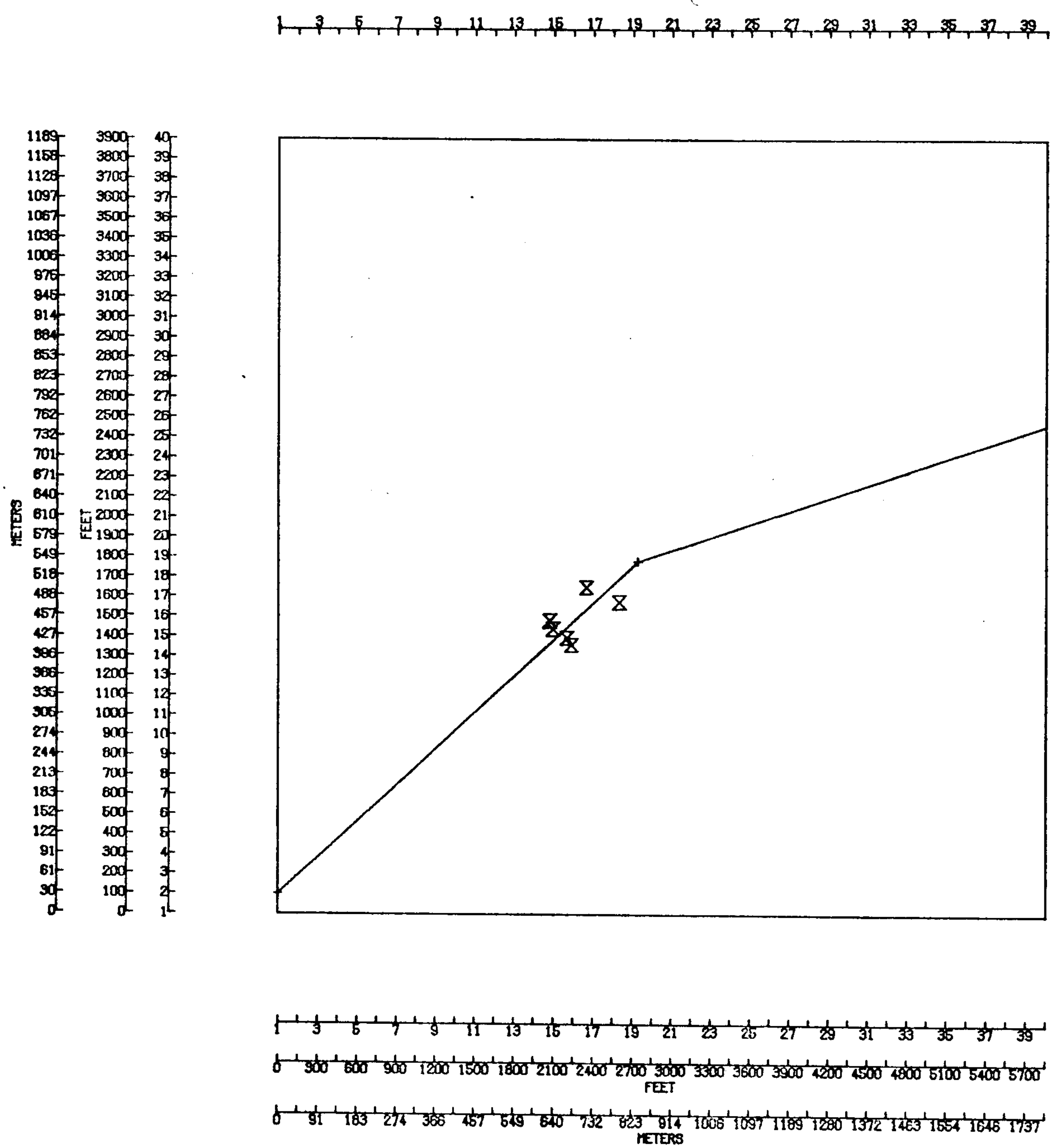

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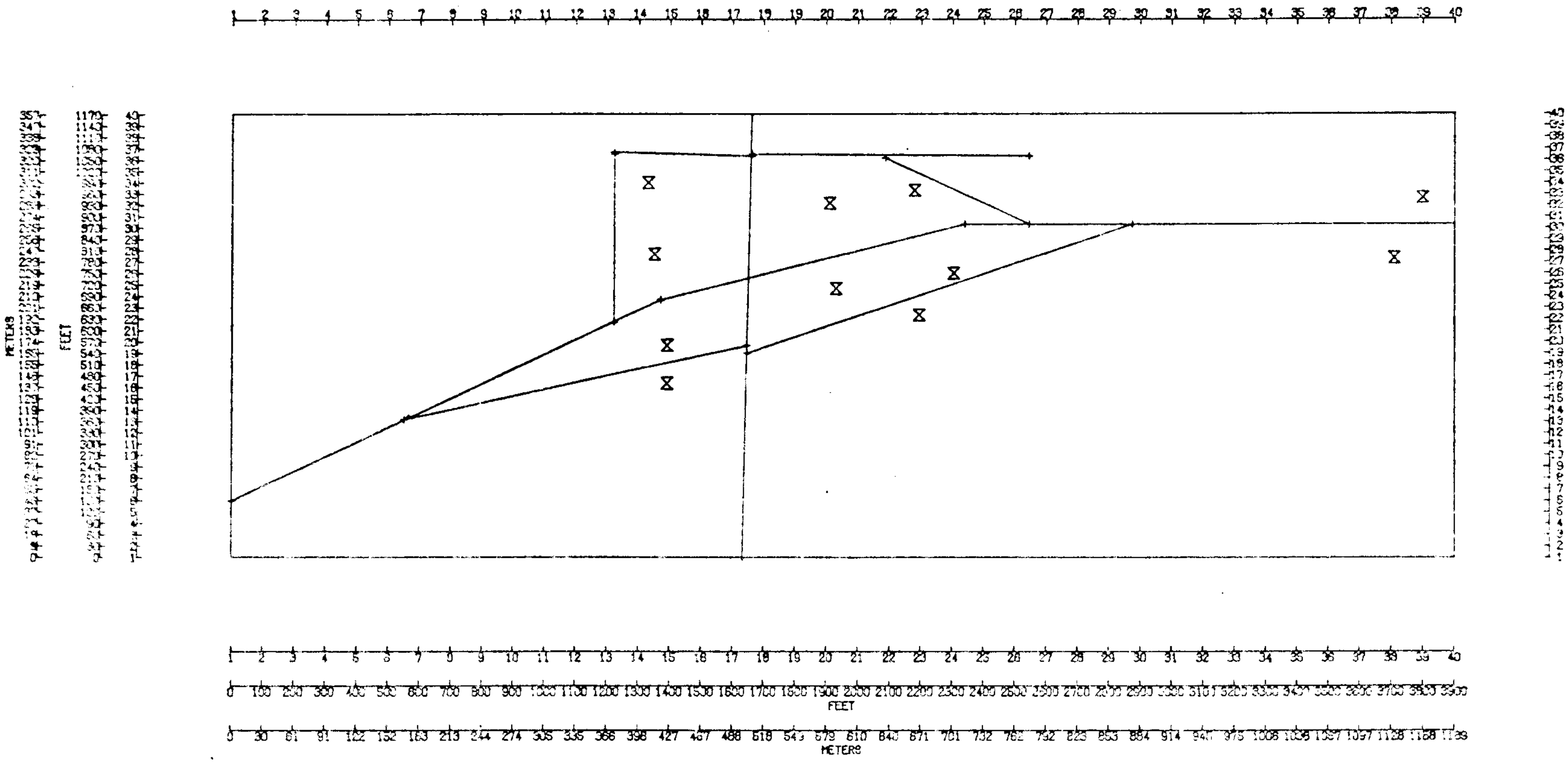
Figure B-5. Seattle Site Map



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