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COMPARISON OF SIX HIGHWAY AIR POLLUTION DISPERSION MODELS USING SYNTHETIC DATA

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16. Abstract

This is the second of two studies conducted by the Transportation Systems Center (TSC) to test the performance of highway air pollution dispersion models, using synthetic data (i.e., either measured or artificially constructed input data for models, consisting of traffic and meteorological parameters). In the first study (DOT-TSC-OST-77-33, dated June 1977), thirteen models were tested with a portion of the Airedale air quality data base. In the present study, six models (including five of the original thirteen) were tested with a new synthetic data base. The air pollution predictions of the six models were compared in pairs, and various measures of the difference between the predictions of each pair were calculated. A group of three models generating very similar predictions was discovered; these are called Consensus Models. In the first study, using the same analytical approach, these three models were also found to be Consensus Models, along with others which could not be tested in the present study. Synthetic data testing can only reveal the degree of agreement among model predictions. The capability of these models to predict real-world air pollution cannot be determined until an air-quality data base suitable for model validation become available.

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PREFACE

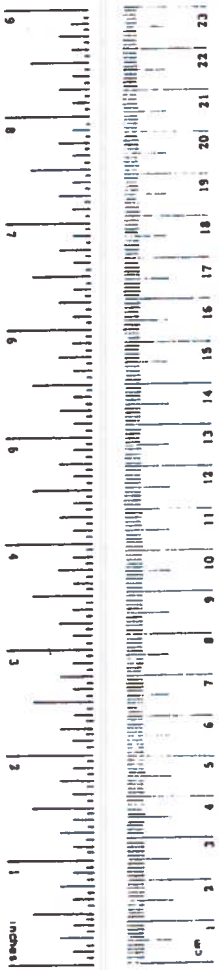
In response to legislation requiring that each federal agency carefully and systematically consider the environmental effects of its actions, the Office of the Assistant Secretary for Systems Development and Technology initiated the Technology for Environmental Analysis (TEA) program at the Transportation Systems Center in FY'72. This program develops unified technological capabilities in air pollution assessment as part of a family of techniques and capabilities necessary to support the development in the Office of the Secretary, and in the operation administrations, of planning procedures related to the environmental impact of transportation systems and facilities.

An important goal of this program for the past six years has been to develop and maintain expertise on the availability, applicability and performance of techniques for analyzing the environmental impact of transportation-generated air pollution. The work reported here is a sequel to the study and evaluation of thirteen highway air pollution dispersion models previously published by TSC in Highway Air Pollution Dispersion Modeling. A Preliminary Evaluation of Thirteen Models, by E.M. Darling Jr., D.S. Prerau and P.H. Mengert, DOT-TSC-OST-77-33. June 1977.

METRIC CONVERSION FACTORS

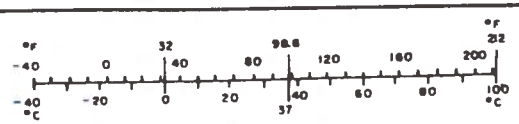
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

1.1 BACKGROUND

In 1972 the Office of the Secretary of Transportation initiated the Technology for Environmental Analysis program at the Transportation Systems Center (TSC). An important goal of this program was to develop and maintain expertise on the availability, applicability and performance of techniques for analyzing the environmental impact of transportation-generated air pollution. To help achieve this goal, TSC has acquired both air pollution dispersion models and air quality data, and initiated a program to test and evaluate these models.

Since the Center has yet to acquire air quality data suitable for model testing and validation, it has been necessary to use synthetic data in the model tests conducted to date. Synthetic data are either measured or artificially constructed (but physically realizable) sets of input data for air pollution dispersion models, containing highway geometry, traffic, and meteorological parameters. Testing is conducted by inputting the synthetic data to a group of dispersion models, and then comparing their predictions at prescribed receptor locations. Note that measured pollution values either do not exist (in the case of artificially constructed input data) or are not accurate enough to be used (which is the case with the data currently available at TSC). Therefore, the tests conducted to date only consider the agreement among model predictions; these tests cannot reveal how well the models predict actual air pollution.

1.2 THE THIRTEEN MODEL STUDY

This is the second TSC report on dispersion model testing with synthetic data. The first report* was concerned with the testing of thirteen highway air pollution dispersion models, using a portion of the Airedale data base (acquired by Environmental Research and Technology Inc., in Washington DC.) as input. Of the thirteen models tested in that study, six were of the Gaussian type, six of the conservation of mass type, and one was exponential. For convenience, some of the models were tested entirely in-house at TSC, and others were run at the developer's facilities (using data provided by TSC) with the model output being returned to the center for analysis. Table 1-1 lists the participants, model types, and testing modes for this initial study.

The predictions of the thirteen models were compared one versus another in pairs, using the following three distance measures: average absolute difference, 80th percentile difference, and correlation coefficient. Models with predictions that were found to be close together (in terms of the three distance measures) were said to form clusters. Only one such cluster was discovered, comprising the following five models: AeroVironment (AER), California Division of Highways CALINE I (CAL), Environmental Research and Technology (ERT), TSC/EPA (TSC) and Walden Research Corporation (WAL). These five models were designated as Consensus Models to indicate the degree of mutual agreement among them.

1.3 THE PRESENT STUDY

This second study used the same distance measures described above. It was conducted in an attempt to confirm the results of the initial study. However, due to funding limitations only three of the original five consensus models (CAL, TSC and WAL, all of the Gaussian type) could be included in this second study.

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* Darling, E. M. Jr.; Prerau, D.S.; Downey, P.J.; Mengert, P.H. Highway Air Pollution Modeling: Preliminary Evaluation of Thirteen Models, Report No. DOT-TSC-OST-77-33, June 1977.

TABLE 1-1. THIRTEEN MODEL STUDY PARTICIPANTS

COMPANY/AGENCY	CODE	Model Type			Testing Mode	
		Gaussian	Conservation	Other	Contract	In-House
AeroVironment	AER		X		X	
California Division of Highways	CAL	X				X
Center for the Environment & Man	CEM		X		X	
Environmental Research & Technology	ERT		X		X	
Environmental Systems Laboratory	ESL	X				X
General Electric	GE			X		X
Intera	INT		X		X	
Kaman Sciences Corporation	KAM	X			X	
Lockheed Missiles and Space Company, Inc.	LOC		X		X	
Systems Control, Inc.	SCI	X			X	
System, Science and Software	SSS		X		X	
TSC/EPA	TSC	X				X
Walden Research, Inc.	WAL	X				X

A total of six dispersion models were tested; all were run at TSC. (These models had been acquired by the Center over the past five years.) Five of the models were of the Gaussian type; one (the GE model) was exponential. The five Gaussian models were those developed by California Division of Highways (CAL); Environmental Systems Laboratory (ESL); The Research Corporation of New England (TRC); Transportation Systems Center and the Environmental Protection Agency (TSC/EPA): and Walden Research Associates (WAL). Appendix C contains a description of each of these models.

Section 2 discusses the synthetic model input data constructed for these tests; Section 3 describes the cluster analysis methodology; Section 4 presents the results for both the entire synthetic data sample and for selected stratified subsamples; and Section 5 contains the summary and conclusions. Three technical appendices follow.

2. THE SYNTHETIC DATA

The synthetic model input data constructed for this study (see Table 2-1) were designed to cover as wide a range of parameter values as possible while still being of practical size. While no data set of reasonable size can encompass all possible values for a given parameter, the range of values selected here are thought to be sufficient to represent a sample of physically realizable variables. A total of fifty-four different combinations of parameters were used. Since each model predicted pollutant concentrations at twelve receptors for each of these cases, the model comparison testing was based on 648 data points.

Scatter diagrams of model predictions for all 15 pairs of the 6 models are shown in Appendix A.

2.1 SITE PARAMETERS

The data set consists of three at-grade roadway sites. Site 1 is a two-lane roadway with no center strip, site 2 is a four-lane roadway with a ten-foot center strip, and site 3 is an eight-lane roadway with a fifty-foot center strip. The lane width is twelve feet in all cases. At the first site both lanes have traffic in the same direction; at the other two sites the traffic is in two directions with an equal number of lanes in each direction.

2.2 EMISSION PARAMETERS

Two years, 1980 and 1990, were considered. The emission factors for these years were taken from the California Division of Highway Air Quality Manual: Motor Vehicle Emission Factors For Estimates of Highway Impact On Air Quality. Both peak and off-peak cases were considered. For the peak hour cases, the traffic speed was 30 mph; the vehicles per hour per lane was 1450 in the direction of maximum traffic and 950 in

the other direction (i.e., a 60/40 split). For the off-peak cases, the traffic speed was 45 mph and there were 950 vehicles per hour per lane in all lanes (i.e., a 50/50 split).

2.3 METEOROLOGICAL PARAMETERS

Three wind angles relative to the road were used - 15, 45 and 90 degrees. The wind speed was 1 meter per second and the stability class was 6 - very stable. The last two are worst case values.

2.4 RECEPTOR PLACEMENT

Twelve receptor locations were selected: three heights - 0, 10 and 20 feet - at each of four distances from the roadway - 50, 75, 100 and 300 feet. These receptor locations were chosen in order to permit changes to be detected in the relative predictions of models as a function of, (1) distance from the roadway and (2) height. The three heights span the lowest two stories of an average building where air pollution is likely to be highest; the maximum distance of 300 ft. is the typical distance where the air pollution contribution from a highway approaches zero.

TABLE 2-1. SYNTHETIC MODEL INPUT DATA

SITE	CASE NO.	NO. OF LANES	CENTER STRIP WIDTH (FT.)	PEAK OFF-PEAK*	WIND ANGLE (DEG.)	VEHICLE SPEED (MPH)	YEAR
1	1	2	0	1	15	30	1980
	2	2	0	1	15	30	1990
	3	2	0	1	45	30	1980
	4	2	0	1	45	30	1990
	5	2	0	1	90	30	1980
	6	2	0	1	90	30	1990
	7	2	0	2	15	30	1980
	8	2	0	2	15	30	1990
	9	2	0	2	45	30	1980
	10	2	0	2	45	30	1990
	11	2	0	2	90	30	1980
	12	2	0	2	90	30	1990
	13	2	0	3	15	45	1980
	14	2	0	3	15	45	1990
	15	2	0	3	45	45	1980
	16	2	0	3	45	45	1990
	17	2	0	3	90	45	1980
	18	2	0	3	90	45	1990
2	19	4	10	1	15	30	1980
	20	4	10	1	15	30	1990
	21	4	10	1	45	30	1980
	22	4	10	1	45	30	1990
	23	4	10	1	90	30	1980
	24	4	10	1	90	30	1990
	25	4	10	2	15	30	1980
	26	4	10	2	15	30	1990
	27	4	10	2	45	30	1980
	28	4	10	2	45	30	1990
	29	4	10	2	90	30	1980
	30	4	10	2	90	30	1990
	31	4	10	3	15	45	1980
	32	4	10	3	15	45	1990
	33	4	10	3	45	45	1980
	34	4	10	3	45	45	1990
	35	4	10	3	90	45	1980
	36	4	10	3	90	45	1990
3	37	8	50	1	15	30	1980
	38	8	50	1	15	30	1990
	39	8	50	1	45	30	1980
	40	8	50	1	45	30	1990
	41	8	50	1	90	30	1980
	42	8	50	1	90	30	1990
	43	8	50	2	15	30	1980
	44	8	50	2	15	30	1990
	45	8	50	2	45	30	1980
	46	8	50	2	45	30	1990
	47	8	50	2	90	30	1980
	48	8	50	2	90	30	1990
	49	8	50	3	15	45	1980
	50	8	50	3	15	45	1990
	51	8	50	3	45	45	1980
	52	8	50	3	45	45	1990
	53	8	50	3	90	45	1980
	54	8	50	3	90	45	1990

*1, morning peak, 2, evening peak, both with: traffic speed, 30 mph; vehicles per hour per lane of 1450 in the direction of maximum traffic and 950 in the other direction (i.e., a 60/40 split). 3, off-peak with: traffic speed, 45 mph; vehicles per hour per lane, 950 for all lanes (i.e., a 50/50 split).

3. CLUSTERING ANALYSIS

3.1 APPROACH

By comparing the predictions of models in pairs for the same set of input data points, measures of the "distance" between their predictions can be computed. A "model cluster" can then be defined as a group of models whose predictions are less than some distance D apart, where $D = (d_1, d_2, \text{---} d_n)$ is the cluster diameter defined by the threshold distances, d_i, $1 < i < n$, for the n distance measures. If a single predominant cluster is found, then that will be called the "Consensus Cluster", and all models in the cluster will be called Consensus Models in order to emphasize the degree of mutual agreement among them.

3.2 ADVANTAGES AND DISADVANTAGES

The concept of Consensus Clusters has an immediate application of air quality analysis and associated decision-making. Federal DOT officials must often rely on predictions generated by models when making decisions on the environmental impact of transportation systems. If a model in the Consensus Cluster has been used for a particular analysis then the approving Federal official can at least be assured that the analysis represents a consensus of several existing models.

Similarly, at the state level, highway engineers are often confronted with the task of selecting suitable models for use in determining the air quality impact of proposed highways. Several such models are in the public domain, while others are the property of companies who perform air quality analyses for a fee. Since models will differ in the expense of running them (i.e., the computation costs) and in the level of state manpower resources required to perform the analysis, the cost of using the various models may vary widely. Therefore, the identification of models that produce similar

predictions could result in considerable cost savings in selecting a model for a particular application.

Furthermore, if challenged in a court case the State DOT performing the environmental impact study would be in a stronger position to defend the model if it had been selected from a group which had previously been demonstrated to produce similar predictions.

The concept of Consensus Models has yet another advantage, namely, that synthetic data sets can easily be generated for any desired combination of highway geometry, traffic parameters, meteorological conditions and receptor locations. If it were discovered that similar clusters of model predictions occurred with many different synthetic data sets, then one would have increasing confidence in designating the models in these clusters as Consensus Models.

A disadvantage of this approach is that in the absence of air quality data suitable for testing the accuracy of models, it is impossible to determine whether the predictions of models in a Consensus Cluster are any more accurate than the predictions of models not in the cluster. Nonetheless, since models within a Consensus Cluster produce results which agree closely with one another, then at least these models are not likely to harbor theoretical or programming errors in their construction.

3.3 MODEL DISTANCE MEASURES

Three measures of the distance between the predictions of any two models were used:

1. Average Absolute Difference (AAD).
2. 80th Percentile Difference (80%).
3. Correlation Coefficient (CC).

These are the same measures that were used in the previous thirteen model study (1).

The Average Absolute Difference between two models, M1 and M2, is calculated as follows:

$$AAD = (1/N) \sum_{p=1}^{N} [M1(p) - M2(p)],$$

where N is the number of input data points, p.

In order to obtain a measure which is unaffected by a few large differences between the predictions of two models, the 80th Percentile Absolute Difference was adopted as a distance measure. This is determined by ordering all of the absolute differences, [M1(p) - M2(p)], and finding the one that is greater than or equal to 80% of these differences.

The correlation coefficient measures the tendency of the predictions of two models to vary linearly. Thus a high correlation coefficient indicates a strong linear relationship between two models, even though there may be considerable absolute difference (i.e., a bias) between their predictions. The correlation coefficient for the pollution predictions of two models, M1 and M2, is defined as follows:

$$CC = \frac{1}{N} \sum_{p=1}^{N} [(M1(p) - M1AV)\ (M2(p) - M2AV)]/[(VAR1)-(VAR2)]^{1/2},$$

where:

$$M1AV = (1/N) \sum_{p=1}^{N} M1(p),$$

$$M2AV = (1/N) \sum_{p=1}^{N} M2(p),$$

$$VAR1 = (1/N) \sum_{p=1}^{N} (M1(p) - M1AV)^2, \text{ and}$$

$$VAR2 = (1/N) \sum_{p=1}^{N} (M2(p) - M2AV)^2.$$

4. RESULTS

4.1 OVERALL RESULTS

In these tests, each model generated 648 predictions (see Section 2), using the data in Table 2-1 as input. A prediction distance matrix was constructed for all model pairs, using each of the three distance measures defined in Section 3. These matrices are shown in Tables 4-1, 4-2, and 4-3.

The mean prediction of the six models is $\bar{p}$ = 2.54 ppm. Four cluster diameters for the mean absolute difference and the 80th percentile difference were defined in terms of $\bar{p}$, namely $0.2\bar{p}$, $0.4\bar{p}$, $0.6\bar{p}$, and $0.8\bar{p}$, or 0.5, 1.0, 1.5, and 2.0 ppm, respectively. In the case of the correlation coefficient r , two cluster diameters were used: r = .75 and r = .65.

The clusters formed by the three distance measures are shown in Table 4-4, for the Mean Absolute Difference, Table 4-5, for the 80th Percentile Difference, and Table 4-6, for the Correlation Coefficient. For the three distance measures, the number of models forming clusters are shown in Table 4-7, for Mean Absolute Difference, Table 4-8, for the 80th Percentile Difference, and Table 4-9, for the Correlation Coefficient. Table 4-10 shows the total number of difference models clustering with each of the six models for each of the three distance measures (summed from the previous three tables), as well as the grand total number of models clustering with each model.

It is clear from Table 4-10 that three models clustered consistently in these tests, namely CAL (CALINE I), TSC, and WAL. These three are called Consensus Models to emphasize the close agreement among their predictions. The remaining three models showed little tendency to cluster, especially G.E. which was not linked with any other model. Table 4-11 shows the mean absolute prediction difference between each of the non-consensus Models. Also shown for each model is the percentage

TABLE 4-1. MATRIX OF THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS (OVERALL RESULTS).

MEAN ABSOLUTE DIFFERENCE (ppm)

	Models					
	CAL	ESL	GE	TRC	TSC	WAL
CAL	0.0	3.09	4.15	1.69	0.90	0.43
ESL	3.09	0.0	3.79	1.74	2.68	3.12
GE	4.15	3.79	0.0	3.82	4.22	4.26
TRC	1.69	1.74	3.82	0.0	1.37	1.70
TSC	0.90	2.68	4.22	1.37	0.0	0.80
WAL	0.43	3.12	4.26	1.70	0.80	0.0

TABLE 4-2. MATRIX OF THE 80TH PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS (OVERALL RESULTS).

80TH PERCENTILE DIFFERENCE (ppm)

	Models					
	CAL	ESL	GE	TRC	TSC	WAL
CAL	0.0	4.80	7.40	2.60	1.30	0.60
ESL	4.80	0.0	6.10	2.60	4.00	4.80
GE	7.40	6.10	0.0	6.50	7.70	7.80
TRC	2.60	2.60	6.50	0.0	2.40	2.80
TSC	1.30	4.00	7.70	2.40	0.0	0.90
WAL	0.60	4.80	7.80	2.80	0.90	0.0

TABLE 4-3. MATRIX OF THE CORRELATION COEFFICIENT BETWEEN MODEL PREDICTIONS (OVERALL RESULTS).

CORRELATION COEFFICIENT

	Models					
	CAL	ESL	GE	TRC	TSC	WAL
CAL	0.0	0.75	0.47	0.69	0.77	0.72
ESL	0.75	0.0	0.39	0.90	0.66	0.51
GE	0.47	0.39	0.0	0.30	0.29	0.46
TRC	0.69	0.90	0.30	0.0	0.60	0.46
TSC	0.77	0.66	0.29	0.60	0.0	0.65
WAL	0.72	0.51	0.46	0.46	0.65	0.0

TABLE 4-4. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS. (OVERALL RESULTS)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
< 0.50	CAL - WAL
< 1.00	CAL - TSC - WAL
< 1.50	CAL - TSC - WAL TRC - TSC
< 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE 4-5. CLUSTERING BY THE 80TH PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS. (OVERALL RESULTS)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
< 0.50	
< 1.00	CAL - WAL TSC - WAL
< 1.50	CAL - TSC - WAL
< 2.00	CAL - TSC - WAL

TABLE 4-6. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS (OVERALL RESULTS).

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
< 0.75	CAL - ESL CAL - TSC ESL - TRC
< 0.65	CAL - ESL - TRC CAL - ESL - TRC CAL - TSC - WAL

TABLE 4-7 NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS. (OVERALL RESULTS)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
< 0.50	1					1
< 1.00	2				2	2
< 1.50	2			1	3	2
< 2.00	3	1		4	3	3
TOTAL	8	1	0	5	8	8

TABLE 4-8 NUMBER OF MODELS CLUSTERING BY THE 80TH PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS. (OVERALL RESULTS)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
< 0.50						
< 1.00	1				1	2
< 1.50	2				2	2
< 2.00	2				2	2
TOTAL	5				5	6

TABLE 4-9 NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS. (OVERALL RESULTS)

CORRELATION COEFFICIENT

Number of Different Models
Clustering with Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
< 0.75	2	2		1	1	
< 0.65	4	3		2	3	2
TOTAL	6	5		3	4	2

TABLE 4-10 NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES. (OVERALL RESULTS)

Total Number of Different Models
Clustering with Each Model

Distance Measures	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
Mean Absolute Difference	8	1	0	5	8	8
80th Percentile	5				5	6
Correlation Coefficient	6	5		3	4	2
TOTAL	19	6	0	8	17	16

TABLE 4-11 MEAN ABSOLUTE DIFFERENCE BETWEEN THE NON-CONSENSUS MODEL PREDICTIONS AND THE AVERAGE OF THE CONSENSUS MODEL PREDICTIONS

	MODELS		
	ESL	GE	TRC
Mean Absolute Difference (ppm)	2.94	4.15	1.51
Percent Exceeding	90.4	78.5	62.3

of its predictions which exceeded the mean prediction of the three Consensus Models. From this, it can be seen that all of the three non-consensus models tended to overpredict. Since a model that tends to overpredict is usually considered to be conservative in its estimates of air pollution, the three non-consensus models appear to be quite conservative on the basis of these tests.

4.2 STRATIFIED RESULTS

The cluster analysis results presented above are based on model predictions for all 648 cases. However, as previously indicated, a wide variety of input parameters were selected in the generation of this synthetic data set in order to allow parametric studies to ascertain the effects on cluster formation of various ways of stratifying the data. It was found that stratification of the data by receptor distance, center strip width or receptor height resulted in the same cluster formation as in the overall case (see Appendix B).

4.3 FURTHER COMPARISON OF THE THREE CONSENSUS MODELS

Finally, the three Consensus Models were compared in pairs for the three stratifications of the data described below. The performance measures used in these comparisons were the Correlation Coefficient and the Signed Error.*

It will be seen that the model predictions never differ by more than ±1.5 ppm in any of these comparisons. The only trend that emerges is a tendency for the TSC model to over-predict with respect to the other two, under certain conditions.

4.3.1 Comparisons by Center Strip Width

Model comparisons were made for center strip widths of 0, 10 and 50 feet.

In Figure 4-1 the variation of the Correlation Coefficient with center strip width is shown. There are no notable trends.

*The Signed Error for models 1 and 2 (e.g., CAL - WAL) is the mean of [the sum of the model 1 predictions minus the sum of model 2 predictions].

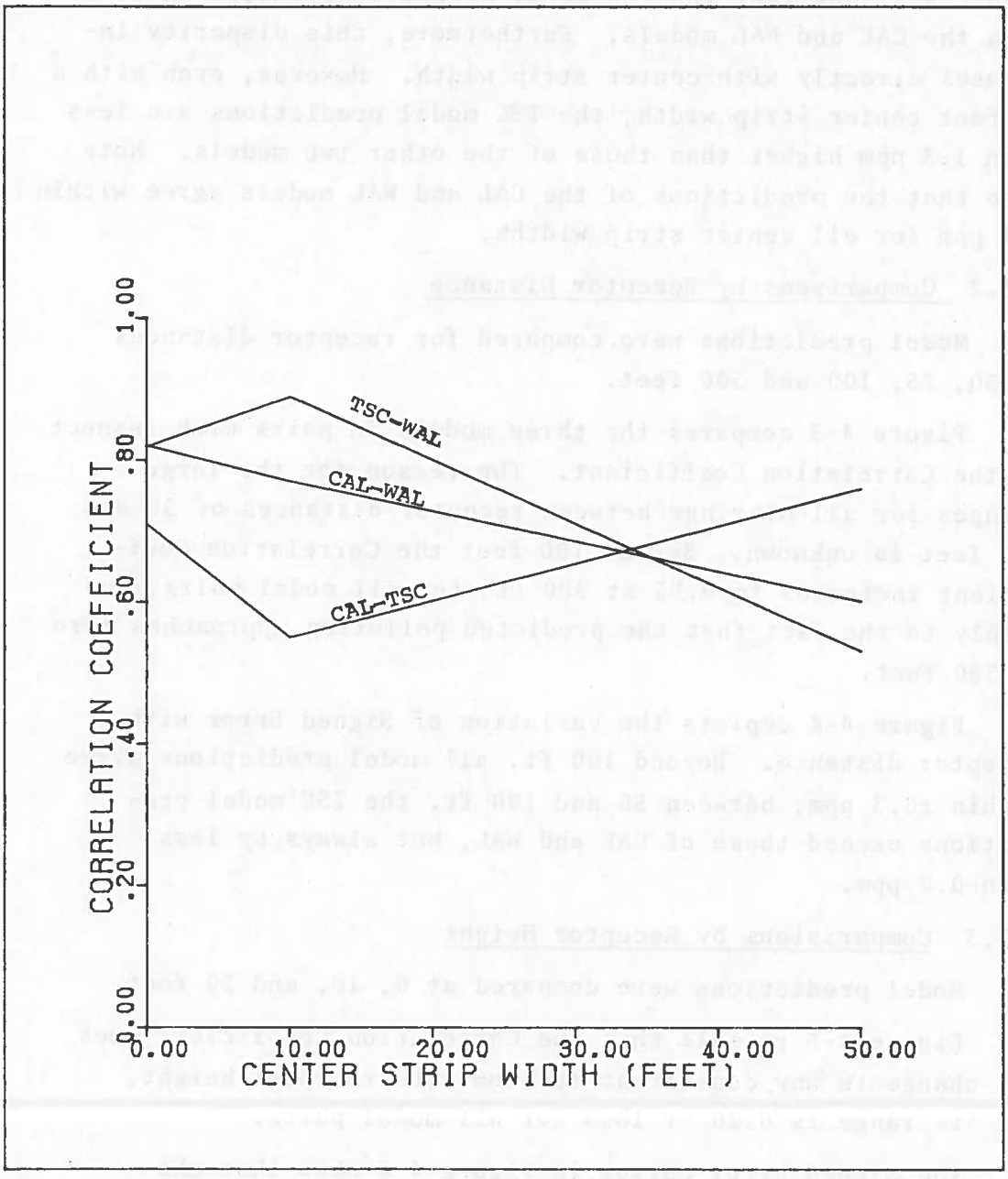

FIGURE 4-1. DATA STRATIFIED BY CENTER STRIP WIDTH, CORRELATION COEFFICIENT

The curves of Signed Error vs. center strip width in Figure 4-2 show that the TSC model predictions exceed those of both the CAL and WAL models. Furthermore, this disparity increases directly with center strip width. However, even with a 50 foot center strip width, the TSC model predictions are less than 1.3 ppm higher than those of the other two models. Note also that the predictions of the CAL and WAL models agree within 0.4 ppm for all center strip widths.

4.3.2 Comparisons by Receptor Distance

Model predictions were compared for receptor distances of 50, 75, 100 and 300 feet.

Figure 4-3 compares the three models in pairs with respect to the Correlation Coefficient. The reason for the large changes for all piarings between receptor distances of 50 and 100 feet is unknown. Beyond 100 feet the Correlation Coefficient increases to 0.95 at 300 ft. for all model pairs, due mainly to the fact that the predicted pollution approaches zero at 300 feet.

Figure 4-4 depicts the variation of Signed Error with receptor distance. Beyond 100 ft. all model predictions agree within ±0.3 ppm; between 50 and 100 ft. the TSC model predictions exceed those of CAL and WAL, but always by less than 0.7 ppm.

4.3.3 Comparisions by Receptor Height

Model predictions were compared at 0, 10, and 20 feet.

Figure 4-5 reveals that the Correlation Coefficient does not change in any consistent fashion with receptor height, but its range is 0.20 or less for all model pairs.

The Signed Error curves in Figure 4-6 show that the TSC model overpredicts markedly at ground level with respect to the other two models. At 10 feet all three models agree very closely and at 20 feet TSC underpredicts with respect to the others.

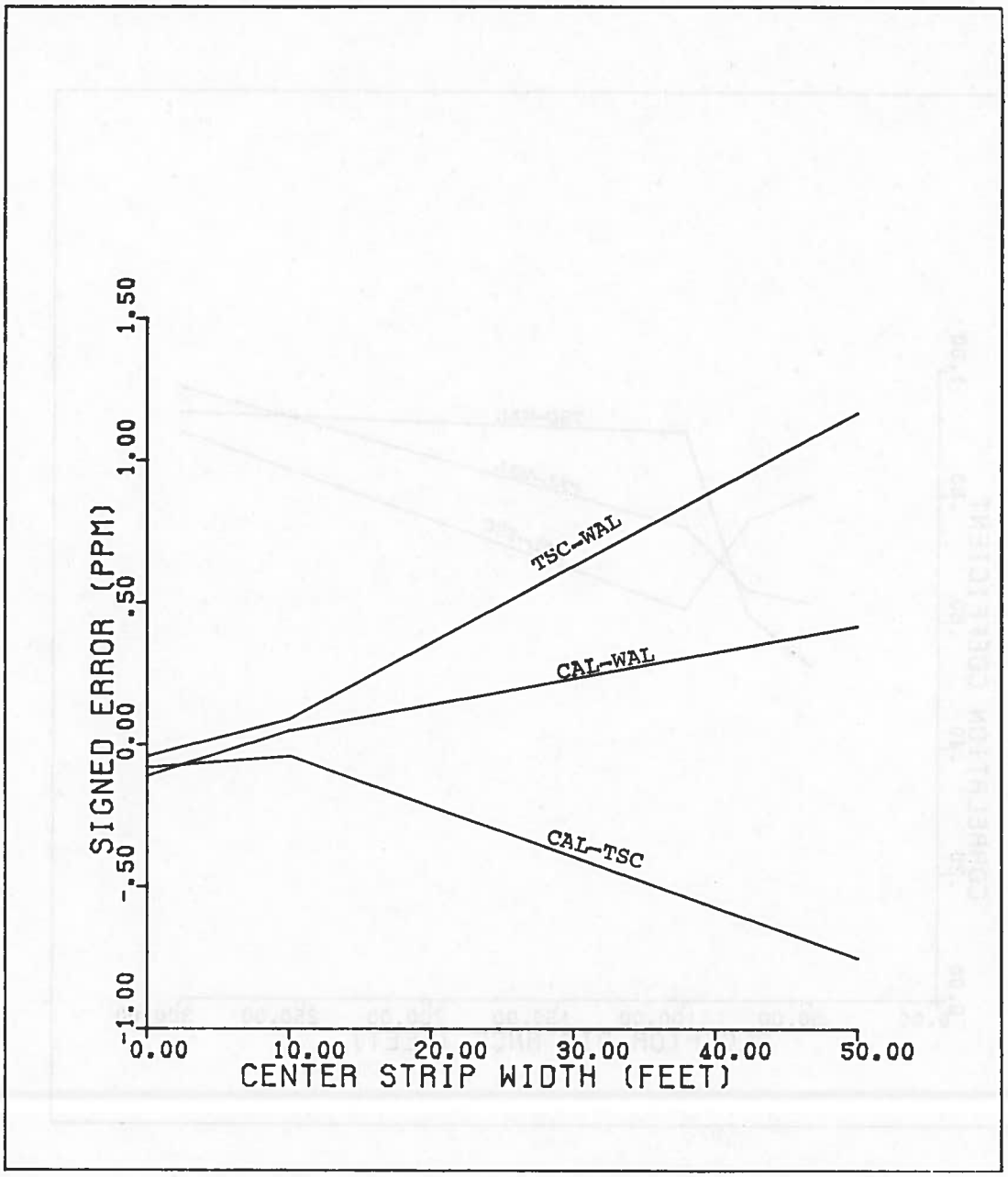

FIGURE 4-2. DATA STRATIFIED BY CENTER STRIP WIDTH, SIGNED ERROR

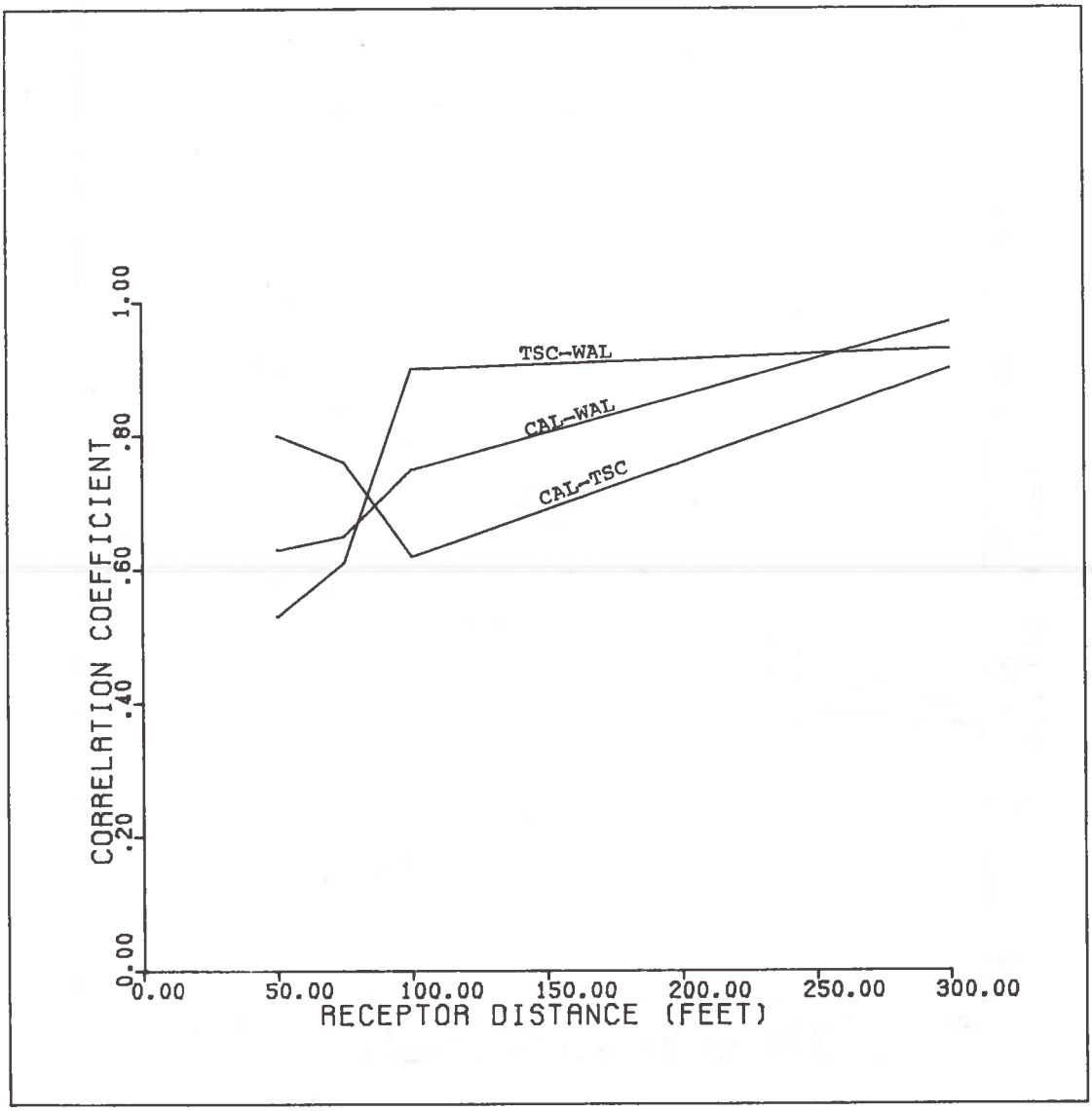

FIGURE 4-3. DATA STRATIFIED BY RECEPTOR DISTANCE, CORRELATION COEFFICIENT

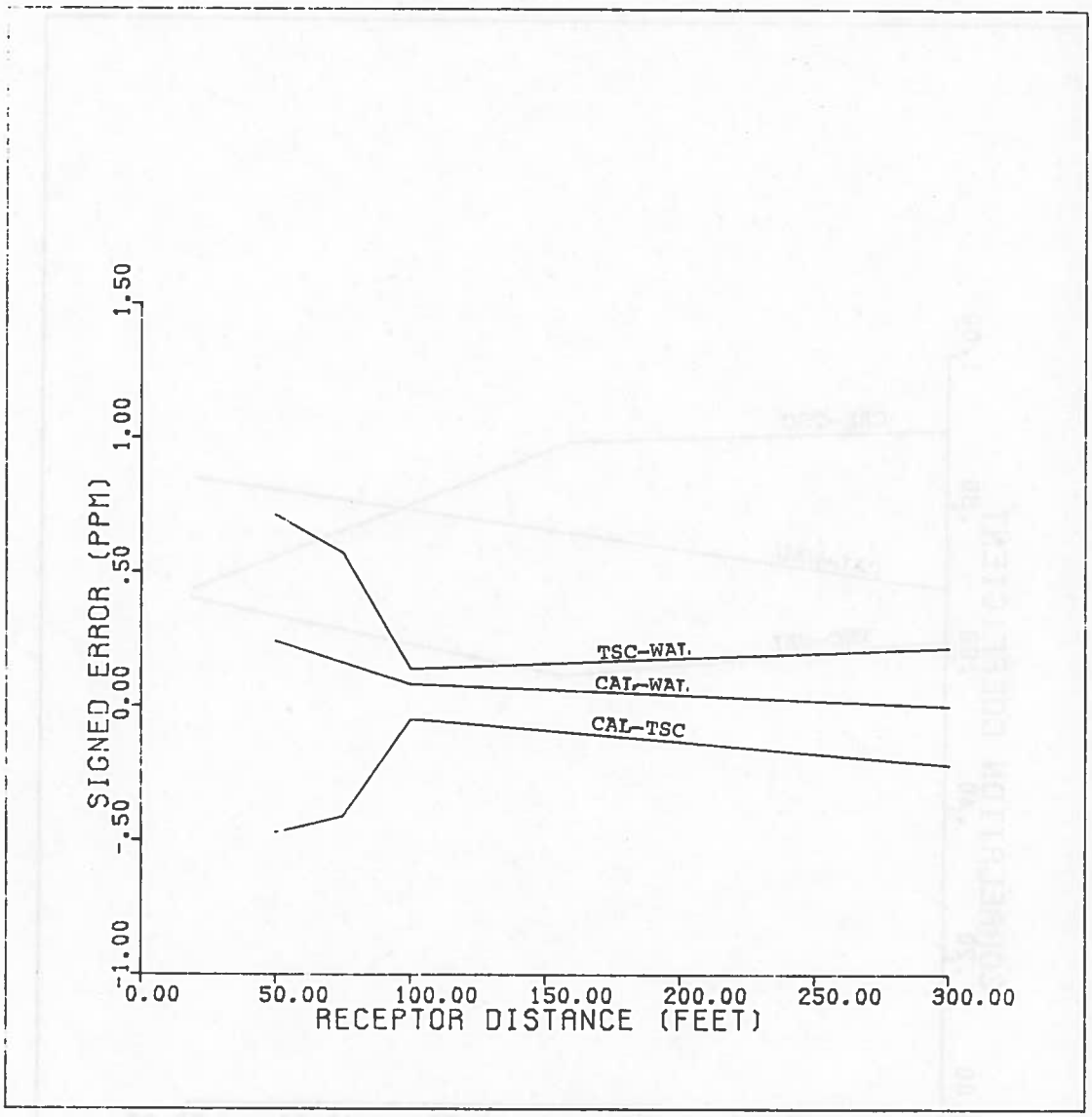

FIGURE 4-4. DATA STRATIFIED BY RECEPTOR DISTANCE, SIGNED ERROR

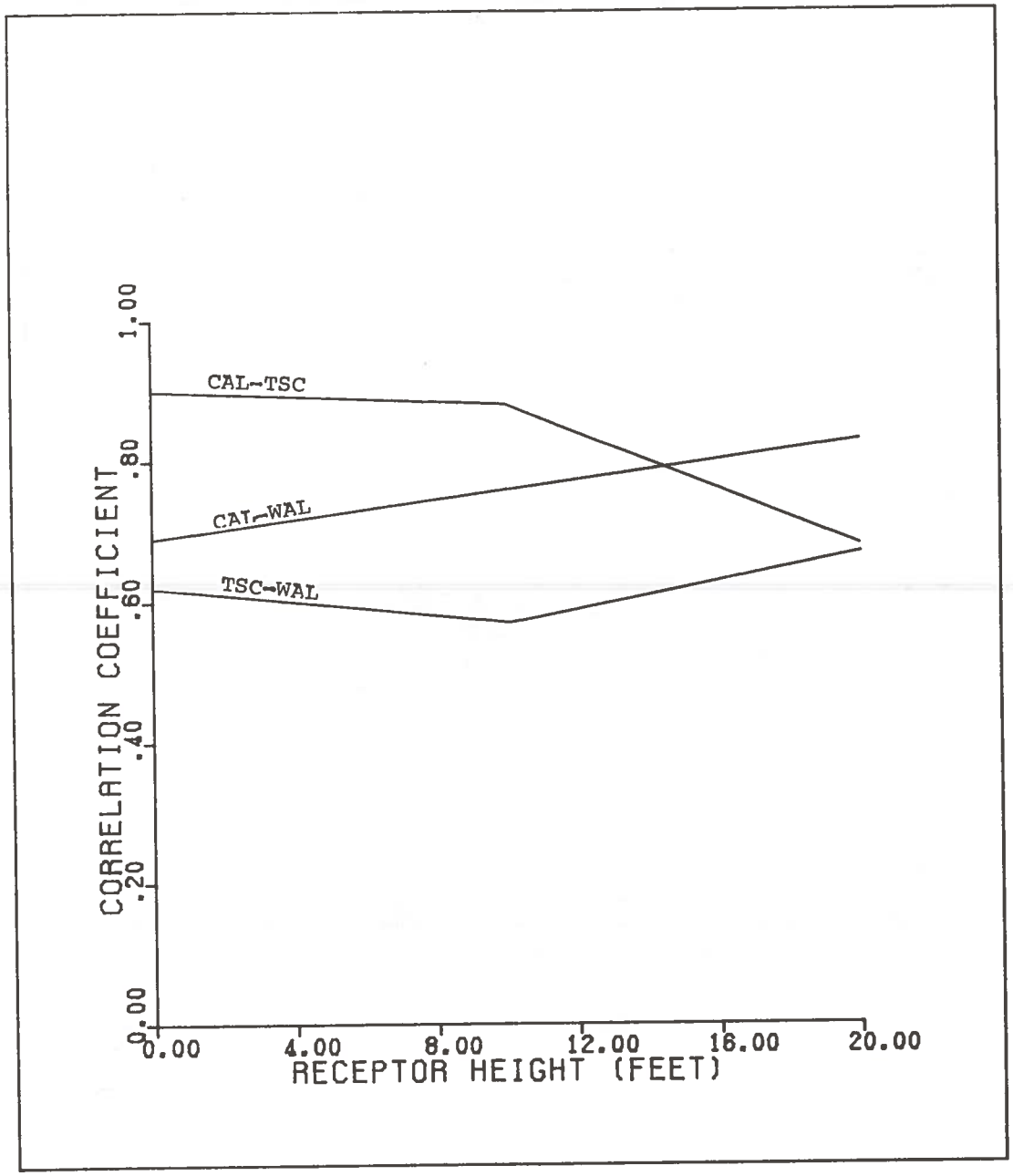

FIGURE 4-5. DATA STRATIFIED BY RECEPTOR HEIGHT, CORRELATION COEFFICIENT

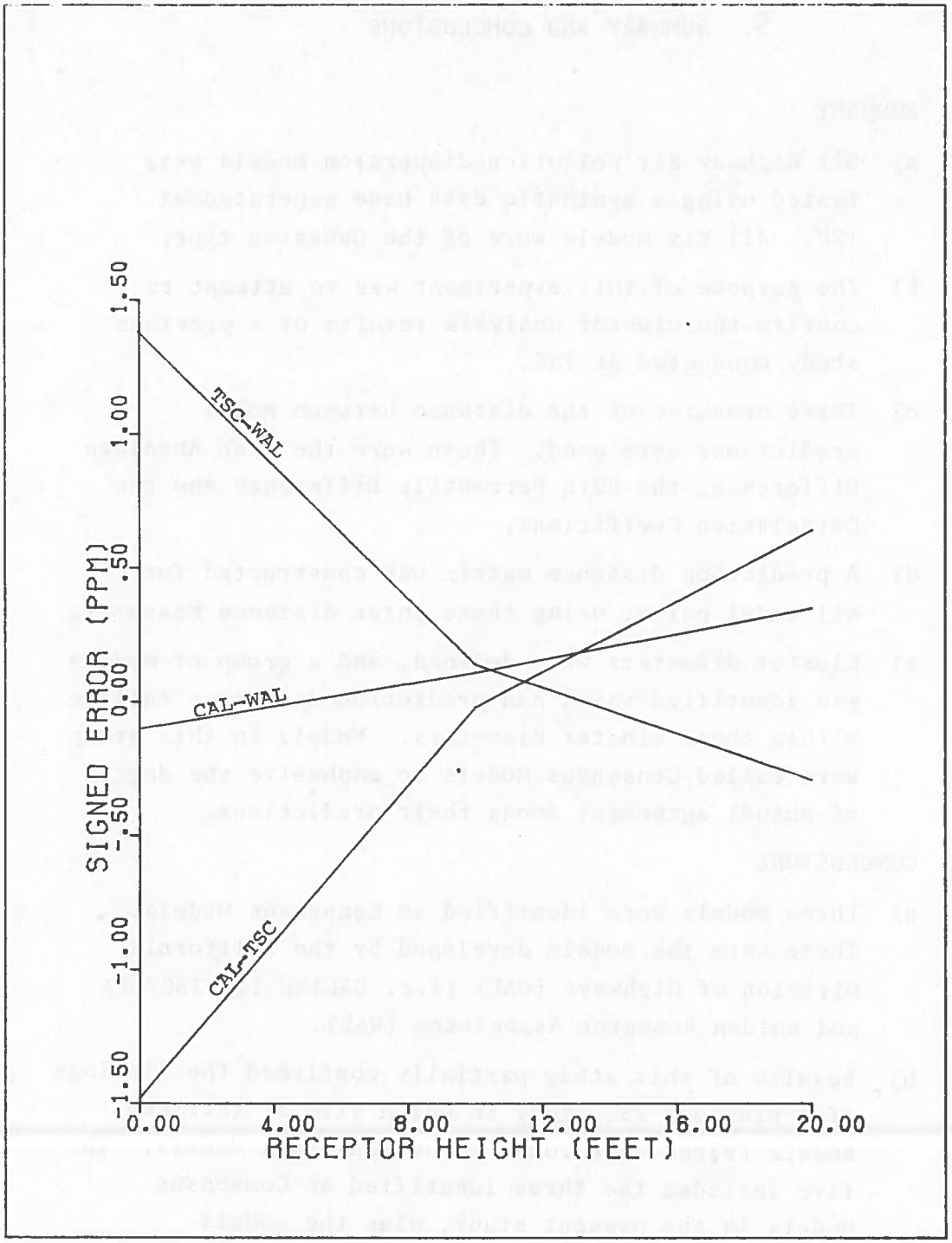

FIGURE 4-6. DATA STRATIFIED BY RECEPTOR HEIGHT, SIGNED ERROR

5. SUMMARY AND CONCLUSIONS

5.1 SUMMARY

a) Six highway air pollution dispersion models were tested using a synthetic data base generated at TSC. All six models were of the Gaussian type.

b) The purpose of this experiment was to attempt to confirm the cluster analysis results of a previous study conducted at TSC.

c) Three measures of the distance between model predictions were used. These were the Mean Absolute Difference, the 80th Percentile Difference and the Correlation Coefficient.

d) A prediction distance matrix was constructed for all model pairs, using these three distance measures.

e) Cluster diameters were defined, and a group of models was identified which had prediction distances falling within these cluster diameters. Models in this group were called Consensus Models to emphasize the degree of mutual agreement among their predictions.

5.2 CONCLUSIONS

a) Three models were identified as Consensus Models. These were the models developed by the California Division of Highways (CAL) (i.e. CALINE I), TSC/EPA and Walden Research Associates (WAL).

b) Results of this study partially confirmed the findings of a previous TSC study in which five of thirteen models tested were found to be Censensus Models. The five included the three identified as Consensus Models in the present study, plus the models developed by AeroVironment, and Environmental Research and Technology.

c) The other three models which were tested in this study, when compared to the Consensus Models, tended to be conservative in their predictions (i.e., to overpredict pollutant concentrations).

d) The three models designated as Consensus Models in this study are not necessarily more accurate than the other three models. Model accuracy can only be determined when a large sample of air quality data suitable for model validation become available.

APPENDIX A

SCATTER DIAGRAMS* OF THE MODELS

*For viewing convenience, only every ninth point is plotted.

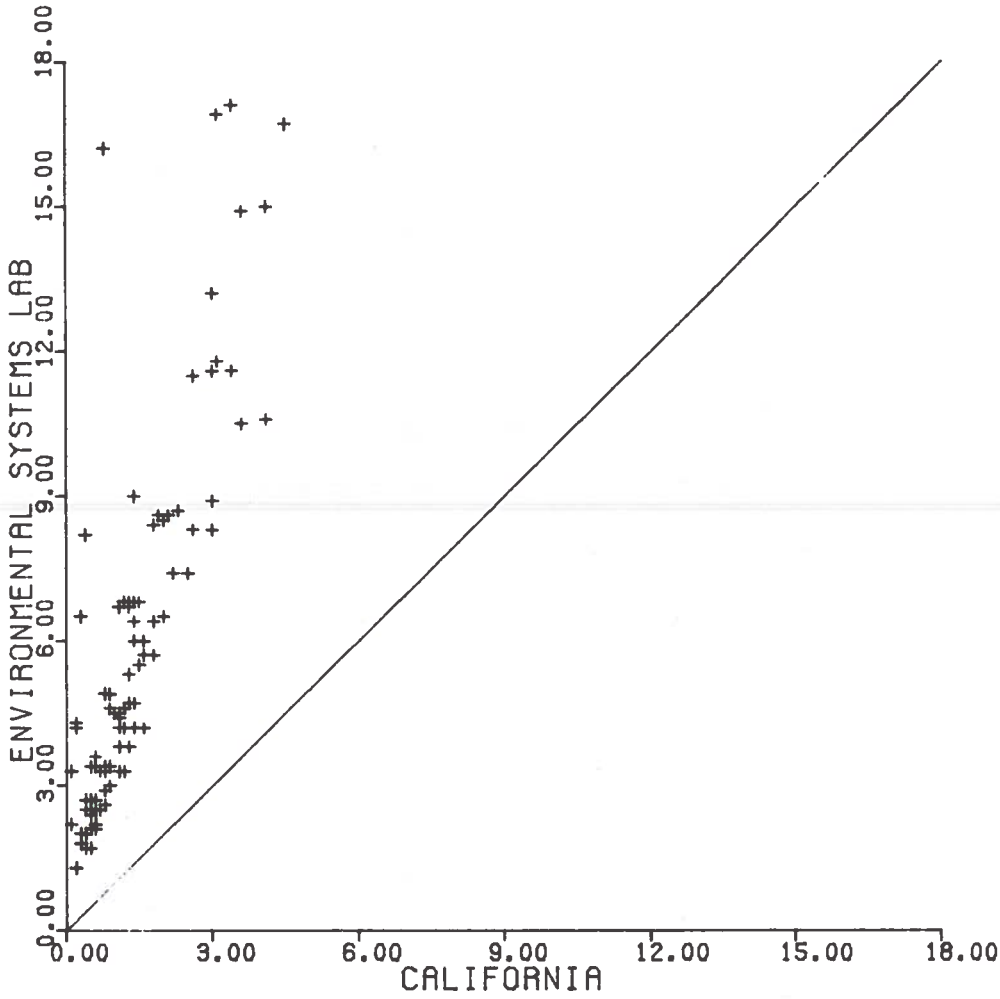

Figure A-1. Environmental Systems Lab Model

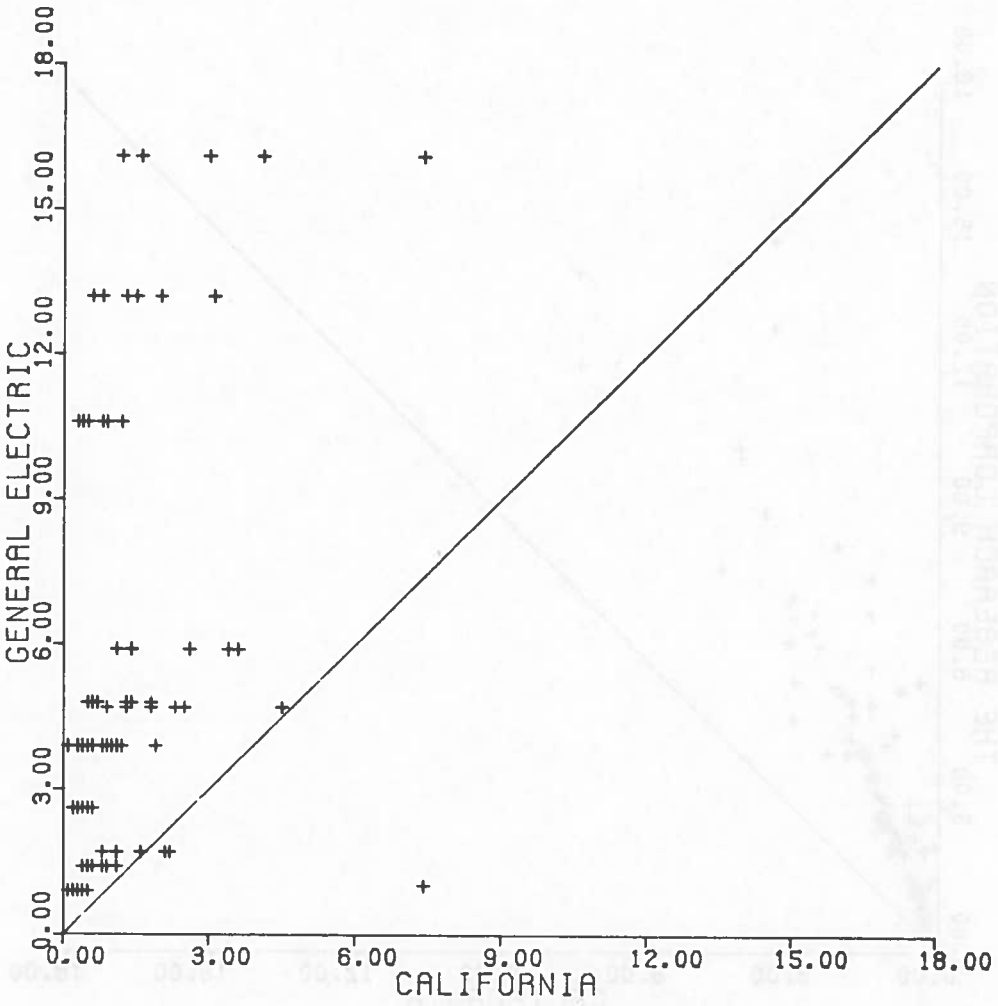

Figure A-2. General Electric Model

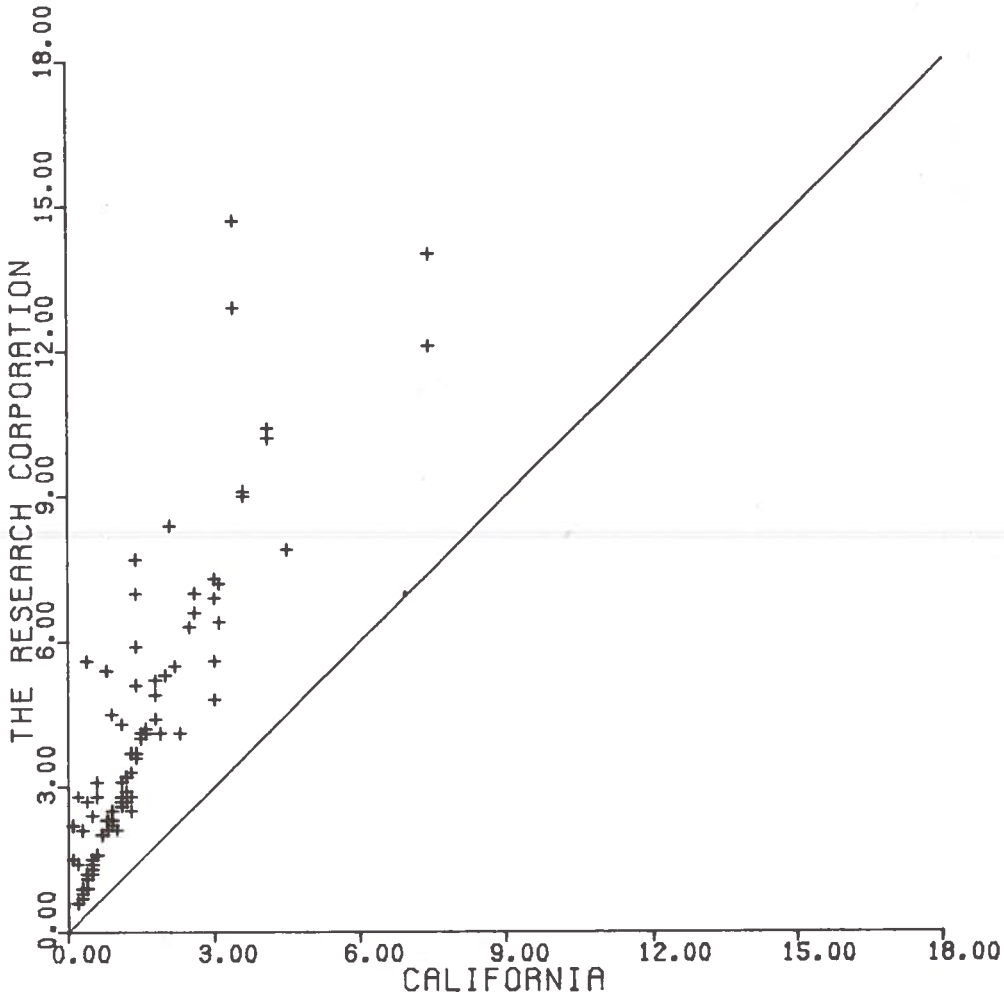

Figure A-3. The Research Corporation Model

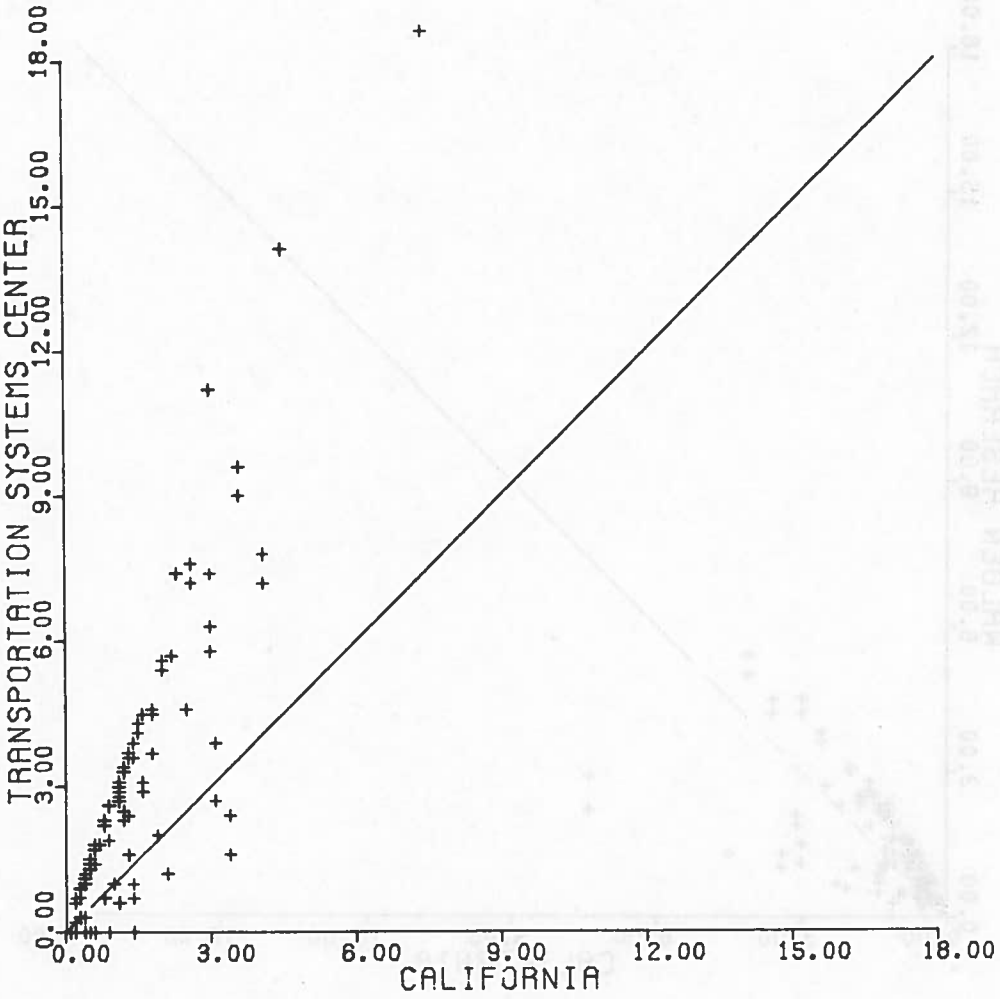

Figure A-4. Transportation Systems Center Model

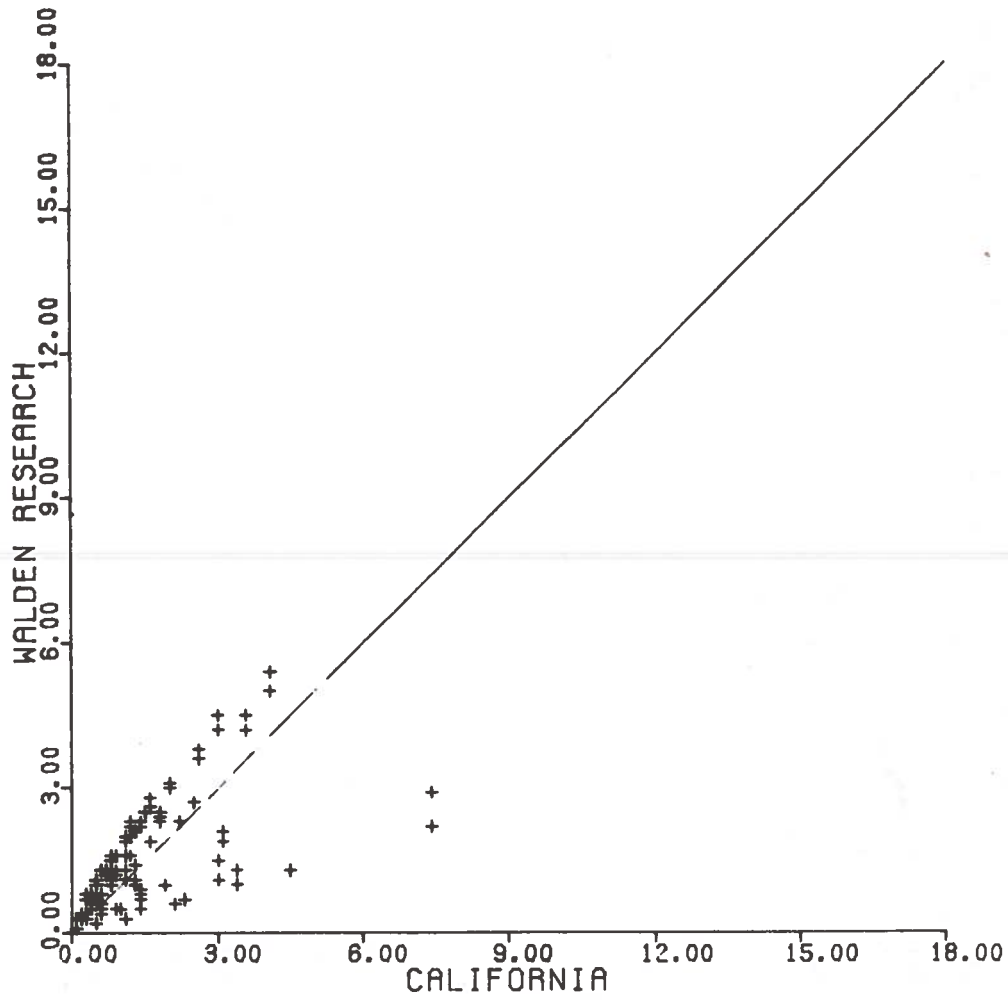

Figure A-5. Walden Research Model

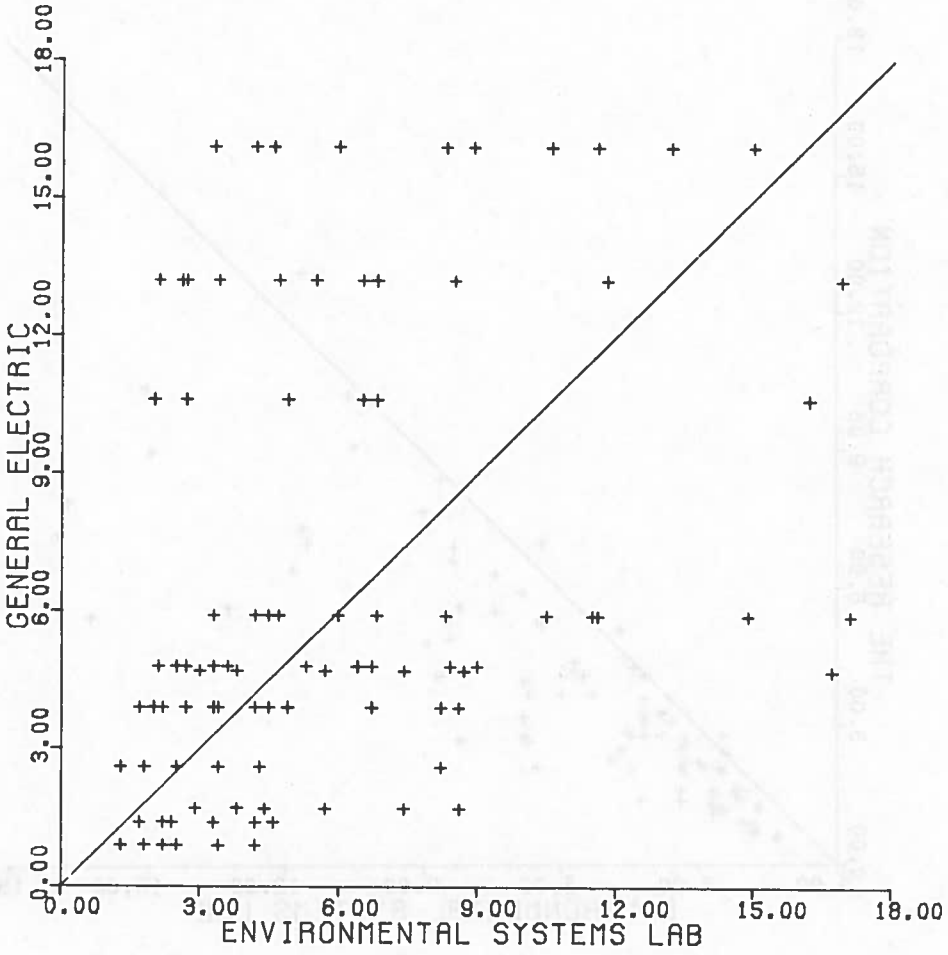

Figure A-6. General Electric/Environmental Systems Lab Model

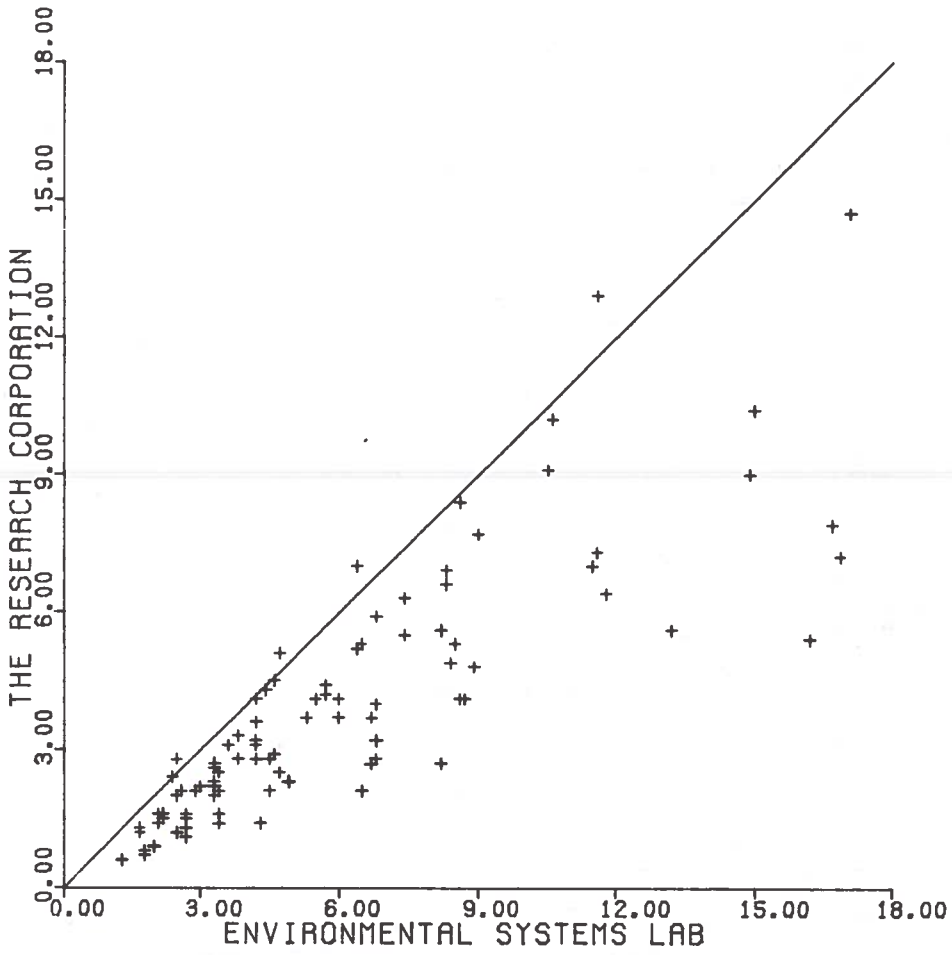

Figure A-7. The Research Corporation/Environmental Systems Lab Model

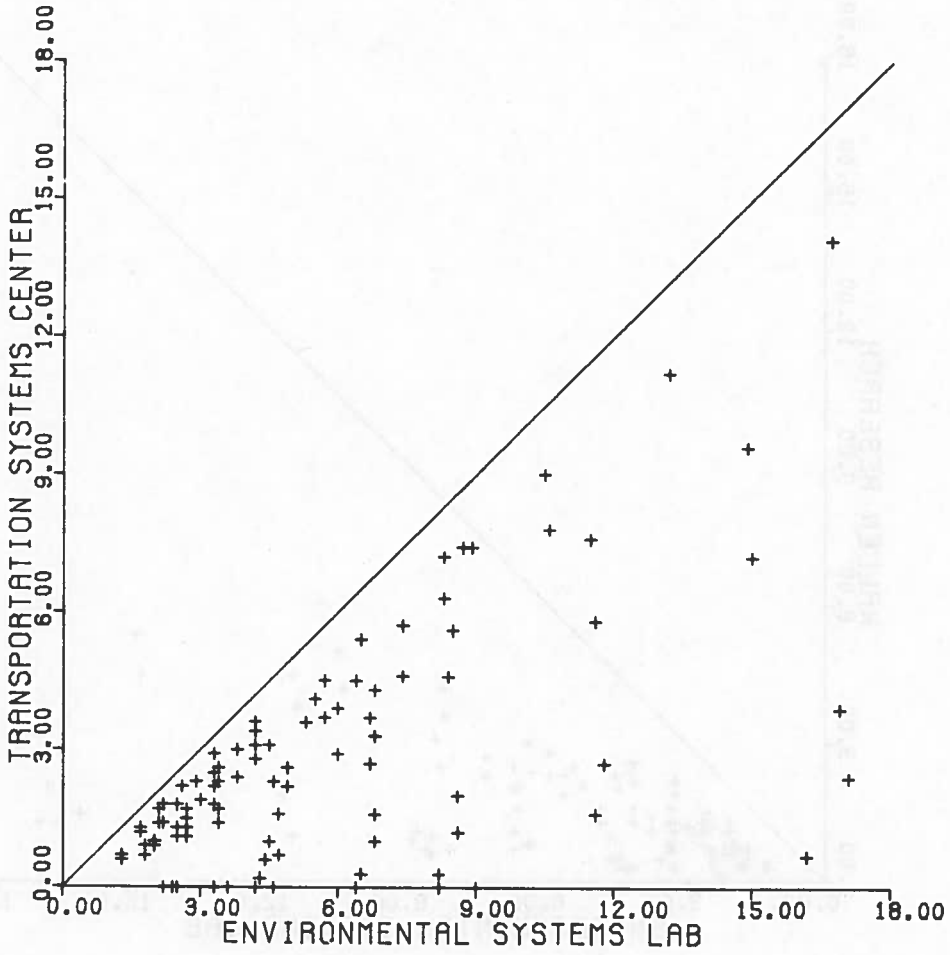

Figure A-8. The Transportation Systems Center/Environmental Systems Lab Model

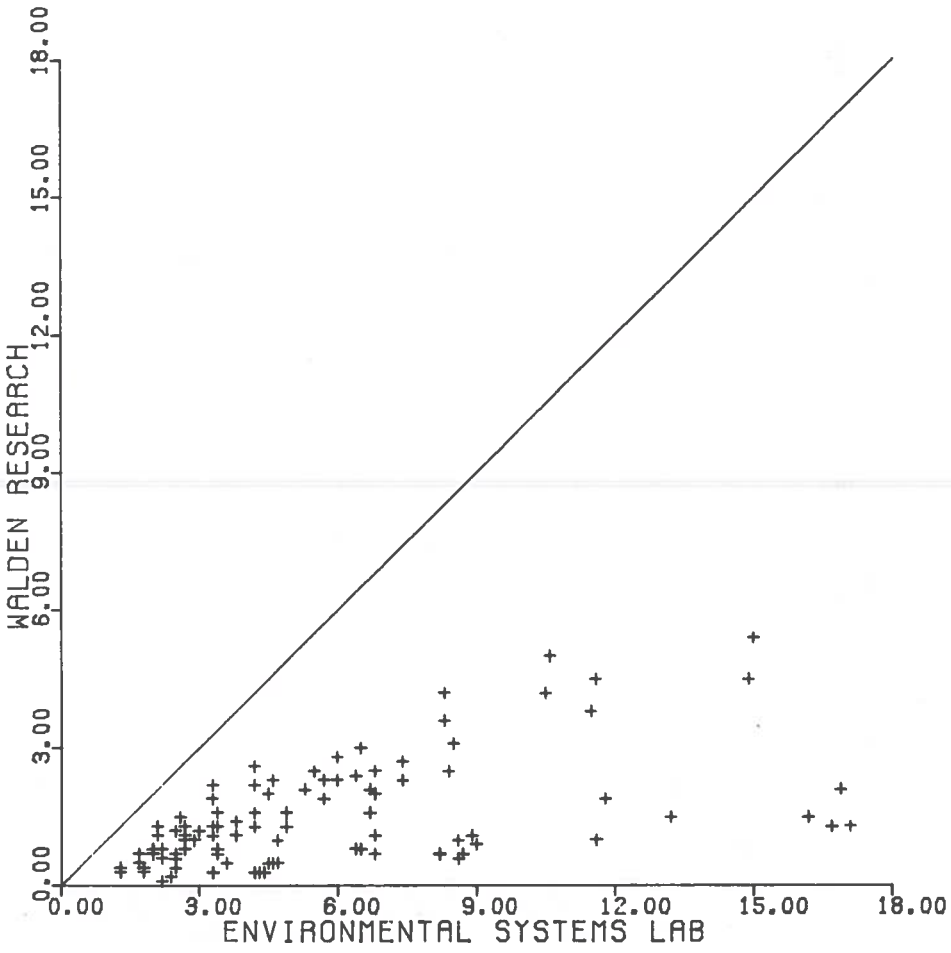

Figure A-9. The Walden Research/Environmental Systems Lab Model

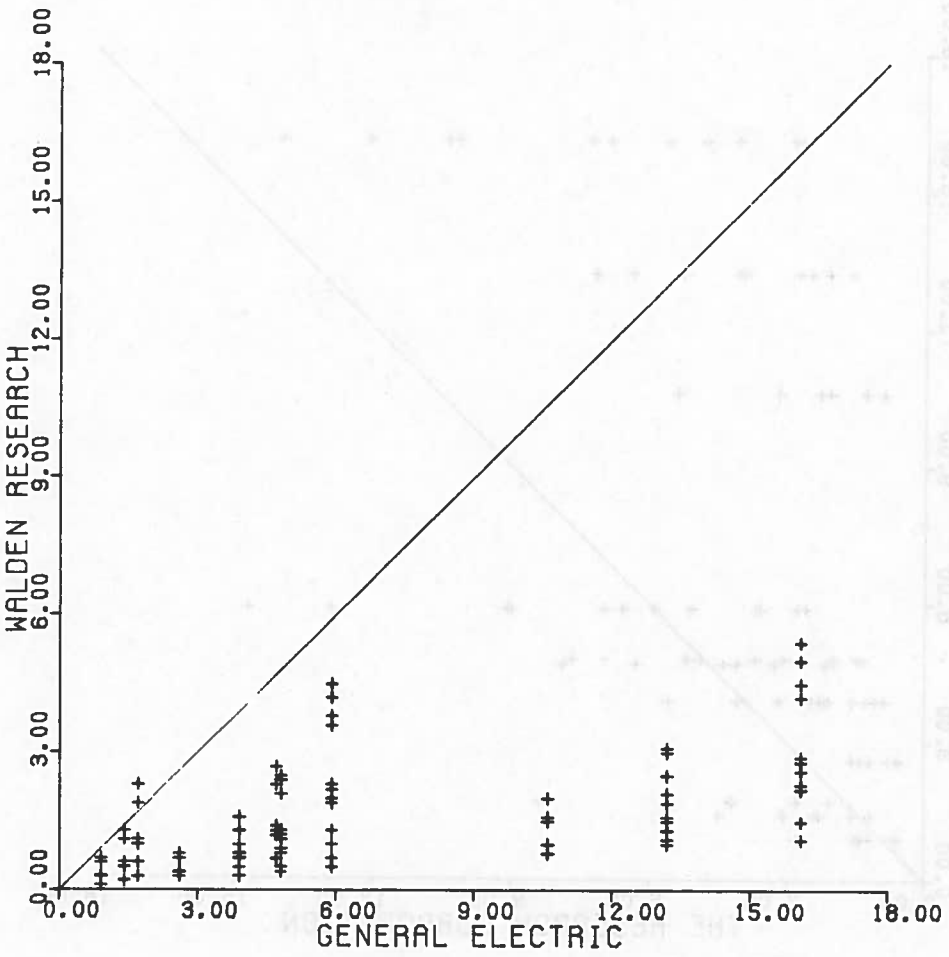

Figure A-10. The Walden Research/General Electric Model

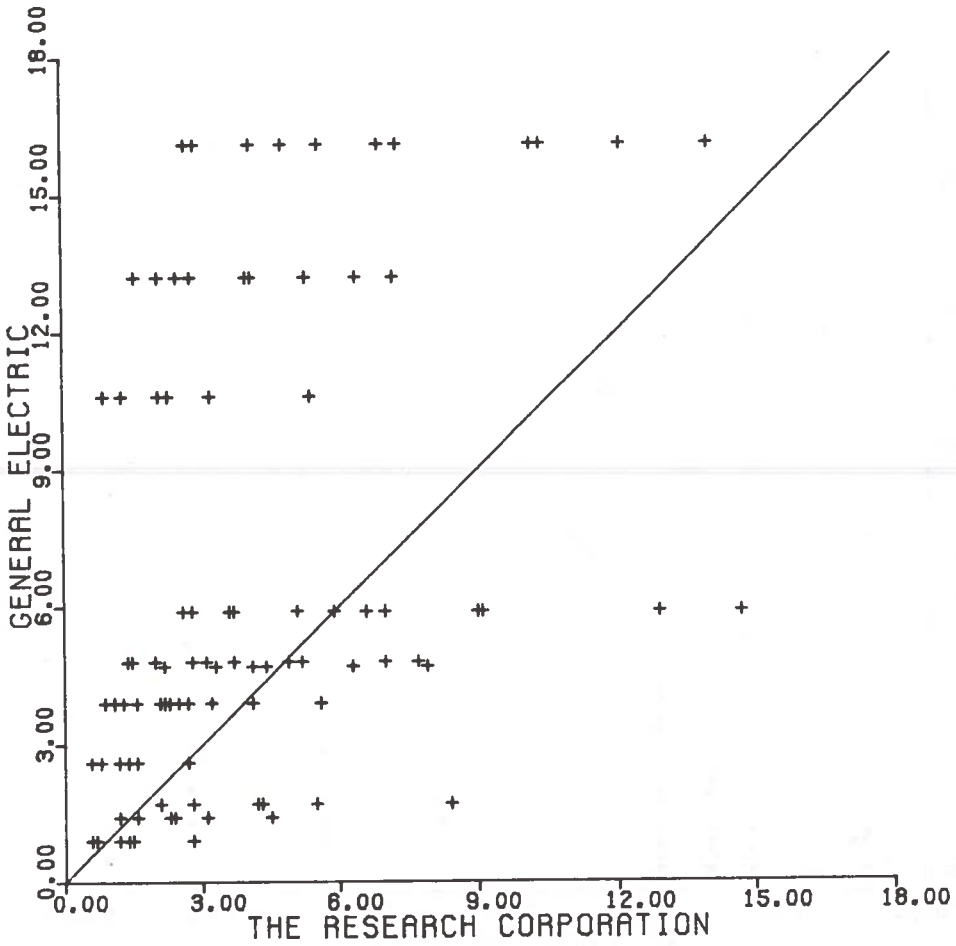

Figure A-11. The General Electric/Research Corporation Model

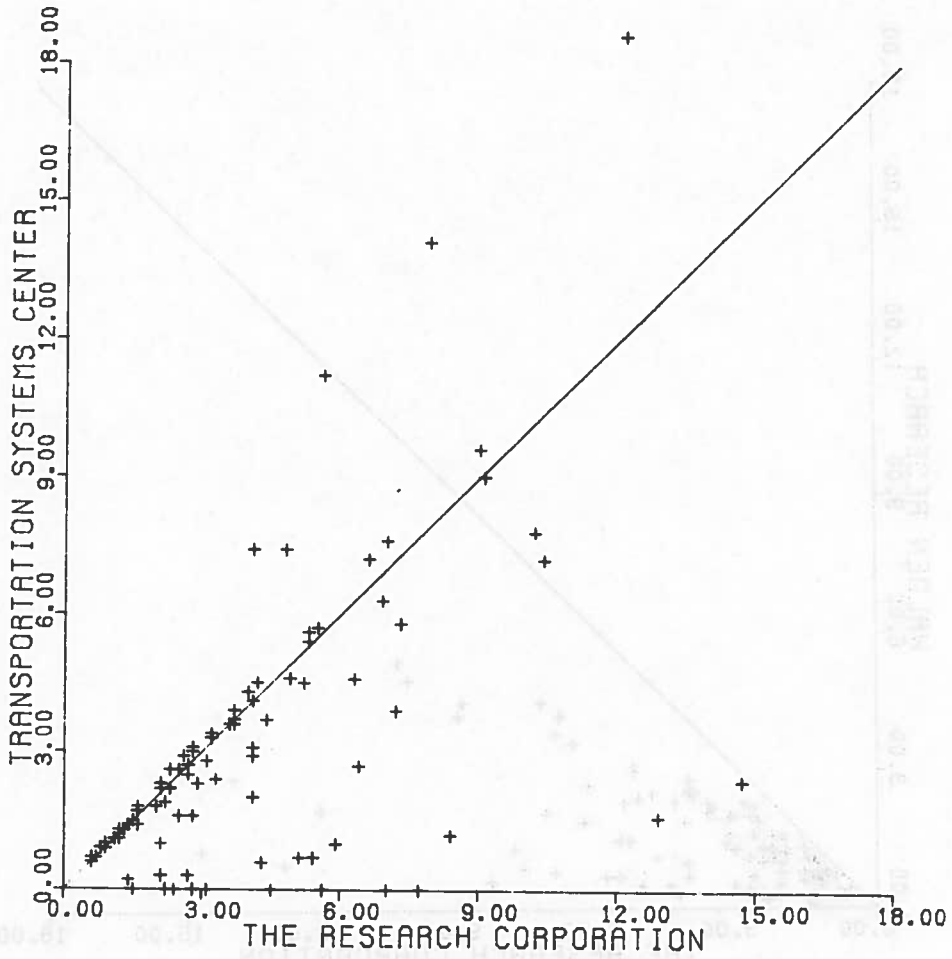

Figure A-12. The Transportation Systems Center/Research Corporation Model

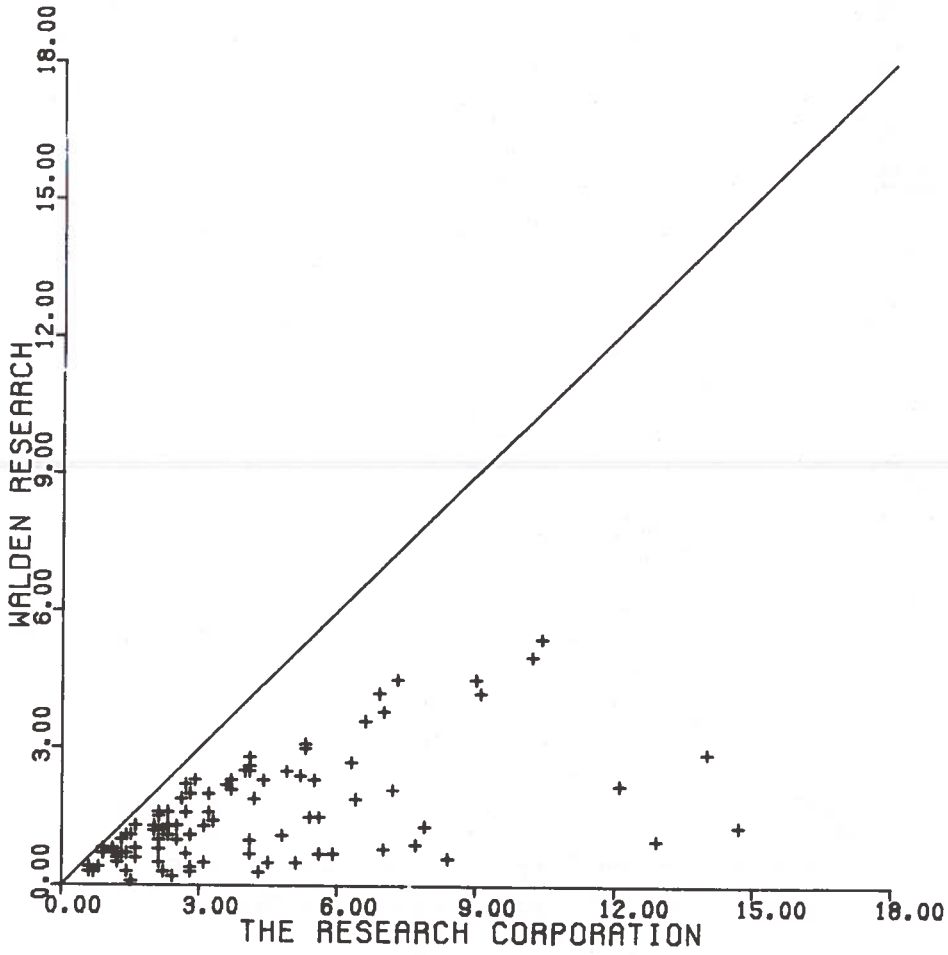

Figure A-13. The Walden Research/Research Corporation Model

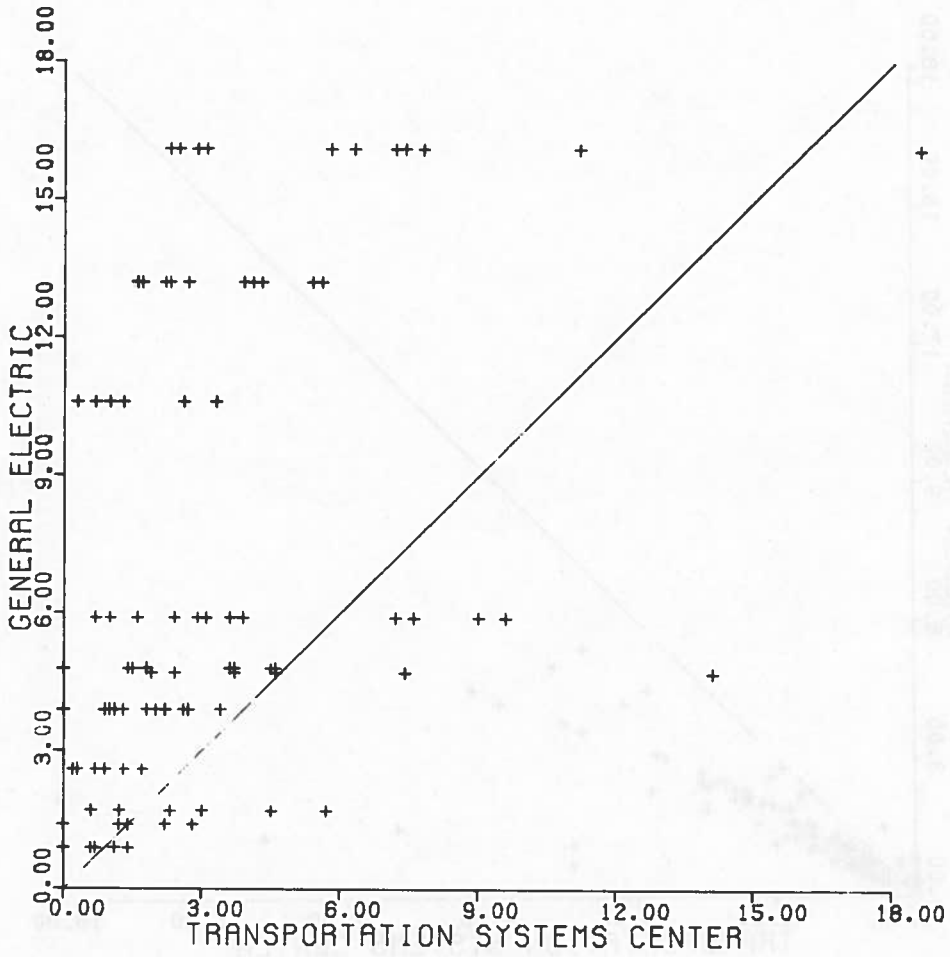

Figure A-14. The General Electric/Transportation Systems Center Model

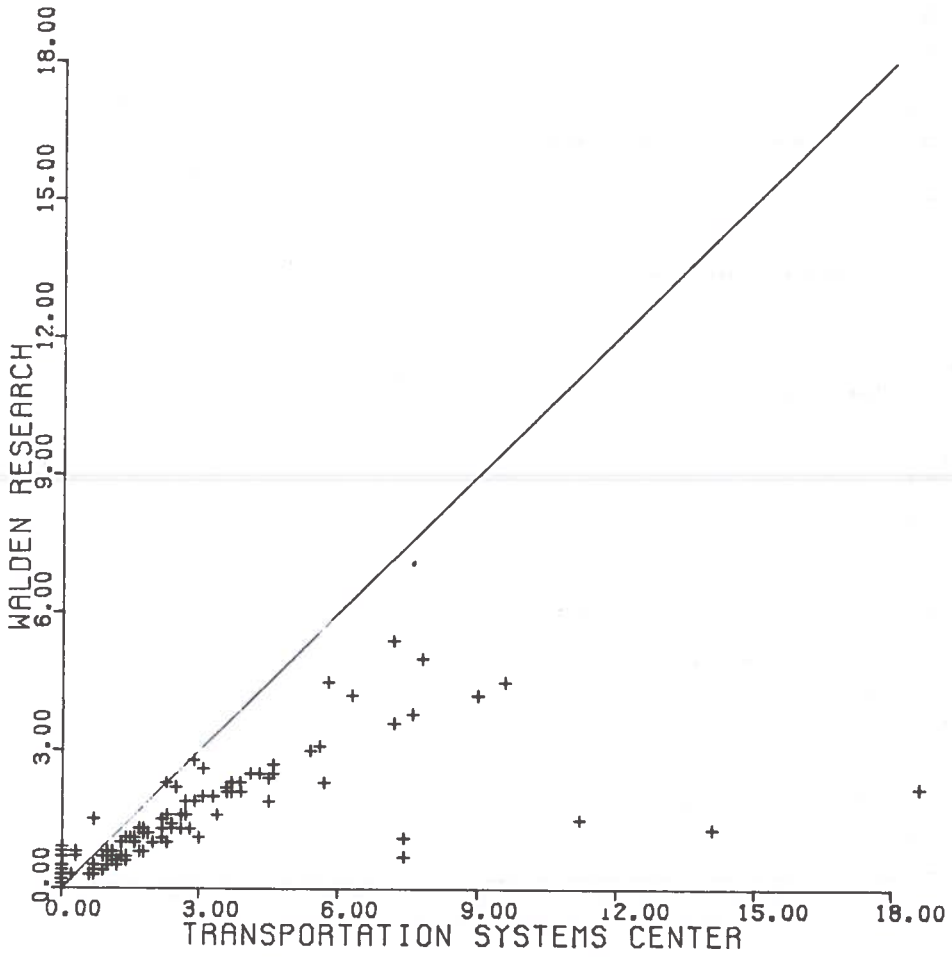

Figure A-15. The Walden Research/Transportation Systems Center Model

APPENDIX B
THE STRATIFIED TEST RESULTS

TABLE B-1. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 0 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	
≤ 1.00	CAL - WAL
≤ 1.50	CAL - WAL
≤ 2.00	CAL - TSC - WAL TRC - TSC

TABLE B-2. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 0 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	CAL - WAL TSC - WAL
≤ 1.00	CAL - TSC - WAL
≤ 1.50	CAL - TSC - WAL TRC - WAL
≤ 2.00	CAL - TRC - TSC - WAL

TABLE B-3. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Center Strip: 0 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
$\geq$ 0.75	CAL - WAL TSC - WAL ESL - TRC
$\geq$ 0.65	CAL - TSC - WAL ESL - TRC

TABLE B-4. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 0 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1					1
≤ 1.50	1					1
≤ 2.00	2			1	3	2
TOTAL	4			1	3	4

TABLE B-5. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 0 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models
Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	1				1	2
≤ 1.00	2				2	2
≤ 1.50	2			1	2	3
≤ 2.00	3			3	3	3
TOTALS	8			4	8	10

TABLE B-6. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Center Strip: 0 ft.)

CORRELATION COEFFICIENT

Number Of Different Models Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
$\geq$ 0.75	1	1		1	1	2
$\geq$ 0.65	2	1		1	2	2
TOTAL	3	2		2	3	4

TABLE B-7. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Center Strip: 0 ft.)

TOTAL NUMBER OF DIFFERENT MODELS
CLUSTERING WITH EACH MODEL

	MODELS					
Test	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	4			1	3	4
80th Percentile	8			4	8	10
Correlation Coefficient	3	2		2	3	4
TOTAL	15	2		7	14	18

TABLE B-8. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 10 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	CAL - WAL TSC - WAL
$\leq$ 1.00	CAL - TSC - WAL
$\leq$ 1.50	CAL - TRC - TSC - WAL ESL - TRC
$\leq$ 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE B-9. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 10 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	
≤ 1.00	CAL - WAL TSC - WAL
≤ 1.50	CAL - TSC - WAL
≤ 2.00	CAL - TSC - WAL ESL - TRC

TABLE B-10. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Center Strip: 10 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
$\geq$ 0.75	CAL - WAL CAL - ESL ESL - TRC TSC - WAL
$\geq$ 0.65	CAL - WAL CAL - ESL ESL - TRC TSC - WAL

TABLE B-11. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 10 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	1				1	2
≤ 1.00	2				2	2
≤ 1.50	3	1		4	3	3
≤ 2.00	3	1		4	3	3
TOTAL	9	2		8	9	10

TABLE B-12. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 10 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1				1	2
≤ 1.50	2				2	2
≤ 2.00	2	1		1	2	2
TOTALS	5	1		1	5	6

TABLE B-13. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Center Strip: 10 ft.)

CORRELATION COEFFICIENT

Number Of Different Models Clustering With Each Model

Cluster Diameter	MODELS CAL	ESL	GE	TRC	TSC	WAL
$\geq$ 0.75	2	2		1	1	2
$\geq$ 0.65	2	2		1	1	2
TOTAL	4	4		2	2	4

TABLE B-14. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Center Strip: 10 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	9	2		8	9	10
80th Percentile	5	1		1	5	6
Correlation Coefficient	4	4		2	2	4
TOTAL	18	7		11	16	20

TABLE B-15. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 50 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	CAL - TSC - WAL
≤ 1.00	CAL - TSC - WAL TRC - TSC
≤ 1.50	CAL - TRC - TSC - WAL
≤ 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE B-16. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 50 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	
≤ 1.00	
≤ 1.50	CAL - WAL
≤ 2.00	CAL - WAL TSC - WAL

TABLE B-17. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Center Strip: 50 ft.)

CORRELATION COEFFICIENT

Cluster Coefficient	Clusters
$\geq$ 0.75	CAL - TSC CAL - ESL ESL - TRC
$\geq$ 0.65	CAL - ESL - TRC CAL - ESL - TSC

TABLE B-18. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 50 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	2				2	2
≤ 1.00	2			1	3	2
≤ 1.50	3			3	3	3
≤ 2.00	3	1		4	3	3
TOTAL	10	1		8	11	10

TABLE B-19. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Center Strip: 50 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00						
≤ 1.50	1					1
≤ 2.00	1				1	2
TOTALS	3				1	3

TABLE B-20. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Center Strip: 50 ft.)

CORRELATION COEFFICIENT

Number Of Different Models
Clustering With Each Model

Cluster Diameter	MODELS CAL	ESL	GE	TRC	TSC	WAL
$\geq$ 0.75	2	2		1	1	
$\geq$ 0.65	3	3		2	2	
TOTAL	5	5		3	3	

TABLE B-21. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Center Strip: 50 ft.)

TOTAL NUMBER OF DIFFERENT MODELS
CLUSTERING WITH EACH MODEL

	MODELS					
Test	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	10	1		8	11	10
80th Percentile	2				1	3
Correlation Coefficient	5	5		3	3	
TOTAL	17	6		11	15	13

TABLE B-22. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 0 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	
$\leq$ 1.00	CAL - WAL
$\leq$ 1.50	CAL - WAL TRC - TSC
$\leq$ 2.00	CAL - TSC - WAL TRC - TSC

TABLE B-23. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 0 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	
≤ 1.00	CAL - WAL
≤ 1.50	CAL - WAL
≤ 2.00	CAL - TSC - WAL

TABLE B-24. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Height: 0 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
$\geq$ 0.75	CAL - ESL - TRC CAL - ESL - TSC
$\geq$ 0.65	CAL - ESL - TRC - TSC CAL - WAL

TABLE B-25. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 0 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1					1
≤ 1.50	1			1	1	1
≤ 2.00	1			1	2	1
TOTAL	3			2	3	3

TABLE B-26. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 0 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1					1
≤ 1.50	1					1
≤ 2.00	2				2	2
TOTALS	4				2	4

TABLE B-27. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Height: 0 ft.)

CORRELATION COEFFICIENT

Number Of Different Models
Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
$\geq$ 0.75	3	3		2	2	
$\geq$ 0.65	4	3		3	3	1
TOTAL	7	6		5	5	1

TABLE B-28. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Height: 0 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	3			2	2	3
80th Percentile	4				2	4
Correlation Coefficient	7	6		5	5	1
TOTAL	14	6		7	10	8

TABLE B-29. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 10 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	CAL - WAL CAL - TSC
$\leq$ 1.00	CAL - TSC - WAL
$\leq$ 1.50	CAL - TRC - TSC - WAL
$\leq$ 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE B-30. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 10 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	CAL - TSC - WAL
≤ 1.00	CAL - TSC - WAL
≤ 1.50	CAL - TSC - WAL
≤ 2.00	CAL - TSC - WAL

TABLE B-31. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Height: 10 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
≥ 0.75	CAL - ESL ESL - TRC CAL - WAL CAL - TSC
≥ 0.65	CAL - ESL - TRC CAL - ESL - TSC CAL - WAL

TABLE B-32. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 10 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	2				1	1
≤ 1.00	2				2	2
≤ 1.50	3			3	3	3
≤ 2.00	3	1		4	3	3
TOTAL	10	1		7	9	9

TABLE B-33. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 10 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models
Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	2				2	2
≤ 1.00	2				2	2
≤ 1.50	2				2	2
≤ 2.00	2				2	2
TOTALS	8				8	8

TABLE B-34. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Height: 10 ft.)

CORRELATION COEFFICIENT

Number Of Different Models
Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≥ 0.75	3	2		1	1	1
≥ 0.65	4	3		2	2	1
TOTAL	7	5		3	3	2

TABLE B-35. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Height: 10 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	10	1		7	9	9
80th Percentile	8				8	8
Correlation Coefficient	7	5		3	3	2
TOTAL	25	6		10	20	19

TABLE B-36. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 20 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	CAL - WAL TSC - WAL
$\leq$ 1.00	CAL - TSC - WAL
$\leq$ 1.50	CAL - TSC - WAL TRC - TSC - WAL ESL - TRC
$\leq$ 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE B-37. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 20 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	TSC - WAL
≤ 1.00	CAL - TSC - WAL
≤ 1.50	CAL - TSC - WAL ESL - TRC
≤ 2.00	CAL - TSC - WAL ESL - TRC

TABLE B-38. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Height: 20 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
$\geq$ 0.75	CAL - WAL ESL - TRC
$\geq$ 0.65	CAL - TSC - WAL ESL - TRC

TABLE B-39. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 20 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	1				1	2
≤ 1.00	2				2	2
≤ 1.50	2	1		3	3	3
≤ 2.00	3	1		4	3	3
TOTAL	8	2		7	9	10

TABLE B-40. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Height: 20 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50					1	1
≤ 1.00	2				2	2
≤ 1.50	2	1		1	2	2
≤ 2.00	2	1		1	2	2
TOTALS	6	2		2	7	7

TABLE B-41. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Height: 20 ft.)

CORRELATION COEFFICIENT

Number Of Different Models
Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≥ 0.75	1	1		1		1
≥ 0.65	2	1		1	2	2
TOTAL	3	2		2	2	3

TABLE B-42. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Height: 20 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	8	2		7	9	10
80th Percentile	6	2		2	7	7
Correlation Coefficient	3	2		2	2	3
TOTAL	17	6		13	18	20

TABLE B-43. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 50 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	CAL - TSC - WAL
≤ 1.00	CAL - TSC - WAL TRC - WAL
≤ 1.50	CAL - TRC - TSC - WAL
≤ 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE B-44. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 50 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	CAL - WAL TSC - WAL
≤ 1.00	CAL - WAL TSC - WAL
≤ 1.50	CAL - TSC - WAL
≤ 2.00	CAL - TSC - WAL

TABLE B-45. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 50 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
$\geq$ 0.75	CAL - ESL - TRC CAL - TSC TRC - TSC
$\geq$ 0.65	CAL - ESL - TRC - TSC TRC - WAL

TABLE B-46. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 50 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	2				2	2
≤ 1.00	2			1	2	3
≤ 1.50	3			3	3	3
≤ 2.00	3	1		8	10	11
TOTAL	10	1		8	10	11

TABLE B-47. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 50 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	1				1	2
≤ 1.00	1				1	2
≤ 1.50	2				2	2
≤ 2.00	2				2	2
TOTALS	6				6	8

TABLE B-48. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 50 ft.)

CORRELATION COEFFICIENT

Number Of Different Models
Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≥ 0.75	3	2		3	2	
≥ 0.65	3	3		4	3	1
TOTAL	6	5		7	5	1

TABLE B-49. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Distance: 50 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	10	1		8	10	11
80th Percentile	6				6	8
Correlation Coefficient	6	5		7	5	1
TOTAL	22	6		15	21	20

TABLE B-50. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 75 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	
$\leq$ 1.00	CAL - WAL
$\leq$ 1.50	CAL - TSC - WAL TRC - TSC
$\leq$ 2.00	CAL - TRC - TSC - WAL ESL - TRC

TABLE B-51. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 75 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	
$\leq$ 1.00	CAL - WAL
$\leq$ 1.50	CAL - WAL TSC - WAL
$\leq$ 2.00	CAL - TSC - WAL

TABLE B-52. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 75 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
≥ 0.75	CAL - TSC CAL - TRC ESL - TRC
≥ 0.65	CAL - ESL - TRC - TSC CAL - WAL

TABLE B-53. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 75 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1					1
≤ 1.50	1				1	2
≤ 2.00	2				2	2
TOTALS	4				3	5

TABLE B-54. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 75 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1					1
≤ 1.50	2			1	3	2
≤ 2.00	3	1		4	4	4
TOTAL	6	1		5	6	6

TABLE B-55. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 75 ft.)

CORRELATION COEFFICIENT

Number Of Different Models Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≥ 0.75	2	1		2	1	
≥ 0.65	4	3		3	3	1
TOTAL	6	4		5	4	1

TABLE B-56. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Distance: 75 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	6	1		5	6	6
80th Percentile	4				3	5
Correlation Coefficient	6	4		5	4	1
TOTAL	16	5		10	13	12

TABLE B-57. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 100 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	CAL - WAL
≤ 1.00	CAL - TSC - WAL
≤ 1.50	CAL - TSC - WAL ESL - TRC
≤ 2.00	CAL - TSC - WAL ESL - TRC TRC - TSC

TABLE B-58. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 100 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
≤ 0.50	
≤ 1.00	CAL - WAL TSC - WAL
≤ 1.50	CAL - TSC - WAL
≤ 2.00	CAL - TSC - WAL ESL - TRC

TABLE B-59. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 100 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
≥ 0.75	CAL - WAL TSC - WAL ESL - TRC
≥ 0.65	CAL - WAL TSC - WAL ESL - CAL ESL - TRC

TABLE B-60. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 100 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models
Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	1					1
≤ 1.00	2				2	2
≤ 1.50	2	1		1	2	2
≤ 2.00	2	1		2	3	2
TOTAL	7	2		3	7	7

TABLE B-61. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 100 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50						
≤ 1.00	1				1	2
≤ 1.50	2				2	2
≤ 2.00	2	1		1	2	2
TOTALS	5	1		1	5	6

TABLE B-62. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 100 ft.)

CORRELATION COEFFICIENT

Number Of Different Models Clustering With Each Model

Correlation Coefficient	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
$\geq$ 0.75	1	1		1	1	2
$\geq$ 0.65	2	2		1	1	2
TOTAL	3	3		2	2	4

TABLE B-63. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Distance: 100 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

	MODELS					
Test	CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	7	2		3	7	7
80th Percentile	5	1		1	5	6
Correlation Coefficient	3	3		2	2	4
TOTAL	15	6		6	14	17

TABLE B-64. CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 300 ft.)

MEAN ABSOLUTE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	CAL - TSC - WAL
$\leq$ 1.00	CAL - GE - TSC - WAL
$\leq$ 1.50	CAL - GE - TRC - TSC - WAL ESL - TRC
$\leq$ 2.00	CAL - GE - TRC - TSC - WAL CAL - ESL - TRC - TSC - WAL

TABLE B-65. CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 300 ft.)

80th PERCENTILE DIFFERENCE

Cluster Diameter (ppm)	Clusters
$\leq$ 0.50	CAL - WAL TSC - WAL
$\leq$ 1.00	CAL - TSC - WAL CAL - GE - WAL
$\leq$ 1.50	CAL - GE - TSC - WAL
$\leq$ 2.00	CAL - GE - TSC - WAL TRC - TSC - WAL ESL - TRC

TABLE B-66. CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 300 ft.)

CORRELATION COEFFICIENT

Cluster Diameter	Clusters
$\geq$ 0.75	CAL - TSC - WAL ESL - TSC
$\geq$ 0.65	CAL - TSC - WAL ESL - TSC - WAL ESL - TRC

TABLE B-67. NUMBER OF MODELS CLUSTERING BY THE MEAN ABSOLUTE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 300 ft.)

MEAN ABSOLUTE DIFFERENCE

Number of Different Models
Clustering with Each Model

Cluster Diameter (ppm)	MODELS CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	2				2	2
≤ 1.00	3		3		3	3
≤ 1.50	4	1	4	5	4	4
≤ 2.00	5	4	4	5	5	5
TOTAL	14	5	11	10	14	14

TABLE B-68. NUMBER OF MODELS CLUSTERING BY THE 80th PERCENTILE DIFFERENCE BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 300 ft.)

80th PERCENTILE DIFFERENCE

Number of Different Models Clustering with Each Model

Cluster Diameter (ppm)	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≤ 0.50	1				1	2
≤ 1.00	3		2		2	3
≤ 1.50	3		3		3	3
≤ 2.00	3	1	3	3	4	4
TOTALS	10	1	8	3	10	12

TABLE B-69. NUMBER OF MODELS CLUSTERING BY THE CORRELATION BETWEEN MODEL PREDICTIONS.

(Receptor Distance: 300 ft.)

CORRELATION COEFFICIENT

Number Of Different Models
Clustering With Each Model

Cluster Diameter	MODELS					
	CAL	ESL	GE	TRC	TSC	WAL
≥ 0.75	2	1			3	2
≥ 0.65	2	3		1	3	3
TOTAL	4	4		1	6	5

TABLE B-70. NUMBER OF MODELS CLUSTERING BY ALL DISTANCE MEASURES.

(Receptor Distance: 300 ft.)

TOTAL NUMBER OF DIFFERENT MODELS CLUSTERING WITH EACH MODEL

Test	MODELS CAL	ESL	GE	TRC	TSC	WAL
Mean absolute Difference	14	5	11	10	14	14
80th Percentile	10	1	8	3	10	12
Correlation Coefficient	4	4		1	6	5
TOTAL	28	10	19	14	30	31

APPENDIX C
THE MODEL DESCRIPTIONS

C.1 CALIFORNIA DIVISION OF HIGHWAYS (CAL)

CALIFORNIA DEPARTMENT OF PUBLIC WORKS

SACRAMENTO, CALIFORNIA 95814

INTRODUCTION

This computer program calculates the pollutant concentrations generated by motor vehicles within a highway corridor. The mathematical model, which is based on the Gaussian Diffusion Equation, calculates hourly concentrations of pollutants within the mechanical mixing cell as well at receptor points at given distances from the roadway. The computerized model is capable of estimating pollutant concentrations where the winds are either parallel or at an angle to the highway alignment and where the highway section may be at grade, elevated or in a cut.

This User's Guide is intended primarily to assist users in preparing input data for the computer program. It does not constitute a complete documentation of the program nor an instruction manual for its application. Prospective users should be thoroughly familiar with the contents of a report titled "Mathematical Approach to Estimating Highway Impact on Air Quality" (Report Number FHWA-RD-72-36) and an accompanying Appendix (FHWA-RD-72-37) before attempting to use the program. Report Number 72-36 describes the mathematical formulation, basic assumptions and limitations of the model that is the basis of the computer program. Report 72-36 also contains several problems that have been computed manually illustrating how the model may be applied.

CORRIDOR ANALYSIS

Mathematical Assumptions

The mathematical model presented in this manual is based primarily on the Gaussian Diffusion Equation, that is, the concentrations of pollutants within the plume generated by the vehicles on highways are distributed normally in both the cross-wind and vertical directions. The following are other basic assumptions that went into the development of the mathematical model for highway line sources:

1. Continuous emission sources from vehicles on highways for the time period analyzed.

2. The surface stability classes of the atmosphere are determined from studies made by Pasquill [1] and from an objective system of classifying stabilities from meteorological observations as suggested by Turner [2].

3. The concentration of pollutants on highways within the mechanical mixing cell is independent of surface stability classes. The mechanical mixing cell can be defined as the area on the highway where there is an intense zone of mixing and turbulence caused by the motion of the vehicles. The vertical height of the mixing cell is assumed to be 12 feet. The horizontal width of the mechanical mixing cell is assumed to extend from edge of shoulder to edge of shoulder for medians less than or equal to 30 feet.

4. A uniform wind flow field exists, that is, there is no variation of wind speed with height (wind shear).

5. No aerodynamic effects on air passing over structures, buildings, and other obstructions.

Further discussion of these assumptions along with the limitations and applications is presented later.

Calculations for Crosswinds

Mixing Cell Concentrations

The concentration of pollutants on the highway within the mechanical mixing cell for highways located on elevated, cut, or at-grade sections may be estimated (for any surface stability class) by using the following equation for Ø greater than 12°:

$$C = \frac{1.06\,Q}{K_1 \bar{u} \sin \phi} \qquad (3)$$

Where C = Concentration of pollutant gm/m^3

Q = Emission source gm/sec-m

$\bar{U}$ = Wind speed m/sec (1 mph = 0.447 m/sec)*

K_1 = Empirical coefficient determined by field measurements**.

Ø = Angle of wind with respect to highway alignment as determined from the computer program [5] WNDROS or STAROS based on a 16 point compass reporting system. Ø will be one of the following angles using the highway alignment as a reference or base line:

Ø = 22.5°

Ø = 45°

Ø = 67.5°

Ø = 90° (wind direction is perpendicular to highway alignment).

1.06 = Empirical factor relating the height of the mechanical mixing cell to concentration

To compute the source strength term Q in equation 3 use the following equation:

$$Q = [1.73 \times 10^{-7}] \times [\text{vehicles per hour}] \times [\text{emission factor}] \qquad (4)$$

Where the numerical constant is a factor to convert the units of the product (vph)(gm/mi) to gm/m-sec.

*The minimum recommended wind speed is 2 mph or about 1 m/sec.

**Until sufficient data become available from the Division of Highways Research Project [10] assume $K_1 = 4.24$.

The emission factor used in equation 4 depends on the model year, emission standards, percentage of HDV, average route speed, etc. Values are given by Beaton et al [4] for the primary pollutants emitted by the motor vehicles.

The calculated concentration from equation 3 should be converted to parts per million concentrations by using equation (1).

INPUT

This section describes the formats and input data required by the computer program.

The required inputs to the mathematical model to estimate hourly pollution concentrations on and within the highway corridor are described below:

1) Traffic volume in number of vehicles per hour.

2) Emission factors of vehicles using the highway as a function of heavy duty vehicle (HDV) mix and average route speed.

3) Meteorological parameters, that is, surface stability of the atmosphere and its associated probability of occurrence along with its corresponding wind rose.

4) Type of highway design, that is, a highway located on a fill or viaduct section, cut section, at grade section, etc.

5) Horizontal and vertical dispersion parameters.

Each of the above inputs into the mathematical model is discussed in detail below.

Traffic

The traffic input data for a proposed highway normally will be the peak and off-peak hourly volumes and their associated time of occurrence. This information can be obtained from District Traffic or Urban Planning Departments and will cover the period from the estimated time of completion of the proposed highway to twenty years thereafter. This is discussed in detail in a report by this department [3].

Emission Factors

The input emission factors [4] for carbon monoxide for the estimated time of completion and twenty years hence can be obtained from reference [4] depending on the percentage of Heavy Duty Vehicles (HDV) and the average route speed. If the estimated HDV mix does not correspond to the exact value used in the figures of reference [4] use a direct linear interpolation between the lower and higher HDV mix to obtain a value for the emission factor.

Wind Speed, Direction, and Stability

The output from the computer program [5] WNDROS or STAROS* will give for a specified time, (1) the probability of occurrence for each surface stability Class A through F inclusively and (2) the wind roses for the associated surface stability classes. Stability Class A is the most favorable meteorological condition in terms of the dispersion of pollutants while Stability Class F is the most unfavorable (worst) meteorological condition and results in the highest ground level concentrations. For a quantitative air quality study, it is necessary to compare two meteorological conditions which are obtained from the computer programs WNDROS or STAROS*. The two conditions are (1) the most probable

*The STAR2 computer program has replaced the STAROS program.

surface stability class and its associated wind rose, and (2) the most unfavorable, or worst meteorological conditions its probability of occurrence, and its associated wind rose. The most probable and the worst meteorological conditions are usually estimated for the time periods when the peak and off-peak traffic hours occur. This is discussed in detail in a report by Beaton et al [5].

Type of Highway Design

The input for the type of highway design consists of one of the following:

1. at grade section
2. elevated highways 30 feet or less
3. elevated highways over 30 feet
4. cut section

For each of the above types of design, with the exception of the at grade section, the height of fill, viaduct, or elevated section must be determined. The same applies to the cut section, that is, the depth of cut must be determined. The geometric characteristics can be obtained from plans furnished by the Design Section.

Horizontal and Vertical Dispersion Parameters

The horizontal and vertical dispersion parameters are used in the mathematical model to characterize the transport and dispersion of pollutants for different meteorological conditions.

These dispersion parameters are a measure of the surface stability of the atmosphere which greatly influences the ground level concentrations. Figures 86 and 87 in Appendix* are plots of the vertical and horizontal dispersion parameters. The use of these parameters is illustrated in Example 2.

The following describes the input data layout required by the program:

Card Number 1 (Always Required)

Punch an X in card column 1 to select the cross wind calculations. Punch a P in card column 2 for parallel wind calculations. Punch an X and a P in the respective columns for both calculations.

Card Number 2 (Cross wind input data) (All data right justified)

Card Columns	Format	Symbol	Description
1-10	F10.0	VPH	Vehicles per hour
11-15	F 5.0	EF	Emission Factor (Grams per mile)
16-20	F 5.0	U	Wind speed (Miles per hour)
21-25	F 5.0	PHI	Wind angle (Degrees)
26-30	F 5.0	H	Pavement Height (Feet)
31-35	F 5.0	Z	Receptor Height (Feet)
36-40	F 5.0	D	Distance from edge of Shoulder to receptor (Feet)
41-42	I 2	CLAS	Stability Class (1-6 = A-F)
43-51	F 9.0	MW	Molecular Weight of Pollutant
52-80		(Leave Blank)	

Card Number 3 (Parallel wind input data) (All data right justified)

Card Columns	Format	Symbol	Description
1-10	F10.0	VPH	Vehicles per hour
11-15	F 5.0	EF	Emission Factor (Gram per mile)
16-20	F 5.0	U	Wind Speed (Miles per hour)
21-25	F 5.0	PHI	Wind angle (Degrees)
26-30	F 5.0	H	Pavement height (Feet)
31-35	F 5.0	Z	Receptor height (Feet)
36-40	F 5.0	D	Distance from edge of shoulder to receptor (Feet)
41-42	I 2	CLAS	Stability Class (1-6 = A-F)
43-51	F 9.0	MW	Molecular Weight of Pollutant
52-60	F 9.0	DWD	Downwind distance from point where wind initially becomes parallel to highway (Feet)
61-69	F 9.0	W	Width of highway, shoulder to shoulder (Feet)
70-78	F 9.0	WDTH	Average width of cut (Average of top and bottom widths in feet)
79-80		(Leave Blank)	

OUTPUT

The output of the mathematical model is a series of curves (Figures 1 to 85 in Appendix).* These curves are a plot of the ground level concentration ratio CuK/Q versus the downwind distance. From these curves estimates of hourly concentrations of carbon monoxide can be made for the highway corridor region. These values are solely due to vehicle emissions and must be added to background concentrations to obtain total pollutant concentration levels.

*The appendix for this volume is published separately as Vol. 5. See note at foot of page v of this book.

These appendix curves are divided into four basic groups as described below:

Group 1: Appendix Figures 1 to 6 are for at grade sections where the wind is not parallel to the highway alignment.

Group 2: Appendix Figures 7 to 54 are for elevated sections, that is, fills, viaducts, and bridges where the wind is not parallel to the highway alignment.

Group 3: Appendix Figures 55 to 78 are for cut sections where the wind is not parallel to the highway alignment. These curves can be used to estimate the concentrations of pollutants generated by highways with shallow cuts. (Depth of cut $\leq$ 30 feet.)

Group 4: Appendix Figures 79 to 85 are for highway sections where the wind is parallel to the highway alignment.

The curves in Appendix Figures 7 to 54 indicate the theoretical relative difference in ground level concentrations for highways on elevated sections compared to at-grade sections. In these figures the curve for H=0 represents the at-grade section for winds not parallel to the highway alignment. Detailed field measurements are required to validate this reduction in ground level concentration for elevated sections, however, the relative effects can be seen from the curves. The same reasoning applies to the comparison between at-grade sections and cut sections shown in Appendix Figures 1 to 6 and Appendix Figures 55 to 78, where the winds are not parallel to the highway alignment and for different surface stability classes..

In Appendix Figures 1 through 78 where the winds are not parallel to the highway, the angle of intersection (Ø) between wind direction and the highway centerline has the following application:

Ø = 22.5° corresponds to angles from 12° to 33°

Ø = 45° corresponds to angles from 34° to 56°

Ø = 67.5° corresponds to angles from 57° to 78°

Ø = 90° corresponds to angles from 79° to 101°

Appendix Figures 79 through 85 (where the winds are parallel to the highway alignment) are used where the angle of intersection (Ø) between the wind direction and highway centerline is less than 12°.

Figure 1 illustrates the wind direction and ranges.

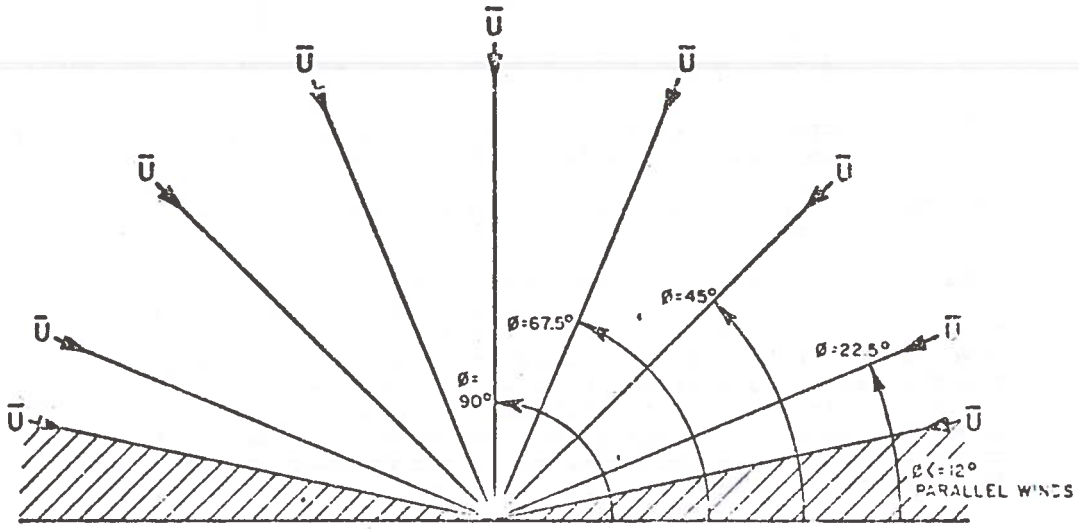

Fig. 1 ANGLE OF INTERSECTION BETWEEN WIND DIRECTION AND HIGHWAY ALIGNMENT IN DEGREES

The variables* on the curves in the Appendix are:

C = Concentration of pollutant in grams per cubic meter (gm/m^3)

$\bar{U}$ = Mean surface wind speed (m/sec)**

Q = Emission source strength $\frac{gm}{sec}$ (winds parallel)

and

$\frac{gm}{sec\text{-}m}$ (winds not parallel)

K = Empirical coefficient determined by field measurements

Until sufficient data become available from the Division of Highways research project [10] assume K = 4.24 on all curves.

The system of units for concentrations should be consistent with the California Air Quality Standards in parts per million by volume or the Environmental Protection Agency Standards in micrograms per cubic meter. The following equations convert the concentration from the curves in grams per cubic meter to parts per million by volume based on a reference temperature of 25°C and pressure of 760 mm of mercury, and from grams per cubic meter to micrograms per cubic meter.

$$ppm = \mu g/m^3 \frac{(0.0245)}{M.W.} \quad (1)$$

Where ppm = Concentration of pollutant in parts per million by colume

$\mu gm/m^3$ = Concentration of pollutant in micrograms per cubic meter

$$1\ \mu gm/m^3 = 10^{-6}\ gms/m^3 \quad (2)$$

M.W. = Molecular weight of the pollutant.

*All units used in the model equations are in the metric system.

**$\bar{U}$ is representative of the undisturbed air flow measured at a height of 10 meters above the ground surface over flat level terrain or modified for surface roughness as defined in reference [5].

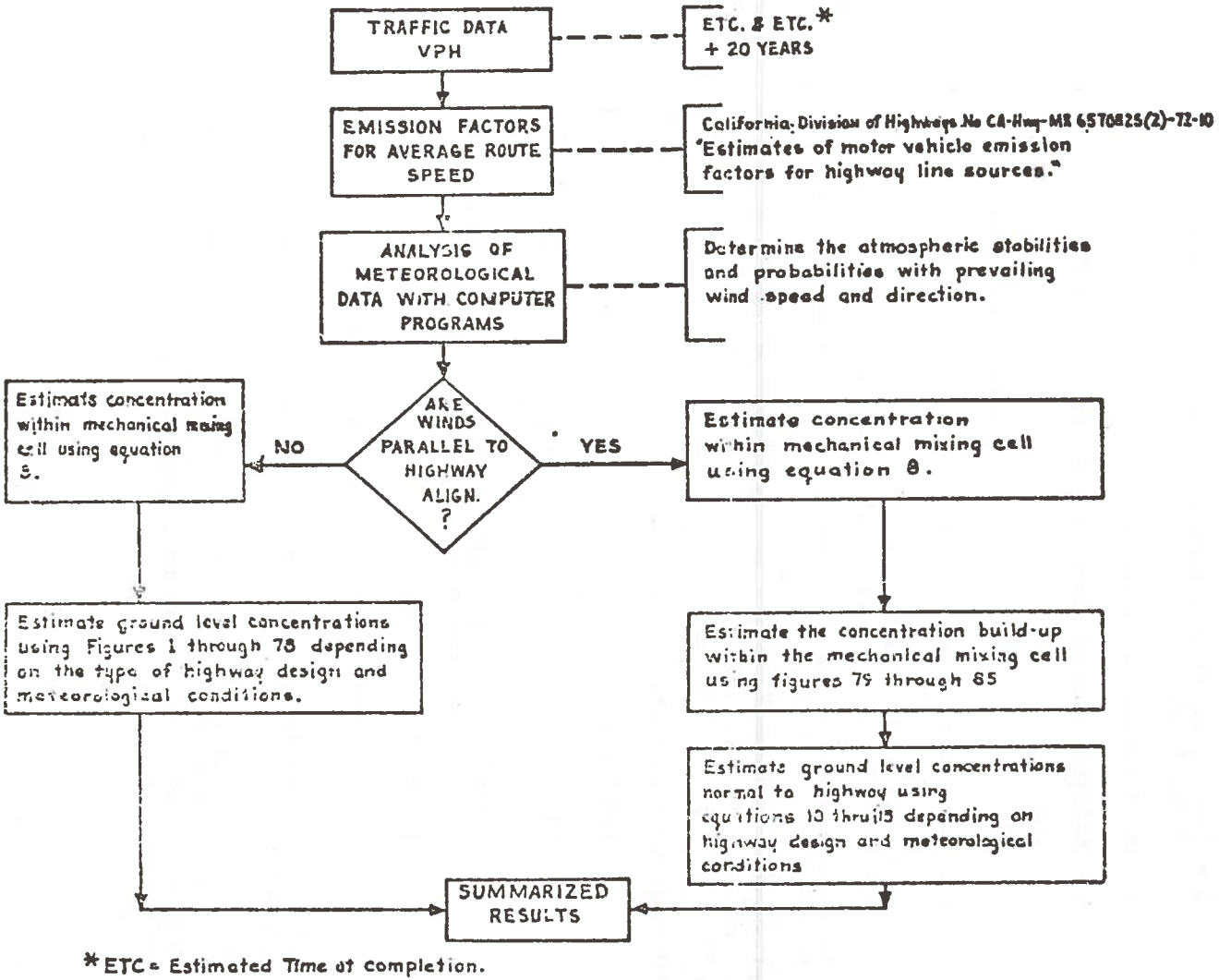

Fig. 3. Systems flow chart for highway line source dispersion model.

SUMMARY

The mathematical analysis of the impact of a highway on the environment requires two analyses: (1) corridor analysis and (2) mesoscale analysis. In the corridor analysis, special consideration is given to estimating the CO pollutant concentrations from the highway to the point downwind where ambient levels are again approached. The mesoscale analysis emphasizes the "air basin concept". This analysis evaluates the effects of the proposed highway on general community air quality. Consideration is limited, at the present, to two primary gaseous pollutants emitted from motor vehicles namely CO and HC.

At the present time the California Division of Highways has concentrated most of its efforts in developing and validating a mathematical model for the highway corridor region. More extensive work with actual field measurement of pollutant concentrations will be made in the future to develop and statistically validate regional models to supplement the present mesoscale analysis.

Figures 14 and 15 are generalized flow charts for the corridor and mesoscale analysis along with the required inputs.

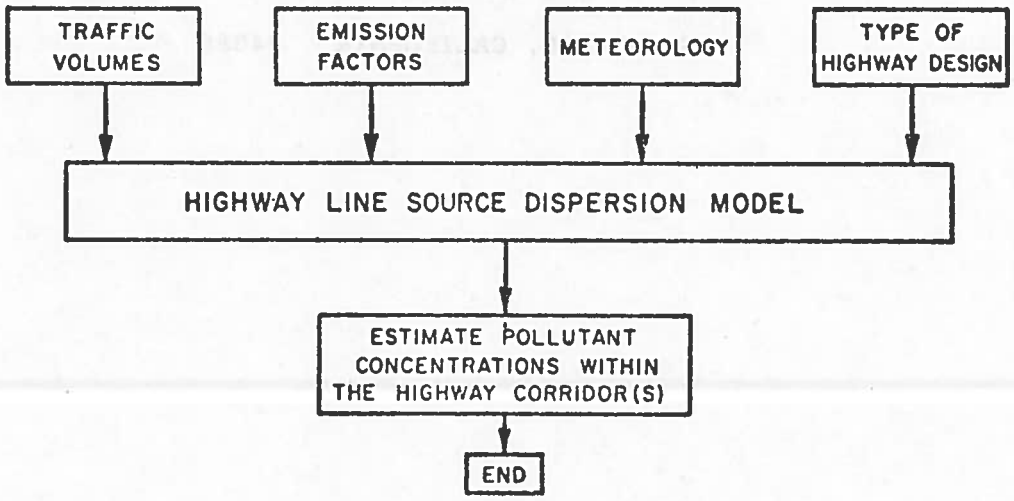

Fig. 14 FLOW CHART FOR CORRIDOR ANALYSIS

C.2 ENVIRONMENTAL SYSTEMS LABORATORY (ESL)

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ESL-ET79
August 1974

ESL HIGHWAY MICROSCALE DISPERSAL MODEL

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ESL HIGHWAY MICROSCALE DISPERSAL MODEL

The ESL Highway Microscale Dispersal Model has been designed to provide accurate and rapid calculations of air pollutant (non-reactive gases and particulates) concentrations from highway traffic. The model has been calibrated and validated using field measurements of carbon monoxide and particulates (especially lead). In the model, the fundamental Gaussian dispersal equation is employed to calculate atmospheric diffusion and transport. A formulation of this type provides for rapid computer calculations which require a minimum amount of computer storage capacity. Readily available tabulations of the error function and the normal cumulative distribution function are employed in the model. For convenience the model requires only the normally available traffic, geometric, and meteorological parameters:

1. Traffic Data (vehicle classification mix, age mix, and speed)

2. Roadway Geometry (cut, at-grade, elevated - distance between roadway surface and ground)

3. Meteorological Conditions (calm or definite wind speed, wind direction, and Pasquill Turbulence Classification).

NOTE: In contrast to many Gaussian Models, the ESL model accepts calms and winds parallel to the roadway.

In addition to the above parameters, highway air pollution dispersal involves such processes as the mechanical generation of turbulence by high-speed vehicles and the absorption of vehicular emissions by the ground. The ESL model incorporates these effects as described below.

Model Description.

The ESL model uses the fundamental Gaussian plume model for a continuous elevated non-reactive point source to calculate the dispersal, transport, and precipitation of vehicular emissions in the atmosphere near the roadway. The general form of this equation, using the coordinate system described in Figure 1, is:

$$\bar{\chi}(x,y,z) = \frac{Q}{2\pi\bar{u}\sigma_y(x)\sigma_z(x)} \exp\left\{-\frac{y^2}{2\sigma_y(x)^2}\right\} \times \left\{\exp -\frac{(z-h)^2}{2\sigma_z(x)^2} + \gamma \exp -\frac{(z+h)^2}{2\sigma_z(x)^2}\right\} \quad \text{(grams/cubic meter)}$$

Where: $\bar{\chi}$ = mean concentration (grams/cubic meters)

$\bar{u}$ = mean wind speed (meters/second)
(Note: Wind speed is considered parallel to X axis).

Q = emission rate (constant, grams/second)

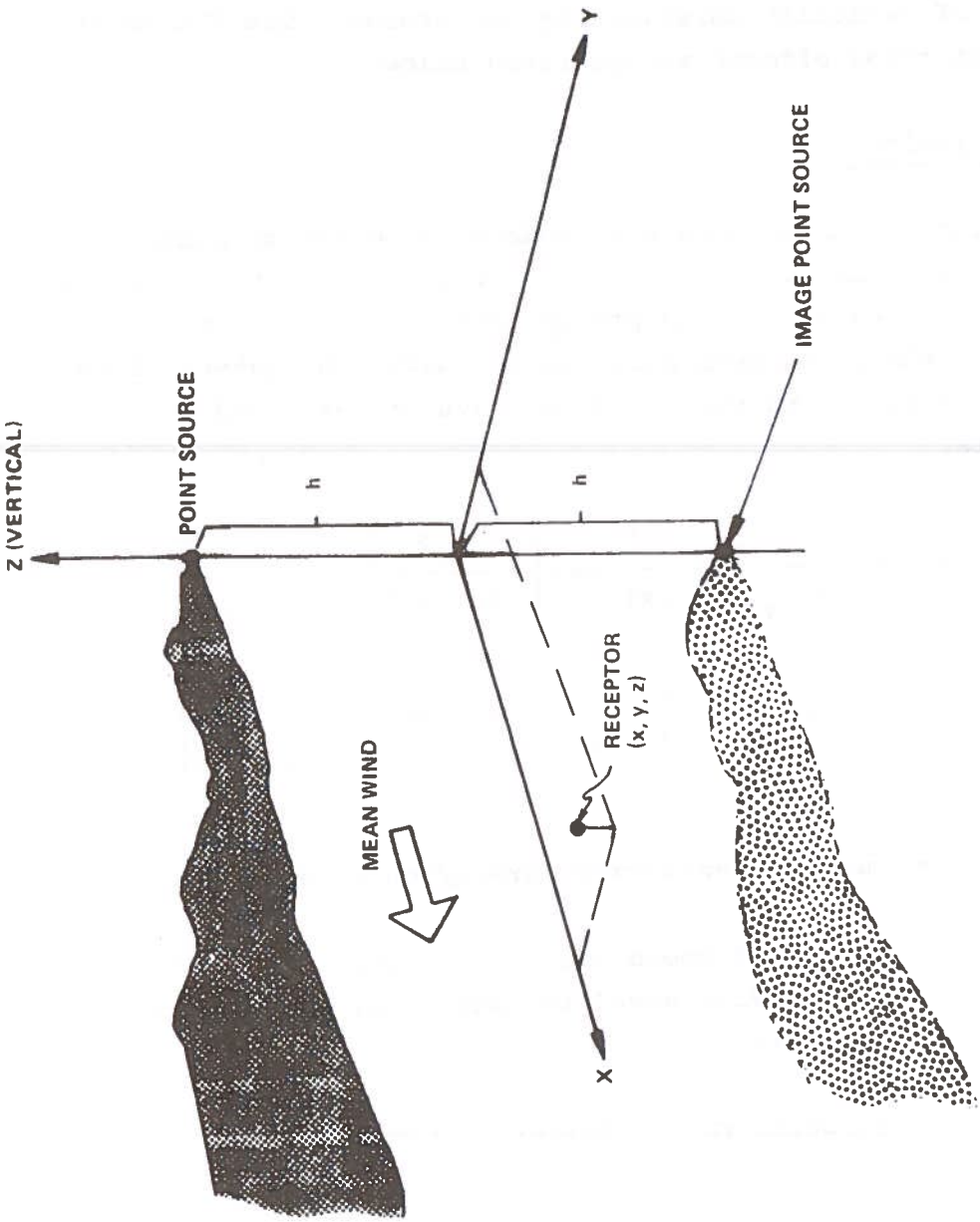


Figure 1. Point Source

h = source height (meters)

γ = absorption coefficient ($\gamma = 1.0$ indicates non-absorbing ground surface)

$\sigma_x(x), \sigma_z(x)$ = standard deviations of lateral and vertical relative concentrations distributions, respectively (meters)

In order to apply the above equation to the highway dispersal problem, the functions $\sigma_x(x)$ and $\sigma_z(x)$ must be defined. The ESL model utilizes the following functions reported in "Meteorology and Atomic Energy" (Clifford, U.S. Atomic Energy Commission, July 1968):

$$\sigma_y(x) = \frac{\sigma_\theta}{1.23} X \qquad \sigma_z(x) = \frac{\sigma_\phi}{1.23} X$$

The σ_θ and σ_ϕ parameters can either be assigned by field measurements or the Pasquill Turbulence Classification.

The high-speed highway vehicular traffic generates mechanical turbulence which rapidly disperses vehicular emissions throughout a volume over the roadway surface. In simplest terms, the cross section of this volume (or mixing cell) is rectangular in shape with a height Δh and width equal to the roadway. This mixing cell is also assumed to extend along the entire length of the roadway. The vehicular pollutants, then, are assumed to elude from a screen which is the downwind vertical side of the

mixing cell; thus, the screen is located at the downwind edge of the roadway with the height of the mixing cell (Δh) and length of the roadway. For at-grade and elevated roadways, the screen base is placed at the roadway level; however, for cut roadways, the screen base is placed at ground level (but over the downwind roadway edge). Figure 2 diagrams this geometric configuration. The ESL model is then developed by assuming the vehicular emissions elude uniformly from the screen; therefore, the screen can be considered to consist of an infinite array of point sources. The concentration at a receptor point from each point source is calculated by using the Gaussian equation. Consequently, the sum of concentrations from all these point sources is the concentration from the screen. Mathematically, the summing process reduces to integrating the Gaussian equation over the screen. If the receptor point is close to the roadway, the roadway can be considered infinite in length; then, the integration along the length of the screen can be performed analytically to yield:

$$\bar{\chi} = \int_{h_o}^{h_o+\Delta h} \frac{q}{4\pi\bar{u}} \sum_{A=z_o-h,\,z_o+h} \gamma_A \sqrt{\frac{2\pi}{0.661\sigma_\phi{}^2 D^2 + 0.661\sigma_\theta{}^2 A^2 \cos^2\alpha}}$$

$$\times \exp\left[\frac{-A^2 \sin^2\alpha}{2\left(0.661\sigma_\phi{}^2 D^2 + 0.661\sigma_\theta{}^2 A^2 \cos^2\alpha\right)}\right]$$

$$\times \left(1 + \operatorname{erf}\left[\frac{0.813\sigma_\phi D \tan\alpha}{\sqrt{2}\ 0.813\sigma_\theta\left(0.661\sigma_\phi{}^2 D^2 + 0.661\sigma_\theta{}^2 A^2 \cos^2\alpha\right)}\right]\right) dh$$

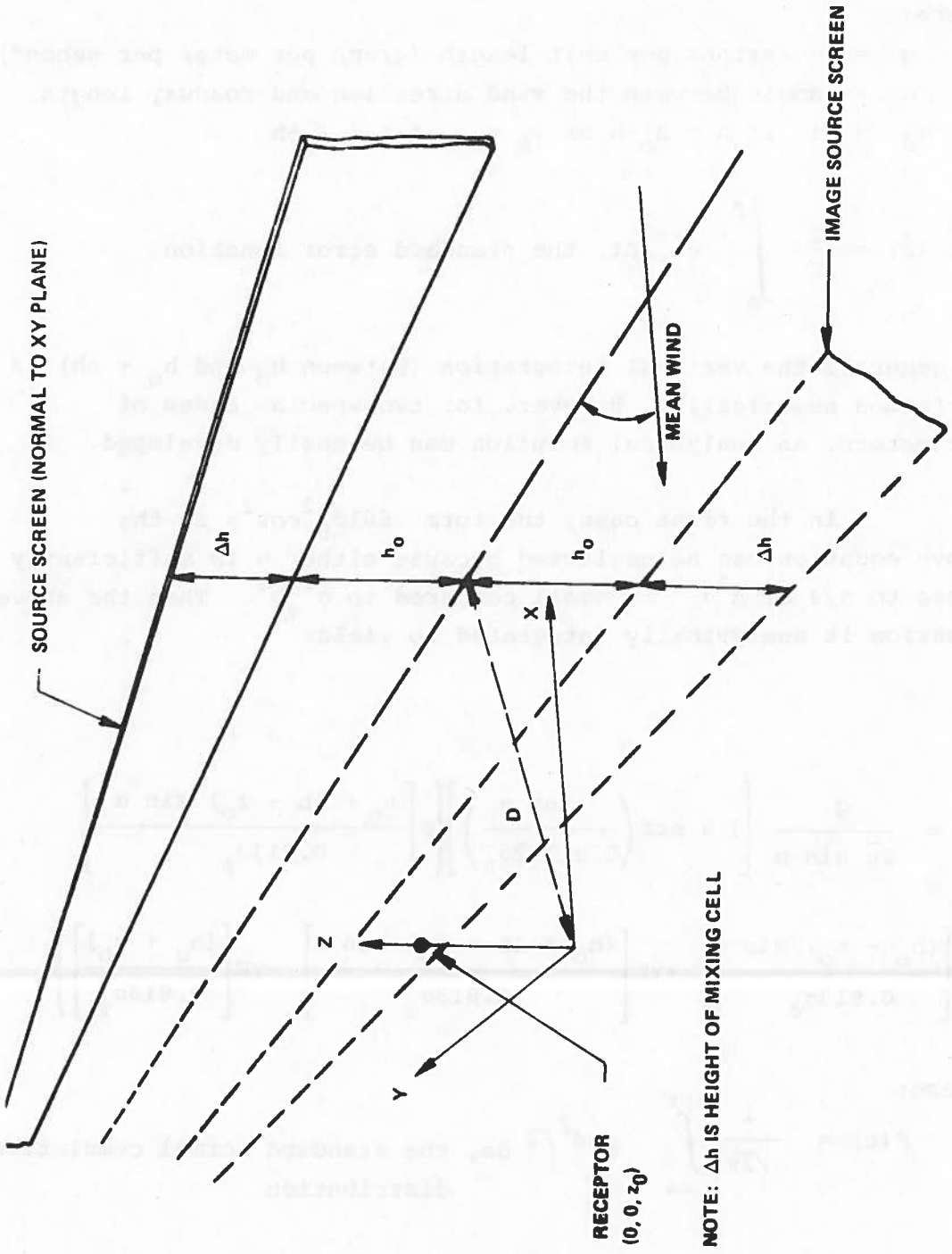


Figure 2. Infinite Vertical Strip Source Above XY - Ground Plane

Where:

q = emissions per unit length (grams per meter per second)

α = angle between the wind direction and roadway length

γ_A = 1 if $A = Z_o - h$ or $\gamma_A = \gamma$ if $A = Z_o + h$

$$\text{erf}\ (Z) = \frac{2}{\sqrt{\pi}} \int_o^Z e^{-t^2}\, dt, \text{ the standard error function}$$

In general, the vertical integration (between h_o and $h_o + \Delta h$) is performed numerically. However, for two special cases of parameters, an analytical solution can be easily developed.

In the first case, the term $.661\sigma_\theta^2 \cos^2\alpha$ in the above equation can be neglected because either α is sufficiently close to $\pi/2$ or $A^2\sigma_\theta^2$ is small compared to $\sigma_\phi^2 D^2$. Then the above equation is analytically integrated to yield:

$$\bar{\chi} = \frac{q}{2\bar{u} \sin\alpha}\left[1 + \text{erf}\left(\frac{\tan\alpha}{0.813\sqrt{2}\sigma_\theta}\right)\right]\left\{F\left[\frac{(h_o + \Delta h - z_o)\sin\alpha}{0.813\sigma_\phi}\right]\right.$$

$$\left. -F\left[\frac{(h_o - z_o)\sin\alpha}{0.813\sigma_\phi}\right] + \gamma F\left[\frac{(h_o + \Delta h + z_o)\sin\alpha}{0.813\sigma_\phi}\right] - \gamma F\left[\frac{(h_o + z_o)}{0.813\sigma_\phi}\right]\right\}$$

Where:

$$F(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} e^{-s^2/2}\, ds, \text{ the standard normal cumulative distribution}$$

In the second case if $\alpha = o$, the equation is also analytically integrable to yield:

$$\bar{\chi} = \frac{q}{2\sqrt{2\pi}u}\left[\ln\left(\frac{h_o + \Delta h - z_o + \sqrt{\left(h_o + \Delta h - z_o\right)^2 + 0.661\sigma_\phi{}^2 D^2}}{h_o - z_o + \sqrt{\left(h_o - z_o\right)^2 + 0.661\sigma_\phi{}^2 D^2}}\right)\right.$$

$$\left. +\gamma \ln\left(\frac{h_o + \Delta h + z_o + \sqrt{\left(h_o + \Delta h + z_o\right)^2 + 0.661\sigma_\phi{}^2 D^2}}{h_o + z_o + \sqrt{\left(h_o + z_o\right)^2 + 0.661\sigma_\phi{}^2 D^2}}\right)\right]$$

Application of the Model.

In order to apply the model, it is necessary to define the following parameters for one of the three above mathematical equations:

traffic related: q -- emissions per unit length per unit time

Δh -- height or mixing cell

roadway-related: h_o -- distance between the roadway surface and the ground

pollutant-related: γ -- absorption coefficient

meteorological: $\bar{u}$ -- wind speed

α -- angle between the wind direction and roadway

$\sigma_\theta, \sigma_\phi$ -- horizontal and vertical wind direction variancies, respectively

ESL has applied the model to predict air pollution dispersal from highways in over six states geographically distributed throughout the nation. What follows is the methodology developed and employed to calculate the above parameters. For some of these parameters, in particular Δh, the assigned value is based entirely on experimental field data. These parameters have been found to vary among the various locations; however, in the absence of local data, typical values can be assigned.

Regarding traffic related parameters, the value of q is calculated by using the methodology described in the U.S.E.P.A.'s publication: "Compilation of Air Pollutant Emission Factors" (AP-42). The value of Δh has been determined by regression analyses utilizing field data to be approximately 10 feet; thus, this value is inserted in the absence of local data.

Regarding the roadway related parameter, the value of h_o is simply taken as the difference between the road height and the mean ground level for elevated and at grade roadways. For cuts, h_o is set equal to zero (i.e., the emitting screen is placed at ground level above the roadway surface).

Regarding the pollutant-related parameter, the value of γ for carbon monoxide is taken as unity. This assignment has been extensively verified by field tests. Since carbon-monoxide is essentially unreactive the absence of absorption is expected. Because the chemical reactions of other gaseous pollutants are relatively slow, in previous studies, ESL has assumed that the unity assignment would apply to hydrocarbons and total nitrogen oxides. However, in the case of particulates, the value γ has been observed to be approximately 0.5; thus, this value is applied in the absence of other data.

Regarding the meteorological parameters, there are two types of meteorological situations which must be addressed:

(1) A meteorological situation in which there is a definite wind speed, wind direction and Pasquill Turbulence Class.

(2) A meteorological situation which is simply described as a calm (i.e., there is no definite wind, and existing air movements are erratic and slow).

Assignment of meteorological parameters in the first situation is relatively straight forward. The actual (or assumed) wind speed ($\bar{u}$) and direction (α) are applied. Using the methodology in the "Workbook of Atmospheric Dispersion Estimates" Bruce Turner 1970, the actual (or assumed) Pasquill Turbulence Class is employed to assign values for σ_θ and σ_ϕ.

Assignment of the meteorological parameters in second situation relies on experimental field data. From validation data which was acquired under very calm meteorological conditions at the bottom of a valley, a regression analysis indicates that the following parameters, when they are substituted into the model equations, accurately calculate the concentrations: $\bar{u} = 0.7$ meters per second, $\gamma = 90°$, and σ_θ and σ_ϕ correspond to the Pasquill Turbulence Class C.

Validation Data.

Under contract to various highway departments throughout the nation, ESL has acquired extensive sets of carbon monoxide and particulate (especially lead) validation data. The majority of this data was acquired using multiple air bags which were simultaneously and automatically filled over a specified time period; during this time period, meteorological and traffic data were also concurrently acquired. The contents of the air bags were analyzed for their carbon monoxide concentration using a gas chromatograph.

Figure 3 shows a typical arrangement of the equipment employed for the measurement of carbon monoxide levels near the roadway. Figures 4 and 5 are photographs of this particular experimental site. Normally such air bags were filled using "Star" Aquarium pumps with a needle valve and bleeder in the output from the pump to the air bag as shown in Figure 6. With different adjustments of the valve, the air bags can be filled in as little as 5 minutes or as long as two hours. Aluminized "Scotch-Pak" bags were used to collect the atmospheric samples.

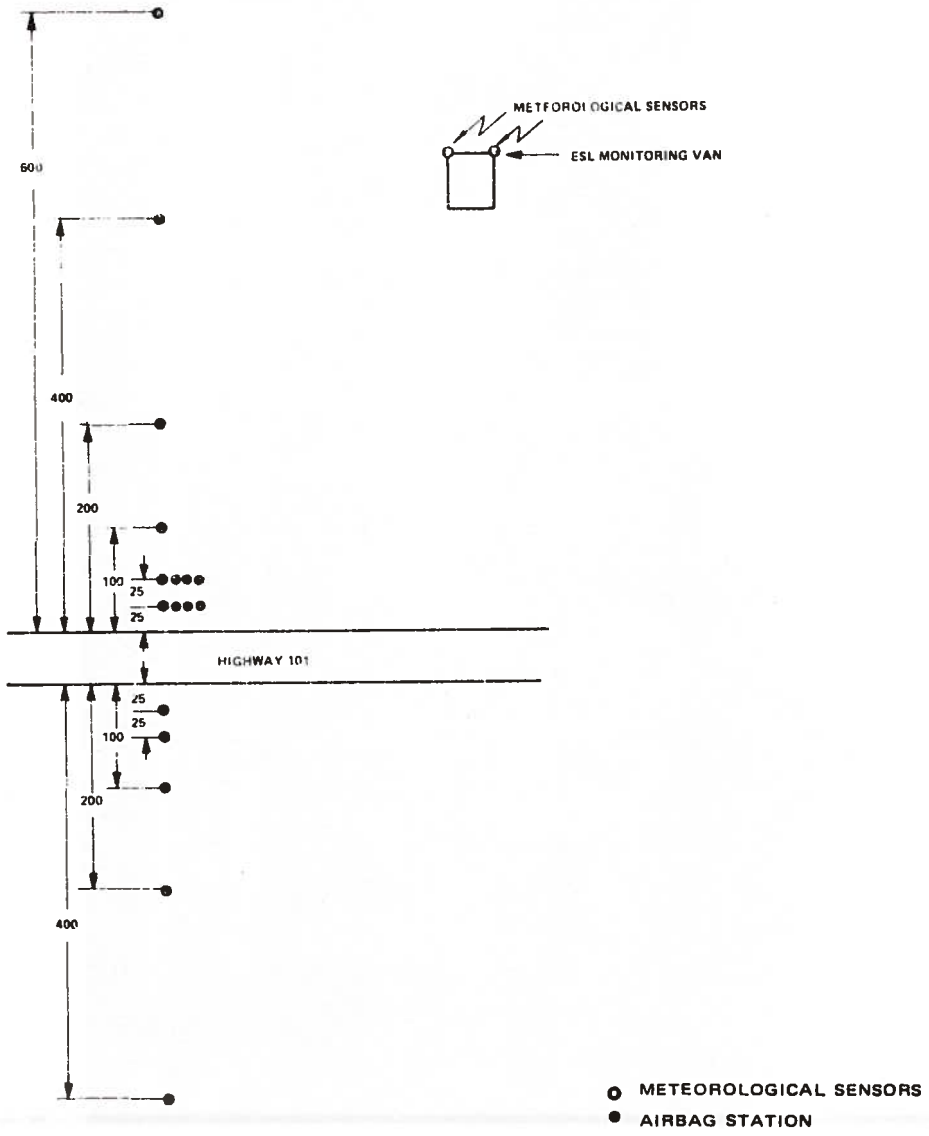
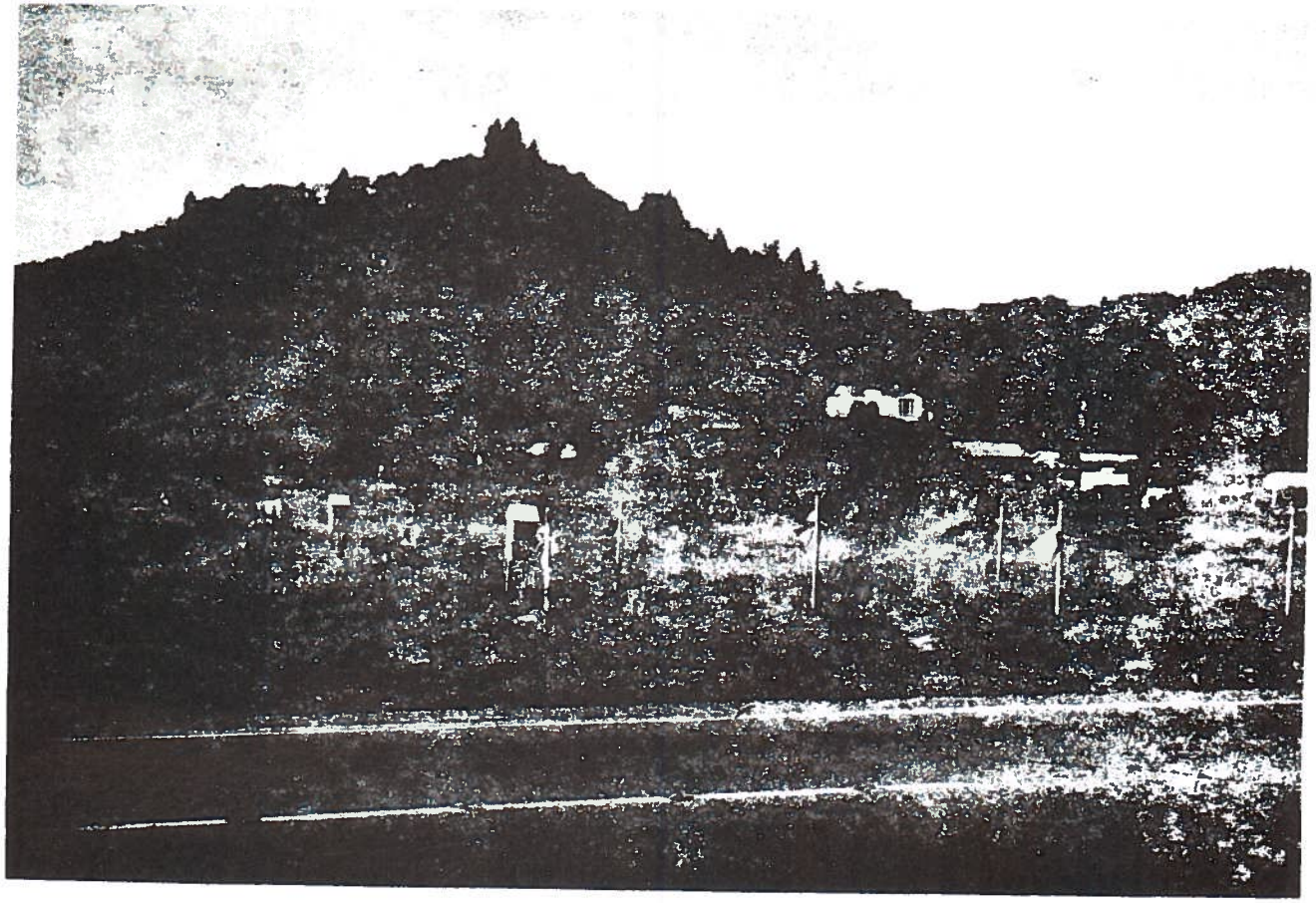


Figure 3. Diagram of a Typical Open Roadway Validation Experiment



NOTE: These remotely controlled air bag samplers and hivols were used in the Field Experiment in Cloverdale, California by Highway 101.

Figure 4. Photograph of Typical Validation Experiment

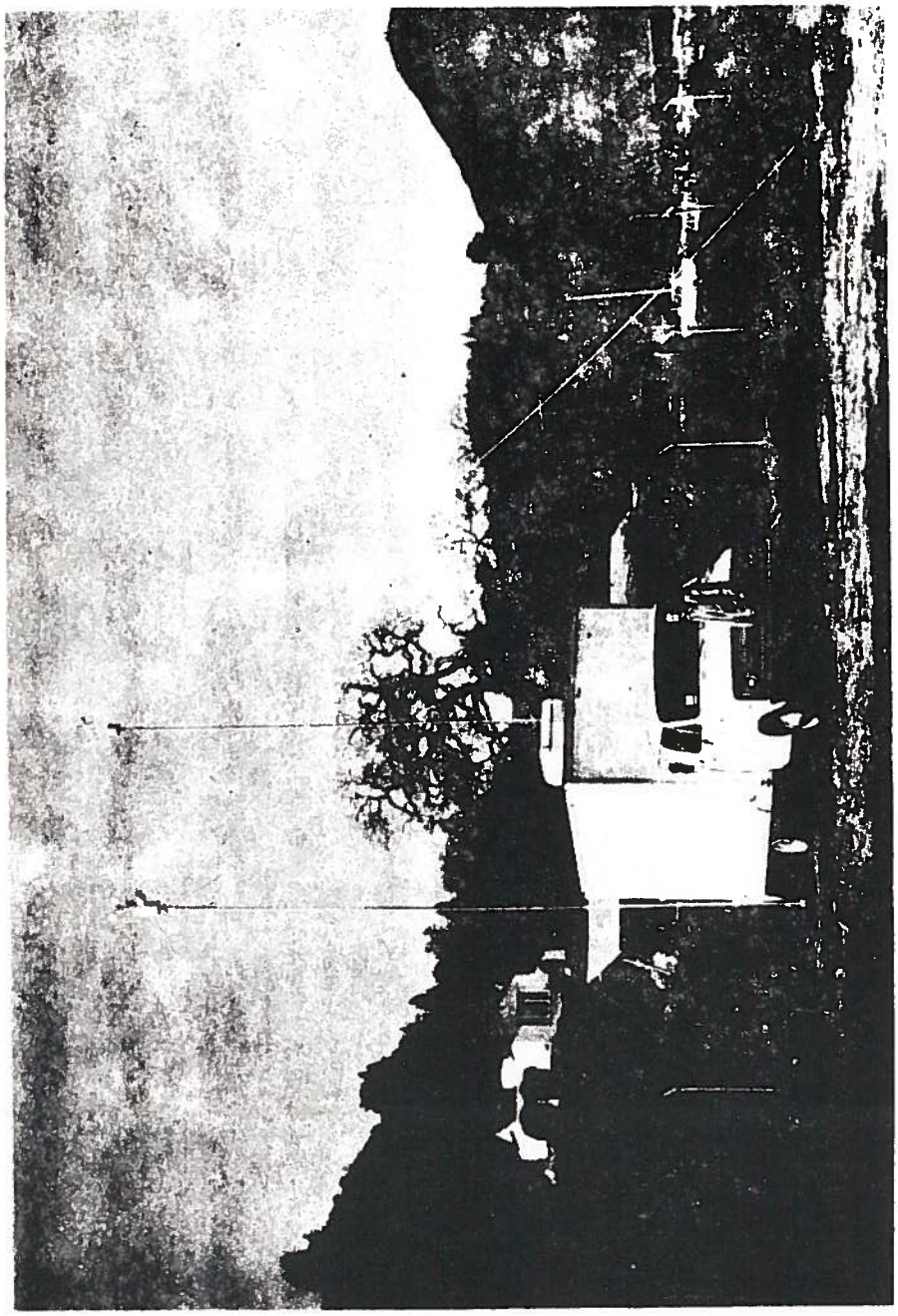


Figure 5. ESL Mobile Van Equipped With Gas Chromatograph

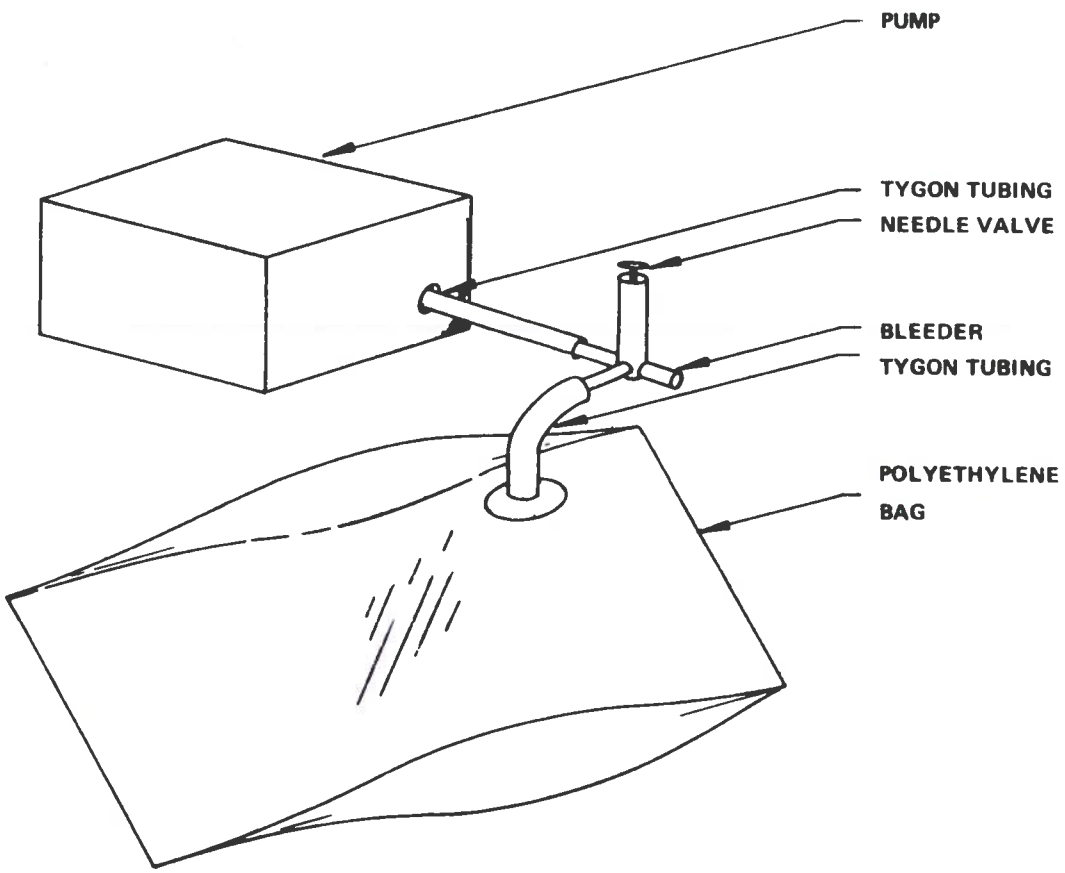


Figure 6. Diagram of Air Bag Pump

Most validation sets of air bags which have been employed in model validation and calibration efforts were filled in approximately 60 minutes. This time period was selected in order to assure that the variance in the concentration measurement from statistical fluctuations in atmospheric dispersal characteristics and traffic emissions would be small compared to the mean values. The good agreement observed between similar data sets and the nearly identical concentrations measured from air bags located at the same distance from the roadway indicate that these conditions were achieved.

The array of air bags was designed to measure several critical parameters. Air bags were located at distances up to 600 feet from the roadway. Bags were located on both sides of the roadway in order to obtain a good estimate of "upwind" background levels and to examine the levels on both sides of the roadway during calm or nearly parallel winds. In addition, several bags were located at the same distance from the roadway but displaced from each other by 3 meters (10 feet) parallel to the roadway. The purpose of these bags is to determine the reliability and variance associated with the measurements. Also, such measurements provide a test on the uniformity of levels parallel to the roadway.

Figure 7 describes a sample of a set of validation data. The error bars describe plus and minus one standard deviation of variance associated with the bags parallel to the roadway. As can be seen in the figure, in this particular situation concentrations measured were less than or equal to 1 mg/m^3 (or 1 ppm) of carbon monoxide. A gas chromatograph was used to

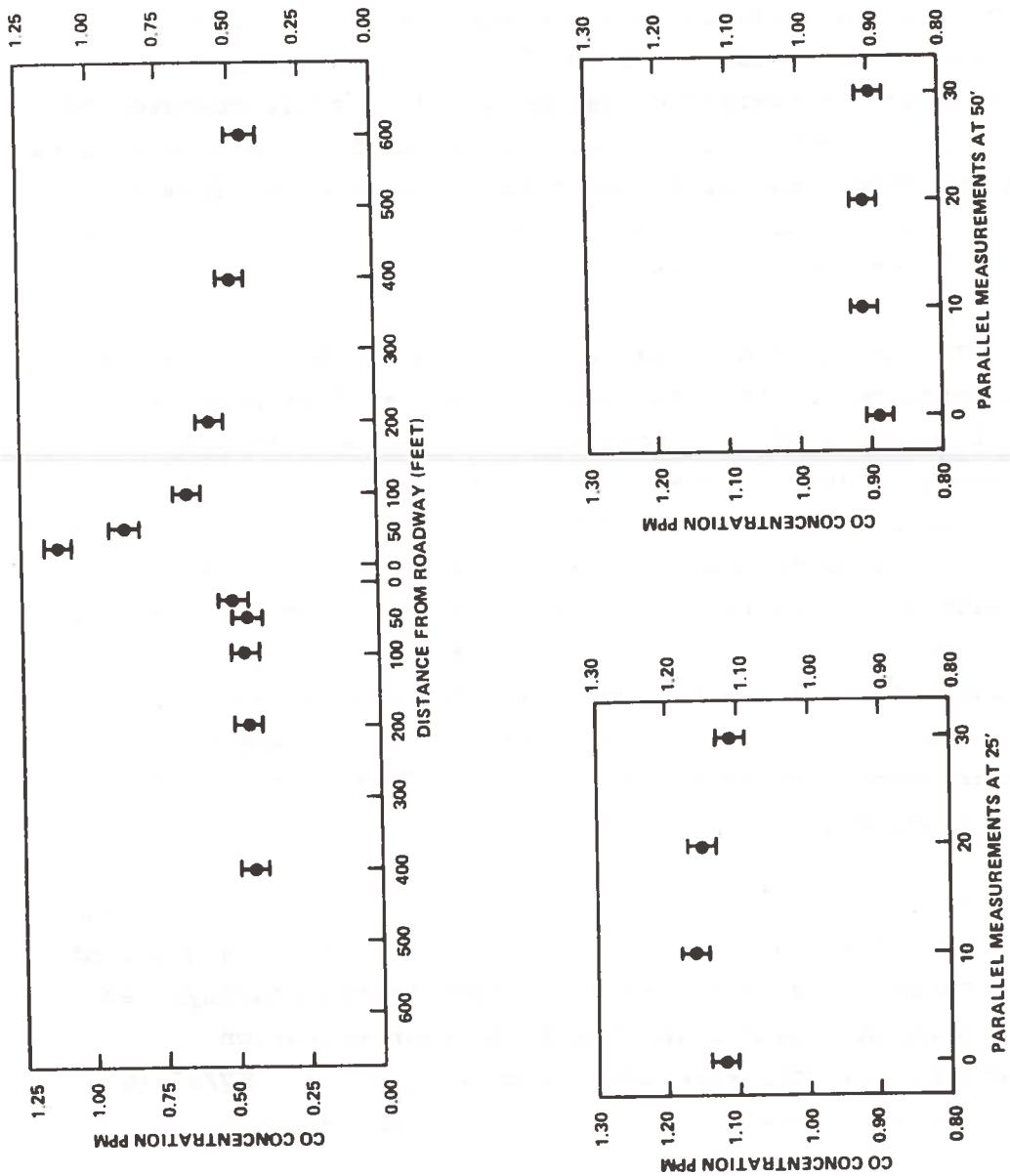


Figure 7. Sample Set of Validation Experimental Data

accurately measure these low concentrations. The gas chromatograph (Beckman Model 6800) measured relative concentrations which were accurate to within 2%. The absolute accuracy was limited to the accuracy of calibration gases. Concurrently with the air bag collection, Hi Vols-were operated at various distances from the roadway to collect particulate validation data.

Least-squares analyses utilizing validation data obtained in this fashion were performed in order to determine the values of the empirical parameters (in particular Δh and γ) and validate the ability of the model to accurately calculate pollutant concentrations near the highway from highway traffic. Figures 8, 9 and 10 are typical comparisons of the model calculations and the measured concentrations for the three major roadway geometric configurations. As seen in these figures, the ESL model accurately calculates concentrations of air pollutants near the roadway.

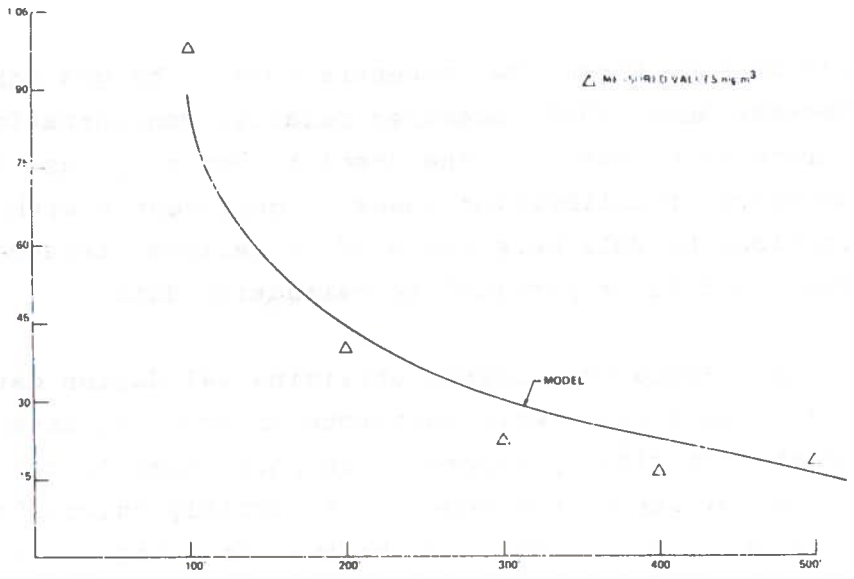


Figure 8. In Cut Highway Configuration

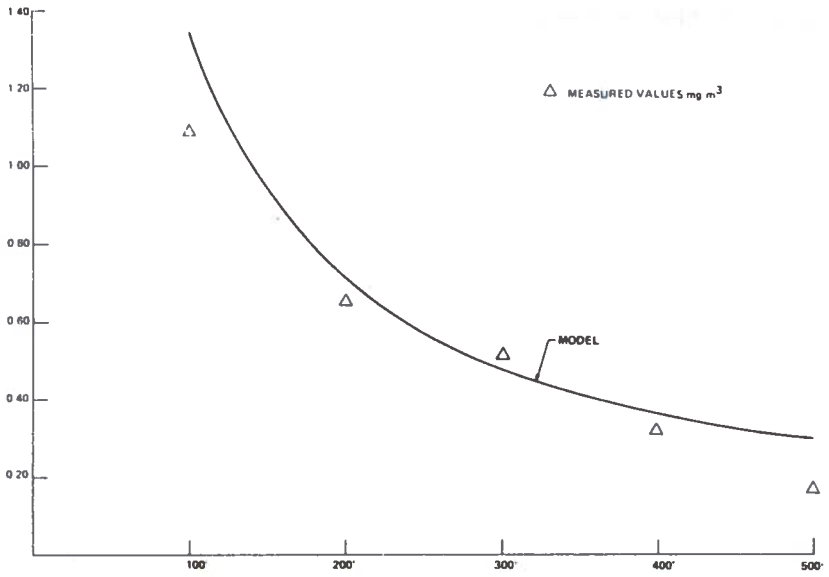


Figure 9. At Grade Highway Configuration

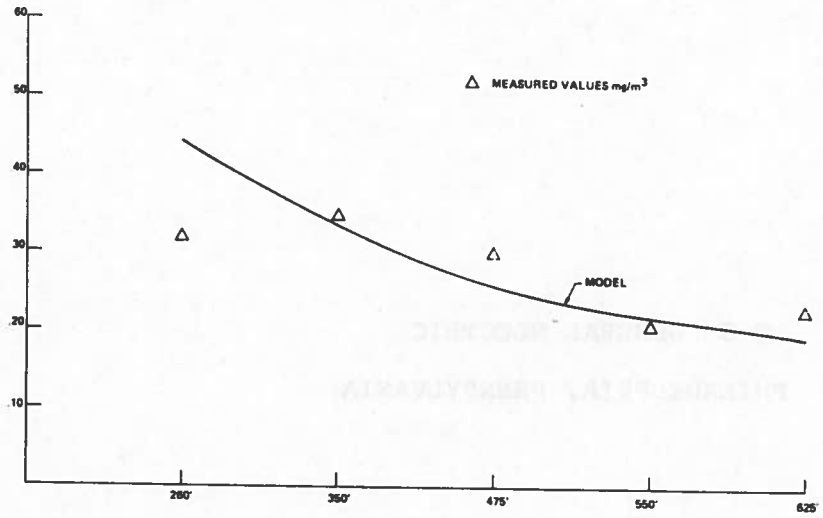


Figure 10. Elevated Highway Configuration

C-3 GENERAL ELECTRIC

PHILADELPHIA, PENNSYLVANIA

The G.E. Model

The model was developed by the General Electric Company under a contract with the City of New York.** The purpose of this contract was to produce a model for predicting air quality (i.e. CO concentrations) in the immediate vicinity of various urban roadway configurations. The configurations studied were the following:

Covered on top, open on one side
Long tunnel, ventilated
Shallow Cut
Short tunnel, unventilated
Deep cut
Grade road
Cantilever cover
Viaduct
City street
Intermittent covered span

The G.E. Model assumes that the decrease in concentration of CO with height can be represented by the following exponential relationship:

$$C = \frac{\dot{M}N}{W(aD+V)} e^{-az} \qquad (1)$$

where $\dot{M}$ = pollutant emissions in mass per vehicle mile
$\dot{N}$ = traffic flow rate in vehicles per hour
a = a constant found to be .015 to .025 $ft.^{-1}$
W = width of the roadway

**Study of Air Pollution Aspects of Various Roadway Configurations, Final Report, New York City Contract No. 209624, General Electric Company, September 1971.

D = diffusion coefficient

V = wind velocity

z = height above vehicle exhaust plane

C = concentration of CO

If z is replaced by the radial distance ρ then (1) becomes:

$$C = CO_x \, e^{-a\rho} \tag{2}$$

where

$$CO_x = \frac{M\dot{N}}{W(aD+V)}$$

which is the concentration resulting from the xth line source.

ρ = the radial distance between the source and the receptor (the point at which the concentration is calculated).

This model was further refined by defining a vehicular pollution factor ϕ where:

$$\phi = \frac{CO_x}{N} = \frac{M}{W(aD+V)} \tag{3}$$

For eight of the ten highway configurations listed above (i.e. all except the tunnels), G.E. discovered that there is a strong linear relationship between ϕ and traffic speed. The regression relationship for the year 1971 was found to be:

$$\phi_i = \left[-0.51\ T_i + 26.9\right] \times 10^{-3} \ \frac{\text{ppm-hr}}{\text{vehicle}} \tag{4}$$

for 15 mph $\leq T_i \leq$ 49 mph

T_i = average traffic speed in lane i.

The total CO concentration at receptor R, CO_R, is then obtained by summing the contribution of the S road lanes:

$$CO_R = \sum_{i=1}^{S} \phi_i \dot{N}_i \, e^{-a\rho_{iR}} \tag{5}$$

C.4 THE RESEARCH CORPORATION OF NEW ENGLAND (TRC)

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WETHERSFIELD, CONNECTICUT 06109

1.0 INTRODUCTION

In 1970, TRC developed a mathematical model to describe the impact on air quality of vehicular emissions associated with proposed highways. Basically, this model consists of a digital simulation of traffic flow, a calculation of the amount and type of pollutants emitted using EPA approved emission factors, and a calculation of the expected distribution of pollutants for various wind conditions and atmospheric stabilities using a Gaussian line source diffusion model. The validity of this original model and its subsequent refinements has been periodically demonstrated by comparing the predictions of the model with the results of actual air quality sampling programs performed by TRC in proximity to existing roadways. However, it has always been considered essential to demonstrate that the predictions of the model are consistent with actual experimental observations recorded by independent agencies.

In this connection, TRC voluntarily took part in a state-of-the-art EPA demonstration survey in 1972. The purpose of that survey was to assess the effectiveness of prediction models in general by comparison of six independent air quality model calculations with carbon monoxide measurements recorded by EPA. Each of the six investigators was given data on highway dimensions, traffic volumes, emission factors, meteorological information and receptor locations for three at-grade highway configurations. Each of the investigators, in turn, exercised their particular model and reported the predicted CO concentrations at each receptor location to the EPA. Only after the results were reported

to EPA did each of the investigators learn the actual values for CO concentration measured by EPA. This study showed good correlation between the predictions of the TRC air quality model and the (EPA) experimental observations and, in fact, constituted the first independent demonstration of the validity of the TRC highway air quality model.

1.1 The TRC Model

The TRC Model consists of two computer simulation routines. The first is a traffic simulation, using as inputs the characteristics of the highway and numbers of automobiles. The second is the line source diffusion model. The simulation model[1] uses EPA emission factors and speed correction curves to determine emissions for the highway by segments. The segment lengths are chosen to be appropriate to the highway being studied and are usually 1000 feet in length, or a factor of 1000 feet. The use of the traffic simulation model results in a more precise emission inventory of the pollutants with time of day. This more precise input to the line source diffusion model results in more precise predicted concentrations on the rationale that the quality of the output of any model is a function of the quality of the input to that model.

The computer routine which provides a line source diffusion model of the air quality is based on the line source described in Turner's workbook on atmospheric dispersion.[2]

$$\chi(x,0,0;H) = \frac{2Q_o}{\sqrt{2\pi}\,\sigma_z\,u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \int_{y_1/\sigma_y}^{y_2/\sigma_y} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{p^2}{2}\right) dp \qquad (-1)$$

where χ = concentration (grams/cubic meter)

Q_o = rate of emissions per unit length of road (grams/sec/meter)

x = downwind distance from the line source (meters)

H = height at which emissions occur; zero for ground releases (meters)

u = average wind speed perpendicular to the line source (meters/second)

σ_z = vertical dispersion coefficient (meters)

σ_y = horizontal dispersion coefficient (meters)

p = an integration variable

y_1 and y_2 are the coordinates of the ends of the line source

$(y_2 - y_1) = L$ = length

Concentration sums for the individual segments represent the net concentration at any given point with respect to its interrelationship with all other segments.

For a specific study, each study highway is subdivided into 1000 foot segments, or multiples of 1000 feet. The emission rate per unit length of road is directly applicable only for the case in which the prevailing wind is perpendicular to the line source (highway segment). When the wind is at an oblique angle to the segment, a deduced effective segment is applied. This is done by multiplying the initial 1000 foot long segment by the cosine of the angle between the oblique wind and a wind orthogonal to the segment.

$$L_{eff} = 1000 \cos \theta \qquad (-2)$$

where θ = angle between the wind direction and the normal (perpendicular) to the line segment. To insure proper distribution over the entire segment length, each of the sources is strengthened by dividing by the same

cosine factor. Thus, source Q_o in equation (-1) above, is replaced by an effective source, $Q_{o_{eff}}$:

$$Q_{o_{eff}} = \frac{Q_o}{\cos \theta} \qquad (-3)$$

The model predicts concentrations at ten points along the perpendicular bisector of each highway segment. The locations vary in distance from 25 to 5000 feet downwind from the highway. These distances allow sensitive resolution of concentration isopleths close to the highway as well as allowing a good representation of concentrations far from the highway. Detailed resolution is not needed at long distances because the rate of change of concentrations with distance is less.

3.0 INPUT PREPARATION

3.1 Base Map

The first step of model input preparation is the construction of a base map. This is done to enable the use of grid coordinates to define the coordinate locations of the beginning and ending points of each of the highway segments. The grid coordinates are derived by constructing a uniform grid on a scale map of the highway. Figure 1 is a sample highway and Figure 2 is an example grid system overlay. Figure 3 illustrates the results of a superimposition. It should be noted that a North arrow appears in Figures 1 and 3. This is important in order that the orientation of the highway and grid system is known. (The angle between North and the direction of the x-axis [see Figure 3] is another of the inputs and is referred to as BSDIR in Section 4.0) When the step of establishing an overlay grid has been completed, it is a relatively simple procedure to read the x- and y-coordinate locations of the beginning and ending points of each of the road segments which were previously defined in the Highway Simulation. These x- and y-coordinates are an input to the model.

3.2 Title Card

Use the same title card as was used for the Highway Simulation. It should contain identification of the specific job for which 52 digits are available.

3.3 Pollutant to be Modeled

A two digit identification of the pollutant to be modeled specifying carbon monoxide as CO, hydrocarbon as HC, or nitrogen oxide

as NO_x, will be entered in digits 1, 2, or 1, 2, 3 of 3 - Data Card.

3.4 Hour of the Day

One of the hours run in the Highway Simulation can be indicated by using digits 8, 9 for values 1 to 12 (digit 9 for 1 digit numbers) and digits 10 for AM or PM hours (use A or P). This entry is made on 3 - Data Card.

3.5 Atmospheric Stability Class (One of the Pasquill Classes, 1 through 6)

The values of σ_y and σ_z vary with the turbulent structure of the atmosphere, height above the surface, surface roughness, sampling time over which the concentration is to be estimated, wind speed, and distance from the source. For the parameter values given here, the sampling time is assumed to be about 10 minutes and the height to be the lowest several hundred meters of the atmosphere. The turbulent structure of the atmosphere and wind speed are considered in the stability classes presented, and the effect of distance from the source is considered in the graphs determining the parameter values. Values for σ_y and σ_z are estimated from the stability of the atmosphere, which is in turn estimated from the wind speed at a height of about 10 meters and, during the day, the incoming solar radiation or, during the night, the cloud cover (Pasquill, 1961). Stability categories (in six classes) are given in Table 1. Class 1 is the most unstable, class 6 is the most stable class considered here. Night refers to the period from 1 hour before sunset to 1 hour after sunrise. Note that the neutral class, 4, can be assumed for overcast conditions during day or night, regardless of wind speed.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies; "slight" insolation corresponds to a solar altitude from 15° to 35° with clear skies. Table 170, Solar Altitude and Azimuth, in the Smithsonian Meteorological Tables (List, 1951) can be used in determining the solar altitude. Cloudiness will decrease incoming solar radiation and should be considered along with solar altitude in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds.

3.6 Wind Speed

The wind speed in meters per second selected as the average for the hour being run will be entered in digits 16 to 20 of 3 - Data Card. Entries can be made in whole units or decimal parts right justified.

3.7 Emission Height of Road Segment

The height of road segment above grade in whole meters will be entered in digits 41 to 50 of 5 - Data Card with the entry being right justified.

3.8 Wind Direction

The wind directions for which the model is to be run will be entered on 6 - Data Card. The directions are 0 to 360 degrees in whole units or decimal parts, right justified.

3.9 Emission Rate Changes

If it becomes necessary to change the emission rates generated by the Highway Simulation due to new sources, the Highway Air Quality

Model offers the option of adding algebraically a delta emission rate value in grams/hour to the particular segment or segments influenced by the new sources. Emissions from other sources can be deleted in a similar manner.

The specific manner in which these inputs are transmitted to the model is discussed in the next section.

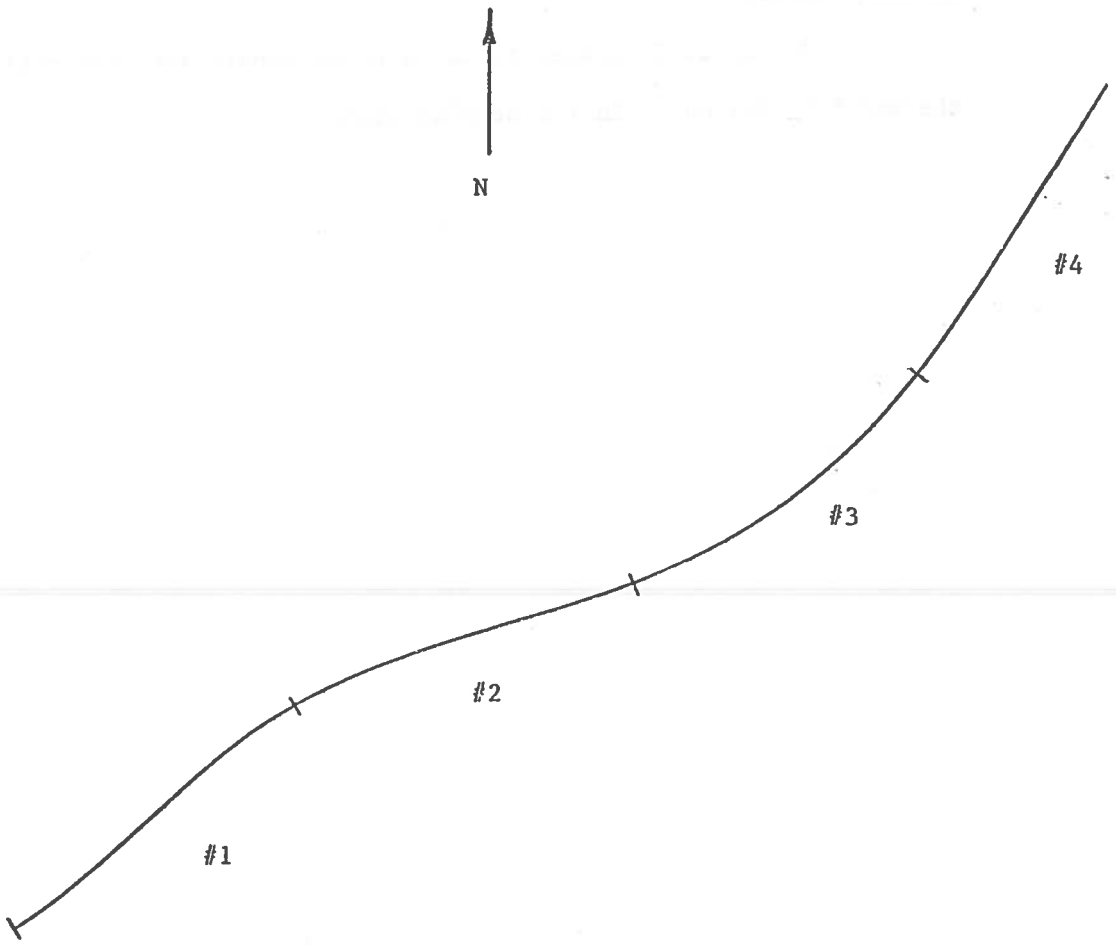


FIGURE 1: HYPOTHETICAL HIGHWAY BROKEN INTO SEGMENTS

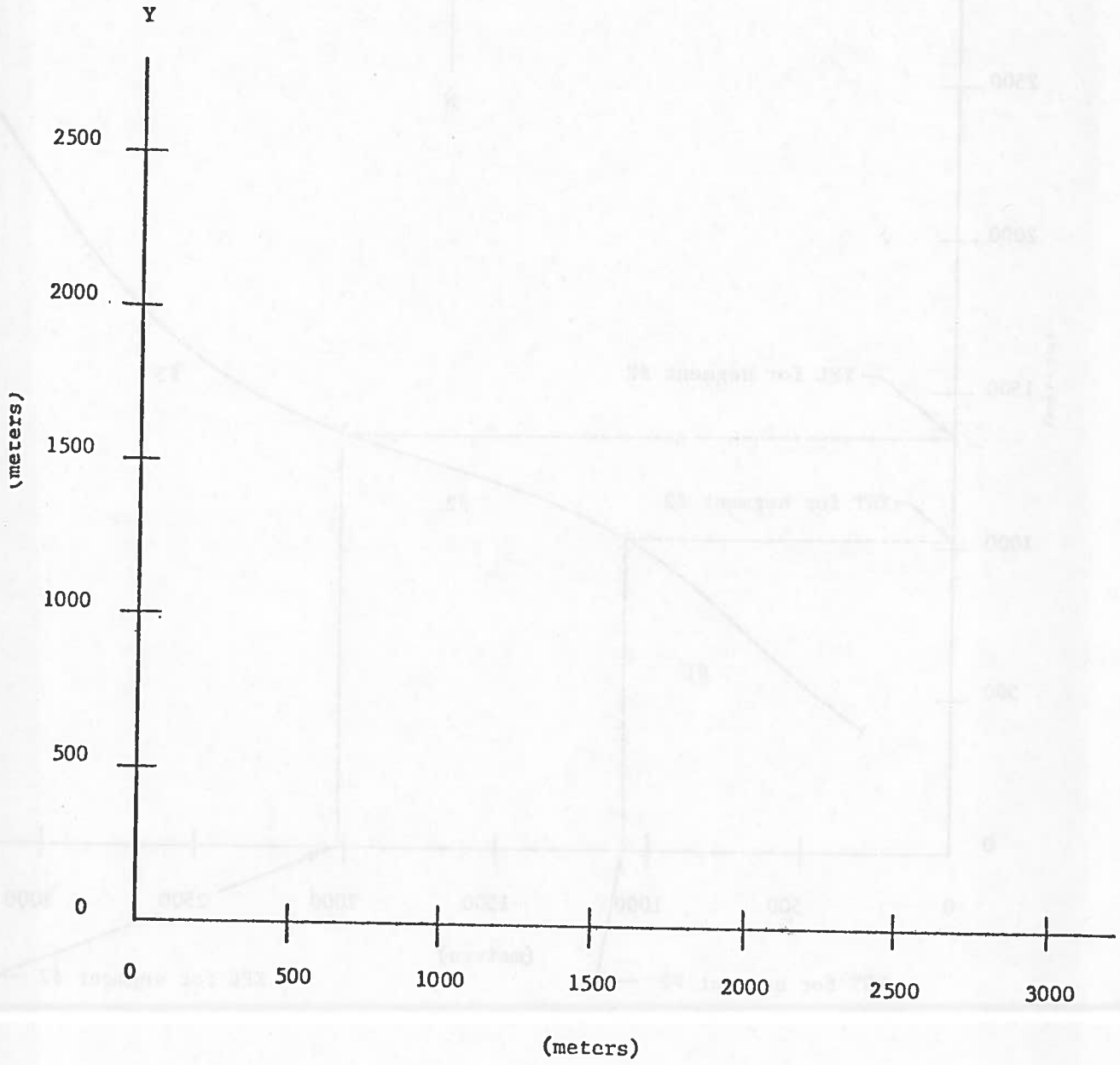
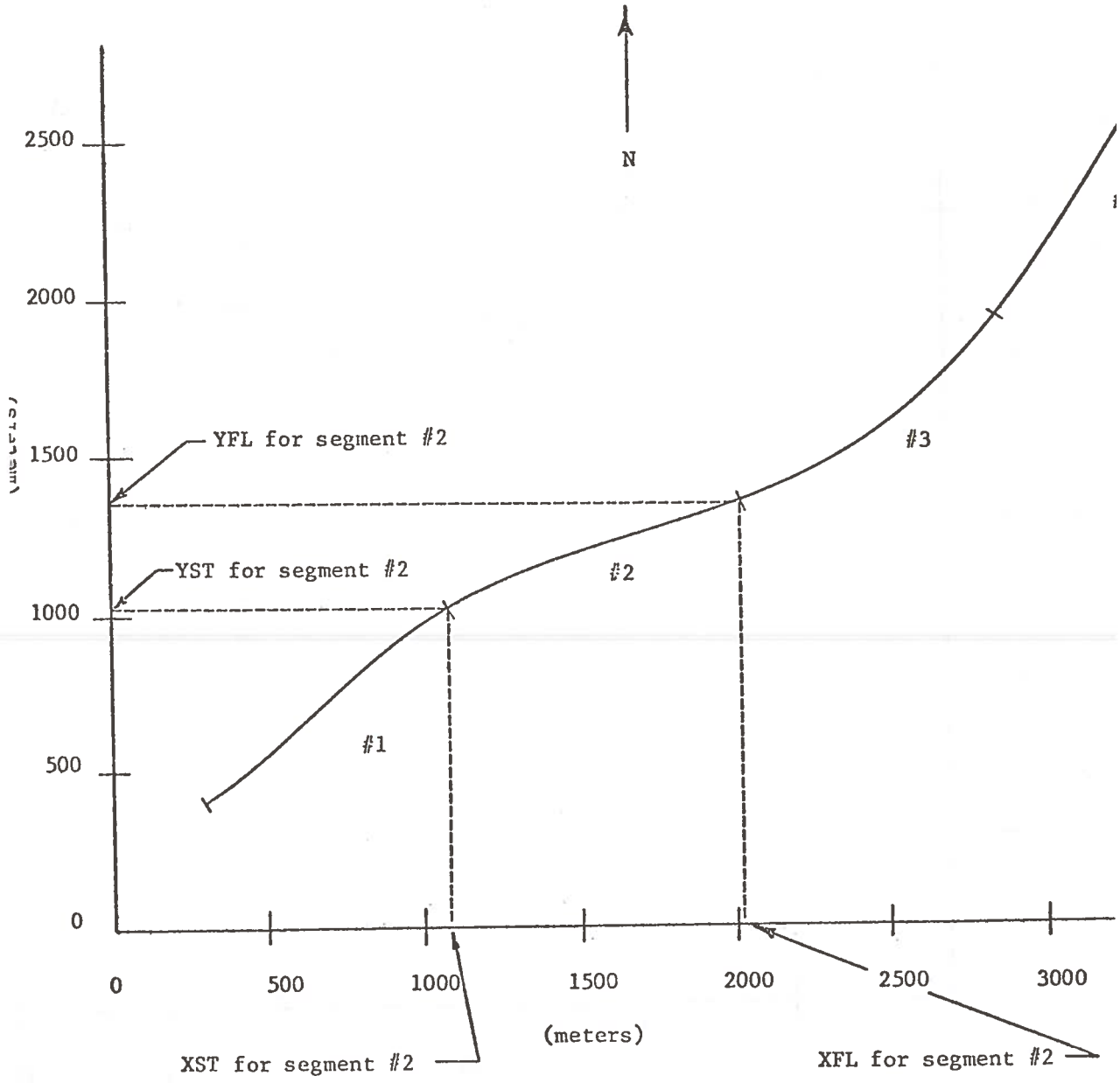


FIGURE 2: POSSIBLE COORDINATE SYSTEM



Note: BSDIR = 90 degrees in this example

FIGURE 3: HIGHWAY AND COORDINATE SYSTEM

C.5 TSC/EPA (TSC)

TRANSPORTATION SYSTEMS CENTER

U.S. DEPARTMENT OF TRANSPORTATION

CAMBRIDGE, MASSACHUSETTS 02142

TSC/EPA Highway Line Source Model

John Zimmerman, EPA
David S. Prerau, TSC
Paul J. Downey, TSC

INTRODUCTION

The TSC/EPA Highway Line Source Model is an air pollution dispersion model of the Gaussian class. The computer program for this model was originally written by John Zimmerman, EPA National Environmental Research Center, Research Triangle Park, North Carolina. Major modifications to the original model were subsequently made by Dr. David S. Prerau and Paul J. Downey of the U. S. Department of Transportation/Transportation Systems Center, Cambridge, Massachusetts. The model program is written in FORTRAN IV. Examples of its usage for modeling a highway, a street, or a complex multilevel interchange are discussed in References 1 and 2.

DESCRIPTION

The Model can calculate the pollutant concentrations at any number of receptors produced by any number of straight line segment sources of uniform emission. A complex set of roadways, e.g. an interchange, can be modeled by a large set of line segment sources. The Model can handle upgrade and downgrade roads as well as horizontal roads.

The Model first calculates the location of line sources to represent each lane of each road segment, based on the location of the center line of the road, the road width, and the width of the center strip. Then it calculates the concentration at each receptor due to each line source. Finally,

it sums the contributions at each receptor due to each lane of each road segment to produce the final computed concentration.

The concentration due to a single line source at a receptor is given by:

$$C(R) = \int_0^L Q_s \, P_R(\ell) d\ell$$

Where:

$C(R)$ is the concentration at receptor R

L is the length of the line source

Q_s is the line source strength

$P_R(\ell)$ is the concentration produced at R by a unit strength point source located a distance from the end of the line source.

To compute the integral, the Model divides the line source into smaller line source segments and computes the sum of the contributions of each segment to the pollutant concentration at the receptor. The line source is divided into progressively greater numbers of smaller line source segments until successive calculated values of pollutant concentration seem to have converged. The contribution from each small line source segment is calculated by the trapezoidal rule, which approximates the contribution to the integral by a small line source segment as the average of the contributions of point sources located at each end of the segment. Thus, the above equation becomes :

$$C(R) = \frac{Q_s}{N}\left[\frac{P_R(0) + P_R\left(\frac{L}{N}\right)}{2} + \frac{P_R\left(\frac{2L}{N}\right) + P_R\left(\frac{L}{N}\right)}{2} + \cdots\right] + E_N$$

$$= \frac{Q_s}{N}\left[\frac{1}{2} P_R(0) + \sum_{i=1}^{N=1} P_R\left(\frac{iL}{N}\right) + \frac{1}{2} P_R(L)\right] + E_N$$

Where:

N is the number of line source segments of $\frac{L}{N}$ into which the line source has been divided.

E_N is the error term (which decreases as N increases).

Thus, each step in the calculation of the concentration due to the line source is reduced to the calculation of the concentrations at the receptor due to N point sources. N is continually doubled until a convergence criterion is met.

To calculate the concentration at a receptor due to a point source, the TSC/EPA Model uses the following equation adapted from Reference 3:

$$P_R(x,y,z,H) = \frac{1}{2\pi U\sigma_y\sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right) + \sum_{N=1}^{J} A(N)\right]$$

$$A(N) \triangleq \exp\left(\frac{-(z-H-2NL)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H-2NL)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z-H+2NL)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H+2NL)^2}{2\sigma_z^2}\right)$$

Where:

P_R is the concentration point at receptor R which is located at point (x,y,z) due to a unit point source of pollution located at point (0, 0, H). [x is the downwind distance; y is the crosswind distance, z is the vertical distance].

U is the wind speed

σ_y a function of x, is the standard deviation of concentration in the crosswind direction.

σ_z a function of x, is the standard deviation of concentration in the vertical direction.

L is the height of the mixing layer.

J is chosen such that N=J is the first value of N such that A(N) is less than a given small constant.

This equation is a form of the standard Gaussian plume model of air pollution dispersion. The first exponential accounts for crosswind dispersion. The first z exponential gives the contribution of pollution directly from the source. The second z exponential gives the contribution of pollution which was reflected from the ground. The A(N) terms account for multiple eddy reflections from both the ground and the stable layer.

The TSC/EPA Model considers multiple wind directions, rather than a single wind direction, and computes principal wind direction concentrations by sector averaging. It is possible for the worst-case traffic and meteorological conditions to occur for any wind direction. Since the wind direction is a variable of primary importance in the determination of the pollutant concentration produced at a given receptor by a given road configuration, it is desirable to consider many wind directions for each situation considered. Therefore, the Model iterates on wind direction so that results for several wind directions can be produced sequentially

in one Model run. From these results, the worst-case wind direction can be chosen for each receptor, and thus the worst-case results can be used. In general the worst-case wind direction will be different for each receptor.

Due to the well known variability of wind direction at the low wind speeds usually considered in worst-case computations, a sector-averaged pollutant computation of the following form is used:

$$C_{SA} = \frac{1}{4}\left[C(\theta_n - 22.5°) + 2C(\theta_n) + C(\theta_n + 22.5°)\right]$$

Where

C_{SA} is the sector-average pollutant concentration for a principal wind direction.

$C(\theta)$ is the calculated concentration for wind direction

θ_n is the nominal angle for the principal wind direction.

Using the multiple wind direction capability, sixteen different runs are made using wind directions every 22.5°. The Model then automatically computes the pollutant concentration at each receptor for each principal wind direction, using sector averaging.

INPUTS

1. The endpoints of the center line of each road segment.
2. The width of each road segment.
3. The width of the center strip of each road segment, if any.
4. The height of emissions for each road segment.
5. The emission strength of each lane of each road segment.

6. The wind directions to be used.
7. The wind speed.
8. The height of the mixing layer.
9. The coordinates of the receptors.
10. The ground heights (if non-zero) at each road segment endpoint and at each receptor.

OUTPUTS

1. The endpoints of the center line of each road segment.
2. The width of each road segment.
3. The width of the center strip of each raod segment, if any.
4. The height of emissions for each road segment.
5. The emission strength of each lane of each road segment.
6. The wind directions to be used.
7. The wind speed.
8. The height of the mixing layer.
9. The coordinates of the receptors.
10. The ground heights (if non-zero) at each road segment endpoint and at each receptor.
11. The predicted concentration at each receptor for each wind direction considered.

REFERENCES

1. Eugene M. Darling Jr., David S. Prerau, and Paul J. Downey, COMPUTER ANALYSIS OF AIR POLLUTION FROM HIGHWAYS,STREETS AND COMPLEX INTERCHANGES, A CASE STUDY: PORTIONS OF THE PROPOSED 3-A SYSTEM IN 1978 BALTIMORE, MARYLAND, Report No. DOT-TSC-OST-73-37, U. S. Department of Transportation/Transportation Systems Center, Cambridge, Massachusetts, March 1974.

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3. D. Bruce Turner, WORKBOOK OF ATMOSPHERIC DISPERSION ESTIMATES, Public Health Publication No. 999-AP-26, U. S. Environmental Protection Agency, 1970.

C.6 WALDEN RESEARCH, INC. (WAL)

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WALDEN HIGHWAY MODEL

INTRODUCTION

The Walden Highway Model is an air pollution diffusion model based on the Gaussian Plume equation. The computer program for the Walden Highway Model is a modified version of the Air Quality Display Model (AQDM) [1], originally developed under EPA sponsorship and adapted for computer applications by Martin and Tikvard [2]. This multiple-source model has received extensive application by Federal and State regulatory agencies in evaluating regional air pollution control strategies. The adaptation of this computer model to the current highway application for carbon monoxide (CO) concentrations was made by Walden Research Division of Abcor, Inc., Cambridge, Massachusetts.

Two major modifications were made to the AQDM program. First, a program module VEHEMI was integrated into the Fortran IV source code to accurately determine vehicle emission rates for CO. VEHEMI is designed to compute explicitly the CO emission rate (grams/vehicle mile) for a specified motor vehicle model year mix. In this case, the mix is typical of an urban area on the East Coast in 1972. The method is based on a procedure by Kircher and Armstrong [3] and incorporates such considerations as deterioration and speed adjustment factors. Recent changes in federal automotive emission standards related to amendments to the Clean Air Act of 1970 have been incorporated. Secondly, a unique method for transforming highway line sources into series of point sources was incorprorated into the model to conform to the input-output formats desired in the current application.

DESCRIPTION

The basic univariate Gaussian diffusion equation for the concentration at an elevated receptor due to an elevated point source is given by the expression:

$$\chi(x, y, z) = \frac{Q\,(c-y/c)}{\sqrt{2\pi}\,\sigma_z u\,\left(\frac{2\pi x}{16}\right)} \left\{ \exp\left(-\tfrac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right) + \exp\left(-\tfrac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right) \right\}$$

where:

- $\chi(x, y, z)$ = pollutant concentration at receptor point (x,y,z), (gms/m^3).
- Q = emmission rate, (gms/sec).
- u = mean wind speed, (m/sec).
- σ_z = standard deviation of the plume concentration distribution in the vertical direction, (m).
- H = height of the point source, (m).
- (x,y,z) = coordinates of the receptor relative to the point source, (m)
- c = width, at the receptor, of a 22.5-degree circular sector centered on the point source.

The Gaussian equation is based upon several assumptions, including:

(a) Total reflection of the plume takes place at the earth's surface.

(b) The plume description represents conditions averaged over a time period of several minutes. The "instantaneous" behavior of the plume, particularly during unstable atmospheric conditions is more complex.

(c) The effluent has neutral buoyancy in the atmosphere: no fall-out or buoyancy rise is modeled by the equation.

(d) The time-averaged plume exhibits a Gaussian distribution of concentration, in the vertical dimension. The measure of the spread in this direction (the dispersion coefficient) is considered to be a function of downwind distance and atmospheric stability only.

(e) The plume is a steady-state phenomenon resulting from a constant, continuous emission source, and none of the effluent "disappears" (by chemical change or by absorption of the ground surface, for example). Thus, an area integration of the plume conentration in any plane perpendicular to the center line is constant, regardless of the downwind distance.

(f) Pollutant dispersion in the crosswind direction is modeled using linear interpolation within a 22.5-degree circular sector, corresponding to the 16-point compass used in wind direction measurements.

All diffusion calculations made by the Walden Highway Model use this Gaussian equation. The model treats a highway line source by first breaking it up, one lane at a time, into an aggregate of many small area sources, each about 40 square meters in size, arranged in a line. Each area source is then converted to a "virtual" point source located upwind of the center of the area. The "virtual" point is placed at such a distance upwind that the 22.5-degree sector used in the calculations subtends the area width.

The values of σ_z used in this model are Turner's "Workbook" dispersion coefficients [4] plus 1.7 meters. The "Workbook" coefficients are widely used and are based on field trial data representative of diffusion at or near the ground. The additional 1.7 meter spread is to account for an initial vertical distribution of the emissions, as they diffuse from the roadway edge, due to mechanical turbulence caused by traffic flow. Note that the Gaussian distribution used in the vertical dimension accounts for the elevation of both the highway emissions source and the receptor probe, and the reflection of the plume at the earth's surface.

The CO concentration as calculated is modified by two scaling factors before being output. First, it is multiplied by 0.7374, a factor to convert the averaging time of the concentration from the 10 minutes characteristic of σ_z, to the desired 1-hour period [4]. This time scaling factor will give a conservative estimate of the 1-hour concentration. Finally, a factor of 817. is used to correct the units from grams per cubic meter to parts per million of CO.

REFERENCES

1. Air Quality Display Model, prepared for National Air Pollution Control Administration under contract No. PH 22-68-60, November 1969.

2. Martin, D. O. and Tikvart, J. A., "A General Atmospheric Model for Estimating the Effects on Air Quality of One or More Sources", presented at 61st Annual Meeting, APCA, St. Paul, Minnesota, June 1968.

3. Kircher, D. S. and Armstrong, D. P., An Interim Report on Motor Vehicle Emission Estimation (Draft), EPA Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, October 1972.

4. Turner, D. B., Workbook of Atmospheric Dispersion Estimates, PHS Publication No. 999-AP-26, (Revised), 1969.

APPENDIX

Input

1. The site number.
2. The case number.
3. The total vehicles per hour on the highway segment.
4. The average traffic speed.
5. The stability class.
6. The wind direction.
7. The wind speed.
8. The background concentration at three upwind receptors.

Output

1. The site number.
2. The case number.
3. The predicted concentration at five downwind receptors.

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