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16. Abstract

Air pollution levels in the vicinity of simple signalized intersections were investigated. A thorough review of the literature was performed and a new, simplified predictive model was developed. The new model is known as the Texas Intersection Model (TEXIN) and incorporates the MOBILE-2 and CALINE-3 computer programs with a set of established "short-cut" traffic and excess emissions techniques. The result is an efficient computer program capable of estimating carbon monoxide levels near simple, signalized intersections given minimal geometrical, meteorological and traffic parameters. The TEXIN Model was compared to experimental data near intersections and to corresponding simulations by the Intersection Midblock Model (IMM) and other existing intersection models. The TEXIN Model only requires approximately 10 per cent of the inputs and the computer time required by the Intersection Midblock Model (IMM). The new model also predicts pollution levels with slightly more accuracy than the IMM.

This report and the TEXIN computer program on magnetic tapes are available from the Texas State Department of Highways and Public Transportation and NTIS. They are also available at modest costs from Dr. Jerry A. Bullin, Chemical Engineering Department, Texas A&M University, College Station, Texas 77843, phone 713-845-3361.

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NOMENCLATURE

a	-	acceleration, speed/time
ADPV	-	approach delay per vehicle, s/veh
B_L	-	existing demand of a potentially congesting flow, veh/hr
COID	-	total rate of CO emitted due to vehicles idling, mass/time
COSD	-	total rate of CO emitted due to vehicles slowing, mass/time
COST	-	total rate of CO emitted due to vehicles stopping, mass/time
C	-	concentration, gm/m^3
Cy	-	cycle time, s
D	-	line source length, m
dC	-	incremental concentration, gm/m^3
EF	-	total excess emission factor, gms/m-s
ER	-	pounds of CO emitted per 1000 speed changes
f	-	point source dispersion function
H	-	effective source height, m
ΔH	-	source height correction factor, m
HDGV	-	fraction heavy duty gas vehicles
HDDV	-	fraction heavy duty diesel vehicles
HRS	-	excess hours consumed per 1000 speed changes
i	-	subscript to indicate ith approach
j	-	subscript to indicate jth signal phase
L	-	mixing height, m
LDDT	-	fraction light duty diesel trucks
LDDV	-	fraction light duty diesel vehicles
LDGT1	-	fraction light duty gas trucks
LDGT2	-	fraction medium duty gas trucks
LDGV	-	fraction light duty gas vehicles
M_H	-	conflicting traffic stream, veh/hr
M_{NO}	-	maximum capacity for a given movement, pch

M_1 - capacity of the right turn stream, pch
M_3 - capacity of the through stream, pch
M_4 - capacity of the left turn stream, pch
M_{134} - capacity of all streams using the shared lane, pch
MC - fraction motorcycles
OB - observed CO concentration, ppm
P - impedance factor
PCCC - percent catalyst equipped vehicles in cold start mode
PCCN - percent non-catalyst equipped vehicles in cold start mode
PCHC - percent catalyst equipped vehicles in hot start mode
PCST - percent of vehicles stopping
PD - integral of exponential function
PR - predicted CO concentration, ppm
q - lineal source strength, gm/m-s
QE - central sub-element lineal source strength, gm/m-s
QL - queue length, m
SDPV - stopped delay per vehicle, s/veh
T_g - critical gap, s
TIQPV - time in queue per vehicle, s/veh
TR - residence time, s
TTEI - total vehicles entering intersection, veh-hr/lane
u - wind speed, m/s
U^* - virtual wind speed, m/s
V_f - final speed, length/time
V_o - initial speed, length/time
WT - source strength weighting factor
W2 - roadway half-width, m
X - pollutant concentration, gm/m^3
Y - horizontal distance from source to receptor, m
Z - receptor height, m
σ_y - horizontal dispersion parameter, m
σ_{yo} - initial horizontal dispersion parameter, m
σ_z - vertical dispersion parameter, m
σ_{zo} - initial vertical dispersion parameter, m

IMPLEMENTATION

A user-oriented computer model has been developed to predict carbon monoxide pollution concentrations near simple signalized roadway intersections. The model is written in FORTRAN and has been released with a detailed user's guide. The model is superior in accuracy and functionality to previous intersection pollution models and is highly efficient in terms of computer requirements.

DISCLAIMER

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SUMMARY

Air pollution levels in the vicinity of simple signalized intersections were investigated. A thorough review of the literature was performed and a new, simplified predictive model was developed. The new model is known as the Texas Intersection Model (TEXIN) and incorporates the MOBILE-2 and CALINE-3 computer programs with a set of established "shortcut" traffic and excess emissions techniques. The result is an efficient computer program capable of estimating carbon monoxide levels near simple, signalized intersections given minimal geometrical, meteorological and traffic parameters. The TEXIN Model was compared to experimental data near intersections and to corresponding simulations by the Intersection Midblock Model (IMM) and other existing intersection models. The TEXIN Model only required approximately 10 per cent of the inputs and the computer time required by the Intersection Midblock Model (IMM). The new model also predicts pollution levels with slightly more accuracy than the IMM.

CHAPTER I

INTRODUCTION

The problem of estimating carbon monoxide concentrations due to automobile emissions in the vicinity of roadway intersections is perhaps the most challenging problem in air pollution research today. Extensive work has been performed to monitor and predict automobile emissions and their subsequent dispersion for straight sections of roadways carrying well defined traffic at an average route speed. However, comparatively little quantitative work has been done for the case of roadway intersections. Moreover, significantly larger pollutant concentrations are usually observed at intersections than along straight roadways. For these reasons, pollution "hot spots" at intersections and parking lots have been subjects of increased study in recent years.

The general approach which is most successful for prediction of pollution near straight roadways is to first model the emission source strength due to the vehicular traffic and to separately model the subsequent downwind dispersion. The first model yields a quantity known as an "emission factor" in units of pollutant mass (usually grams of carbon monoxide, CO) per unit distance traveled per vehicle (usually vehicle miles). Inputs to the emissions model normally include average route speed, ambient temperature, vehicle operating characteristics and recent vehicle history. The dispersion models are often based upon a Gaussian plume assumption and require inputs such as highway geometry, average ambient meteorology, and the proper emission factors.

Ideally, it would be desirable to derive correction factors to adjust the results calculated for straight roadways to apply for intersections. Unfortunately, to date such simplified analyses have been impossible. Prolonged and unwieldy calculational schemes for intersection pollution estimation have been derived for current applications. The problems in applying such analyses to intersections stem from patterns of automobile operation near an intersection. Some vehicles may be cruising through at the average speed of the surrounding roadway (as with a green traffic signal), while others may be accelerating, decelerating, or stopped altogether. The variation of traffic signal timing sequences, turning patterns and channelization, as well as effects of simple stop and yield signs, also add to the problem of defining traffic flows within an intersection. Since idling, acceleration and deceleration generate many times more pollution than cruising, and since the emissions during these modes of operation are highly dependent on vehicle age and history (whether it is catalytic-equipped, whether it is in the hot or cold operation mode, etc.), a single emission factor for a given intersection is particularly difficult to obtain.

The above considerations apply even in the simplest case of an at-grade intersection with four right angle corners and no surrounding topographical dispersion barriers. Application of such techniques to more complex configurations such as "street canyon" intersections formed between tall buildings in congested urban areas is thus even more challenging.

Current approaches to analyzing air quality at intersections usually involve "worst case" estimates which may be a factor of four to seven above the realistic average value. These procedures often involve questionable traffic and emission estimates based upon data obtained from straight roadways and often should only be regarded as screening procedures rather than as predictive methods. Thus, the results may be difficult to put into proper perspective in evaluations of the impact of a particular highway design on air quality.

Most of the existing pollution models have been tested against rather limited data bases, especially for intersection configurations. Often the data used for comparison are the same data used for development of the model. One purpose of the current research is to assimilate all available data and to compare data to predictions by major estimation methods.

The main problems which all existing estimation procedures have in common are that they require very detailed traffic and meteorological inputs and/or a great deal of manual computation time. Often for highway design engineers, the very conservative answers (i.e., extreme overprediction) obtained by these methods make it difficult to justify the required effort. The most significant achievement of the current work was the development of a highly simplified, user-oriented pollution model for intersections which is of equal or better accuracy than existing techniques.

A. OBJECTIVES

The research described herein has been conducted in response to Federal Highway Administration (FHWA) RFP No. DTFH61-80-R-00340 under Texas Transportation Institute (TTI) project 2-8-81-541 and is intended to provide an improved perspective in the analysis of highway air pollution hot spots. The study was directed toward the simple case of intersections formed by four right angle corners with negligible topographical or background pollution effects. This fundamental analysis has yielded results which should guide later work for more complex configurations.

The main objectives of the proposed research were to evaluate the estimation methods for carbon monoxide vehicle emissions at simple signalized intersections by existing analytical, numerical, and graphical techniques and to subsequently evaluate carbon monoxide levels at receptors in the vicinity of the intersection. Comparisons with existing experimental data were made and a simplified, user-oriented intersection pollution model was developed.

The new model, dubbed the Texas Intersection Model (TEXIN Model), was developed by the Chemical Engineering Department and the Texas Transportation Institute at Texas A&M University, and is basically a combination of various short-cut techniques adapted from established traffic and air pollution theory. TEXIN incorporates the first existing air pollution dispersion model with link capabilities, CALINE-3, with the MOBILE-2 emissions program and with existing traffic flow models. The study should enable design engineers to easily evaluate pollution impacts from intersections considering temporal and spatial variations of traffic, emissions and meteorology, the nature of receptors, and their relation to local intersection air quality.

B. OVERVIEW OF PROJECT REPORT

The remainder of this report has been organized in the following manner. A complete review of past and current research is presented in Chapter II. Emphasis is placed upon existing intersection pollution models and experimental data bases. In Chapter III, the development of the TEXIN Model is described and pertinent equations are given in detail. Comparisons of the new model and other models against the most complete data bases are discussed in Chapter IV. Other less quantitative results of the study are also presented and discussed in that chapter. Project conclusions and recommendations are presented in Chapter V and supporting material such as computer listings are included in the Appendix. A detailed User's Guide is included in the Appendix and has been issued as a separate document (TTI Report No. 2-8-81-541-2F).

CHAPTER II
REVIEW OF THE LITERATURE

The approach traditionally employed for modelling pollutant concentrations near roadways has been to first determine a composite emission rate for the vehicular traffic using an emissions model and to model the subsequent dispersion of pollutants with an atmospheric dispersion model. For this reason, the methods of estimating vehicle emissions in general use today are discussed first and then several atmospheric dispersion models which will be of interest in later chapters are described. These dispersion and emission models apply to many types of roadway geometry. Several composite models whicn predict both vehicle emissions and pollutant concentrations specifically for intersections are also presented. Three of these models will receive extensive use in the remainder of the report. Finally, previous and current experimental research in the field of data acquisition and related modelling of vehicle emissions and dispersion near intersections are reviewed.

A. VEHICLE EMISSION ESTIMATION METHODS

To determine the rate of pollutant emissions from vehicles in actual use, the Enviromental Protection Agency (EPA) has administered a series of exhaust emissions surveillance programs. These programs have resulted in the development of several pollution emissions models as described below.

AP-42

The EPA has developed several standard driving sequences to represent urban emissions. Those of interest are the 1975 Federal Test Procedure (FTP) and the Surveillance Driving Sequence (SDS). The data collected from various surveillance programs using these procedures, along with prototype vehicle data, assembly line test data, and technical judgement form the basis for the existing and projected mobile source emission factors presented in the EPA document, Compilation of Air Pollutant Emission Factors (AP-42) [1].

Modal Analysis Model

The Automotive Exhaust Emission Modal Analysis Model [2] is a computer program employing the emissions measured during the Surveillance Driving Sequence. Five steady state modes are established at the speeds: 0, 15, 30, 45 and 60 mph (0, 24.1, 48.3, 72.4 and 96.5 kph, respectively). Thirty-two other modes represent either periods of acceleration or deceleration from these speeds, and are characterized by an average, constant acceleration and an average speed. The acceleration/deceleration driving modes consist of all the possible combinations of the five steady state speeds.

The primary accomplishment of the Modal Analyis Model was the development of a mathematical model which expanded the emissions from the 37 discrete modes into a continuous function of time such that vehicle emissions can be predicted over any specified driving sequence. The Modal Analysis Model predicts CO, HC and NO_x emission rates for light-duty vehicles only and was last updated in June 1977. Dr. Clyde Lee of the University of Texas Center for Highway Research is currently working to extend the Modal Analysis Model to vehicles other than light-duty (Center for Highway Research Project No. 3-8-79-250).

MOBILE-2

MOBILE-2 [3] is a second generation computer program that predicts emissions from highway motor vehicles using the emission factors and methodologies presented in the previously described EPA publication AP-42. This model can predict CO, HC and NO_x emission rates for light-duty, as well as heavy-duty vehicles, but only for vehicles driving at an average route speed or idling. MOBILE-2 is a March, 1981, revision of MOBILE-1 [4], which was first issued by the EPA in 1978.

B. POLLUTANT DISPERSION MODELS

Two models describing the atmospheric dispersion of pollutants which are in general use today and which are capable of modelling an intersection situation are the

HIWAY-2 and CALINE-3 models. Both models are based upon the assumption of Gaussian dispersion and have been approved for use by the EPA.

HIWAY-2

HIWAY-2 [5] is a revised version of the EPA's original computer program, HIWAY [6], for predicting non-reactive, gaseous pollutant concentrations downwind from roadways. In the computer simulation, each lane of traffic is modelled as a straight line source of finite length with a uniform emission rate. This finite aspect of the model allows application to intersections. HIWAY-2 uses Gaussian equations similar to those presented by Turner [7]. Concentrations are calculated by a numerical integration of the Gaussian plume point source equation over a finite length. The concentration is thus given by:

$$X = \frac{q}{u} \int_0^D f dx \qquad \text{(II-1)}$$

where:
- u = wind speed, m/s
- D = line source length, m
- q = line source emission rate, gm/m-s
- f = point source dispersion function
- X = pollutant concentration, gm/m^3.

Depending on the atmospheric conditions, the model uses one of three possible point source dispersion functions. For stable conditions, the following form is used:

$$f = \frac{1}{2\pi\sigma_y\sigma_z} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right)\left(\exp\left(-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2\right)\right) \quad \text{(II-2)}$$

where: σ_y = standard deviation of the concentration distribution in the crosswind direction, m

σ_z = standard deviation of the concentration distribution in the vertical direction, m

Z = receptor height above ground, m

H = effective source height, m

In unstable or neutral conditions, where σ_z is greater than 1.6 times the mixing height, L(m):

$$f = \frac{1}{\sqrt{2\pi}\ \sigma_y L} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right) \quad \text{(II-3)}$$

In all other unstable or neutral conditions: (II-4)

$$f = \frac{1}{2\pi\sigma_y\sigma_z} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right)\left(\exp\left(-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right)\right.$$

$$+ \sum_{N=1}^{\infty}\left(\exp\left(-\frac{1}{2}\left(\frac{z-H-2NL}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+H+2NL}{\sigma_z}\right)^2\right)\right.$$

$$\left.\left. + \exp\left(-\frac{1}{2}\left(\frac{z-H+2NL}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+H-2NL}{\sigma_z}\right)^2\right)\right)\right)$$

In each of the three equations above, the values for σ_y and σ_z are evaluated for the given stability class and downwind distances, and include factors of initial turbulence caused by vehicles which takes place in the mixing zones as well as ambient turbulence between the mixing zone and the receptor.

The predicted concentration at a selected receptor is calculated as the summation of the numerical integration of equation (II-1) for each line source contributing to that location. Queued traffic can be modelled by considering it as a separate line source with the same physical location as the line source representing the through traffic. Thus, each line source must be assigned an emission factor corresponding to its traffic flow conditions. A more complete discussion of the HIWAY-2 model is given in the HIWAY-2 User's Guide [5].

CALINE-3

CALINE-3 [8] is a third generation model developed by the California Department of Transportation for predicting pollutant concentrations downwind from a line source. CALINE-3 uses a more complex geometrical representation of the roadway than HIWAY-2. It models the roadway as a finite line source and divides the individual highway links into a series of discrete elements. Each element is modelled as an "equivalent finite line source" (EFLS) positioned normal to the wind direction and centered at the element midpoint. Each element is further divided into five discrete sub-elements represented by corresponding segments of the equivalent finite line source, with emissions from each sub-element dispersing in a Gaussian manner downwind. Incremental concentrations from the elements are modelled using the crosswind finite line source (FLS) Gaussian formulation:

$$dC = \frac{q\,dy}{2\pi u \sigma_y \sigma_z} \exp\left(\frac{-y}{2\sigma_z^2}\right)\left(\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right) \qquad \text{(II-5)}$$

where: dC = incremental concentration, gm/m^3

Receptor concentrations are calculated by approximating the crosswind FLS equation with:

$$C = \frac{1}{\sqrt{2\pi}\, u} \sum_{i=1}^{n} \left(\frac{1}{\sigma_{z_i}} \sum_{k=-CNT}^{CNT} \left(\exp\left(\frac{-(z-H+2kL)^2}{2\sigma_{z_i}^2}\right) + \exp\left(\frac{-(z+H+2kl)^2}{2\sigma_{z_i}^2}\right)\right)\right) \qquad \text{(II-6)}$$

where: n = total number of elements

CNT = number of multiple reflections needed for convergence

QE_i = Central sub-element lineal source strength for i^{th} element

WT_j = Source strength weighting factor for j^{th} sub-element

$$PD_{ij} = \frac{1}{2} \int_{Y_j/\sigma_{Y_i}}^{(Y_{j+1})/\sigma_{Y_i}} \exp \frac{-p^2}{2} \, dp$$

Y_j = offset distance for the j^{th} sub-element.

CALINE-3 treats the region directly over the roadway as a zone of uniform emissions and turbulence, designated as the mixing zone, and determines the initial mixing and dispersion. A distinct linear relationship between the initial vertical dispersion parameter and residence time in the mixing zone is used in CALINE-3. CALINE-3 arbitrarily defines mixing zone residence time as:

$$TR = W2/u \qquad \text{(II-7)}$$

where: TR = residence time, sec
W2 = roadway half-width, m

Vertical dispersion curves are formed using the value of σ_z at ten kilometres as defined by Pasquill and the initial vertical dispersion parameter. Horizontal dispersion curves used by CALINE-3 are based on those developed by Pasquill and Gifford. A complete discussion of CALINE-3 is presented in the User's Guide [8]. For historical purposes it may be of interest to consult the earlier California model, CALINE-2 [9].

C. COMPOSITE MODELS FOR INTERSECTIONS

The foregoing discussion presents several models that predict either (1) emission factors, given such inputs as ambient temperature, vehicle mix and history, driving sequence and mode of operation; or (2) pollutant concentrations at selected receptors given such inputs as emission factors, traffic volumes, meteorological data and highway/receptor geometry. For intersection analyses, several models have been developed which utilize combinations of the preceding models and assorted traffic engineering principles to predict pollutant concentrations. The EPA Hotspot Guidelines, the Intersection Midblock Model (IMM), the Indirect Source Guidelines and MICRO are four composite models which will be considered in the following discussion.

Hot Spot Guidelines

In 1978, the U.S. EPA published a series of manuals entitled The Carbon Monoxide Hot Spot Guidelines, Volumes I, II and III [10,11,12]. These guidelines present a method for the identification and analysis of carbon monoxide hot spots (locations where ambient CO concentrations may exceed the National Standards). Development of the guidelines involved many assumptions and generalizations to achieve simplicity in use.

Intersection Midblock Model (IMM)

Volume V of the Hot Spot Guidelines describes the Intersection Midblock Model [13]. The IMM is essentially a computer program that performs the same calculations outlined in Volumes I, II and III [10,11,12] of the Guidelines; however, fewer assumptions are made thus lending increased flexibility to the analysis. It is only intended for carbon monoxide pollution and is designed as a screening procedure to identify potential "hot spots" in urban situations. In 1980 the New York State Department of Transportation chose the IMM as its chief modelling tool but found it too limited and proceeded to modify it for their use [14]. The term "Intersection Midblock Model (IMM)" refers to this modified version in the remainder of this report.

The IMM is a combination of signalization and vehicle queueing estimation procedures using accepted traffic engineering principles. It also predicts emissions using the Modal Analysis Model and the MOBILE-1 program, and models dispersion with the HIWAY-2 model. The general flow diagram for the IMM is shown in Figure 1.

The IMM requires a very extensive set of input data, some of which are difficult to determine and rarely available. The IMM treats each lane as a line source (or link). Thus for each lane, along with the geometry of the link, the volume, velocity into and out of the intersection, the deceleration into and the acceleration out of the link and the lane service capacity must be supplied. Additionally, the signalization (type of control, number and length of phases, and approaches moving during each phase) needs to be specified.

The IMM first calculates various traffic parameters. Once the traffic calculations have been performed, the estimation of emission rates is carried out. Using the

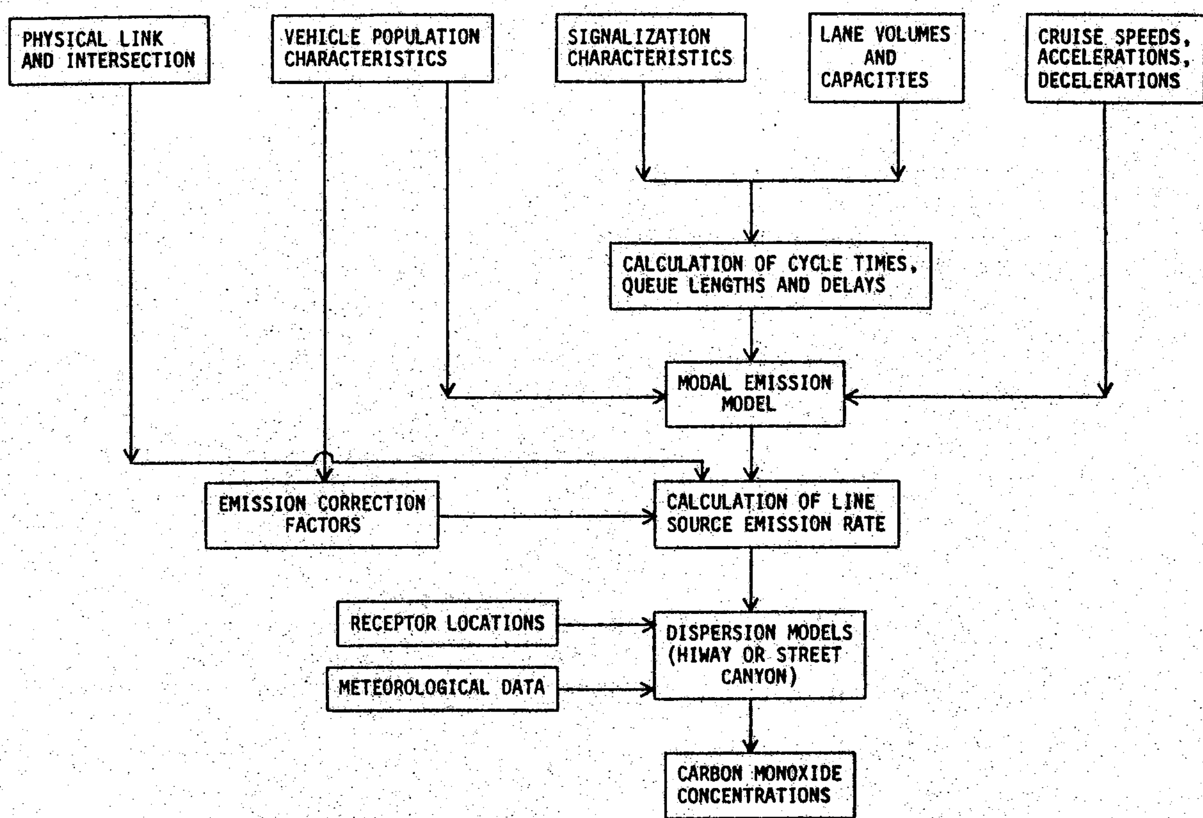


Figure 1: General flow diagram for the Intersection Midblock Model [13].

input parameters of speed into the queue, speed out of the queue, deceleration into the queue and acceleration out of the queue, the IMM utilizes the Modal Analysis Model as a subroutine to calculate cruise and acceleration/deceleration emissions for all approaches. Idle emissions are calculated by use of the MOBILE-1 program. Based on the previously calculated queue lengths, a set of pseudolinks are constructed. These pseudolinks lie along the actual links with the same termination points and center lines as the actual links, but each has a length equal to the calculated queue length for that approach. The only emissions assigned to the actual links are the cruise emissions (calculated with the Modal Analysis Model). The emissions assigned to the pseudolinks are the excess emissions due to accelerating, decelerating and idling.

A correction factor is applied to the emissions calculated from the Modal Analysis Model since these apply only for 1977 emission rates from stabilized light-duty vehicles. The correction factor used is the ratio of the MOBILE-1 composite emission estimate for the specified scenario to the MOBILE-1 composite emission estimate for 1977 stabilized light-duty vehicles.

Once the traffic calculations have been performed and emission rates assigned to each lane, the HIWAY-2 model is employed as a subroutine to calculate carbon monoxide concentrations at selected receptors. For the special case of a "street canyon" intersection between tall buildings in a highly urban area, a special dispersion routine is used.

MICRO

A study was conducted by the Colorado Department of Highways with the objective of determining the impact of traffic signalization decisions on air quality [15,16]. The first phase of this study was to determine automotive emission rates based on the mode of operation (accelerating/decelerating, idling or cruising). To accomplish this, the department obtained emission rate data that was used to update the original Modal Analysis Model. These emission rates were correlated with the product of the acceleration and speed (A.S.) associated with each test. The reasoning was that for a given speed change operation, the power remains constant and thus A.S. remains constant. Best fit quadratic equations for emissions (CO, HC and NO_x) as a function of A.S. were calculated for the data. These equations, in conjunction with the intersection submodel of the regional air quality dispersion model, APRAC-2 [17] (developed by Stanford Research Institute for estimating CO levels resulting from a city wide traffic network) were used by the Colorado Department of Highways as the basis for developing the program MICRO [16].

Like the IMM, MICRO first calculates traffic parameters, then estimates emission rates, and subsequently models the dispersion of pollutants downwind from the roadway. MICRO assumes each stopped vehicle undergoes four modes of operation: steady state cruise, deceleration, idle and acceleration. It assumes that non-stopping vehicles remain in the steady state cruise mode through the entire intersection. Each link is arbitrarily divided into five sections over which emissions are distributed. These are: the steady state, deceleration, decel-idle, accel-idle and the acceleration section.

Total emissions due to accelerating or decelerating vehicles are based on the number of stops, final cruise speed, the product A.S., and the FTP emission rate (100.0 gm/veh-mile for CO, 10.0 for HC, and 2.0 for NO_x). Total emissions due to idling vehicles are a product of the idle emission rate, the average vehicle delay and the number of vehicles delayed. The idle emissions are distributed between the decel-idle and the accel-idle sections. As stated in the MICRO User's Guide [16], the deceleration emissions are distributed among the deceleration, decel-idle and accel-idle sections. Similarly, the acceleration emissions are distributed among the decel-idle and accel-idle sections of the approach link and the acceleration section of the discharge link. Steady state emissions are incorporated into all five sections of each link.

Once the emissions have been calculated along each link, pollutant dispersion is modelled using a Gaussian point source formulation similar to that in the HIWAY-2 Model. The links are subdivided into numerous smaller sections, each of which is considered as a separate point source, and the contributions from the links are summed to give the pollutant concentration at a selected receptor.

Indirect Source Guidelines

The EPA document, Guidelines for Air Quality Maintenance Planning and Analysis - Volume 9 (Revised): Evaluating Indirect Sources [18], presents a method to evaluate the impacts of indirect sources (roadways, parking lots, airports, etc.) on air quality. The evaluation procedure is performed manually through a series of worksheets and flow charts with tables and nomographs to facilitate user application. The Indirect Source Guidelines can be used to model extended line sources, finite line sources and area sources. However, only its treatment of extended and finite line sources are applicable to intersections.

Carbon monoxide concentrations are calculated in a three-step process. In the first step, the network description and traffic demand volume are used to estimate the traffic flow characteristics. Emissions are then computed as the sum of two parts: cruise emissions produced by non-stopping vehicles and excess emissions emitted by stopping vehicles. Lastly, the effect of atmospheric dispersion on actual concentrations at the specified receptor locations is estimated. In the first step of the Indirect Source Guidelines, the same equations used in the IMM are used to evaluate traffic flow characteristics.

The Indirect Source Guidelines provide nomographs that illustrate the variation of cruise, accelerating and decelerating emissions as functions of vehicle speed.

Idling emissions are based on the idle delay time, the 1977 idle emission rate, and the speed from which deceleration begins or to which a vehicle accelerates. The total excess emissions are assumed to be uniform over a specified length of roadway and are calculated using a correction factor (based on MOBILE-1) to account for the fact that the Modal Analysis Model was used in the development.

Atmospheric dispersion of the carbon monoxide is modelled utilizing nomographs derived from the first generation HIWAY model. These nomographs are only available for the three stability classes most likely to result in high CO concentrations (D, E and F). For infinite line sources (such as links with cruise emissions only), the nomographs relate the roadway/receptor separation and the sine of the wind/roadway angle to the normalized concentration, Xu/Q. For finite line sources (such as links over which the excess emissions are emitted), a different family of nomographs relate the wind/road angle the roadway/receptor separation and Yu (or Yd) to the normalized concentration. Yu (or Yd) is the distance from a reference plane 20 metres (65.6 ft) downwind of the receptor location to the upwind (or downwind) end of the link.

For intersections, the total CO concentration at a receptor location is the sum of two components: (1) the finite line source contribution as represented by the excess emissions emitted over the roadway length, and (2) the infinite line source contribution of the free-flowing traffic. Since the dispersion nomographs were derived for a receptor height of 1.8 metres (5.90 ft), additional nomographs are presented relating roadway/receptor separation and actual receptor height to a height correction factor, z, which must be applied to the calculated concentrations. Like the IMM, the Indirect Source Guidelines can only model carbon monoxide pollution.

D. EXPERIMENTAL RESEARCH NEAR INTERSECTIONS

The optimal test of a model's performance in predicting carbon monoxide concentrations near roadways is the comparison of the model's results with actual experimental data. The data base should include roadway/receptor geometry, carbon monoxide levels, and timely traffic and meteorological data. There have been several major studies involving the collection of data near simple signalized intersections. Of the resulting data bases, only two (Texas A&M and California) were considered comprehensive enough for use in this study. A review of previous and current experimental research in the field of data acquisition and related modelling of vehicle emissions and dispersion follows.

Oakbrook Study

The majority of the early experimental work at intersections prior to 1974 was by Patterson and Record [19]. These investigators conducted a traffic monitoring and carbon monoxide analysis program at Oakbrook Shopping

Center, near Chicago. Of interest in the present analysis is the intersection of two nearby arterials, Illinois Route 83 and 22nd Street, which provided regional access to the shopping center. Using the collected traffic, meteorological and pollutant data, Patterson and Record developed an empirical technique for estimating emission profiles at intersections.

To determine the emissions from vehicles stopping and starting, Patterson and Record modified the 1974 Modal Analysis Model to calculate an emission profile at Oakbrook. The assumptions of constant acceleration/deceleration rates and an eight metre (26.2 ft) interval occupied by vehicles represent the idealized behavior of queueing vehicles and were assumed to keep the analyses tractable. The emission profile for a series of cars was calculated by adding the emissions from each vehicle in each eight metre (26.2 ft) interval according to the vehicle's speed and mode in that interval. Essentially, this was done by adding up ten of the single vehicle emission profiles (described above), with each successive profile displaced eight metres (26.2 ft) upstream from the previous one, and then subtracting the cruise emission component. The resulting emission profile does not include idle or cruise emissions, but only the emission in excess of cruise emissions due to stops and starts for a single non-stopping vehicle on a given approach. The excess emission profile for a series of vehicles was calculated by summing the individual profiles and subtracting out the cruise emissions. Figure 2 is such

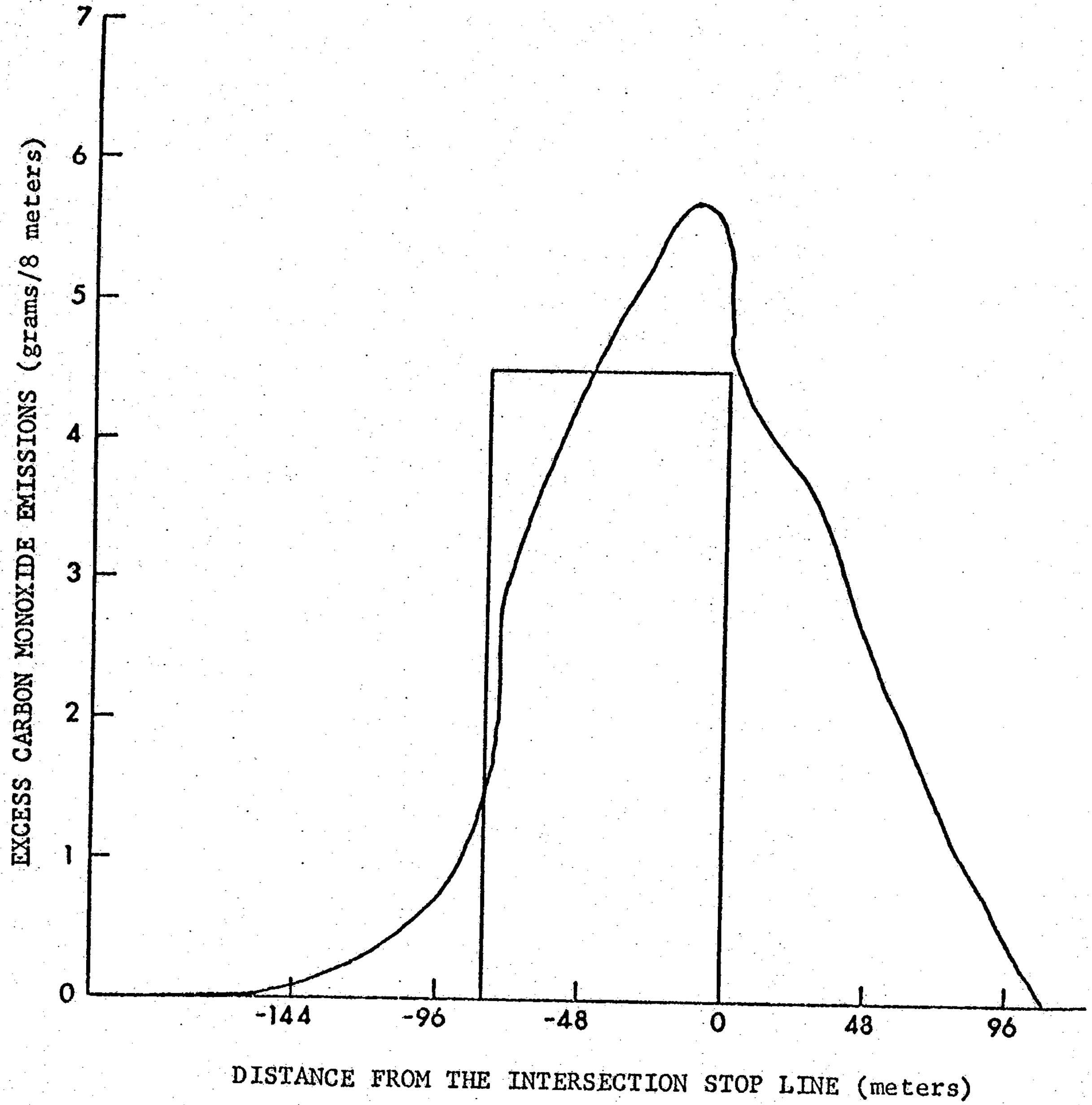


Figure 2. Emission profile and step function approximation of excess emissions for a queue of ten vehicles [19].

a profile. Patterson and Record used a statistical method to derive an equation for the mean total queue length, the length of roadway over which the excess emissions were assumed to be emitted.

To determine emissions due to idling vehicles, Patterson and Record assumed that a stopped vehicle waits during one-half of the red phase. From the idle emission rate calculated by the Modal Analysis Model and knowledge of the red phase length and cycle length, the idle emissions emitted over the queue length were thus calculated. By summing the emissions released by vehicles stopping and starting, idling and crusing over the queue length, Patterson and Record essentially approximated the emission profile generated by the Modal Analysis Model with a step function of width equal to the queue length.

Patterson and Record coupled the technique presented above for estimating emissions with the original EPA HIWAY model in order to compare predicted carbon monoxide concentrations from this composite model with observed values at Oakbrook. A total of 27 comparisons of observed and calculated values were made. These cases were chosen on the basis of relatively low wind speed, suitable wind angle, and completeness of the input data for the hour under study. Two sets of calculated concentrations were computed: (1) those based on an initial vertical dispersion parameter, σ_{z_o}, of 1.5 metres (4.92 ft), and (2) those based on σ_{z_o} = 3.0 metres (9.84 ft). These results are presented in Figures 3 and 4. The average of all calculated

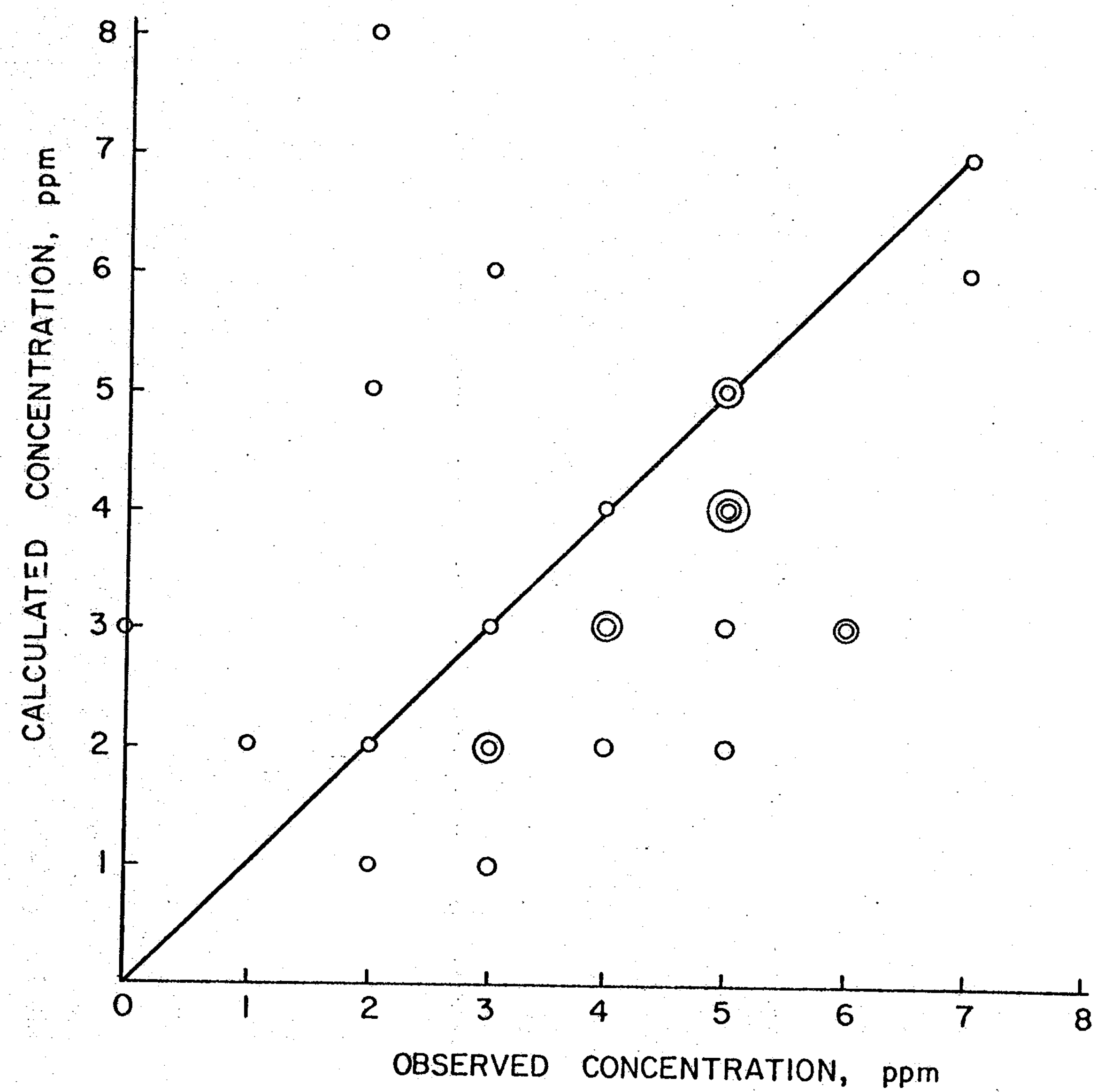


Figure 3. Calculated versus observed concentration of carbon monoxide for Patterson's study at Oak-brook (σ_{z_o}= 1.5m) [19].

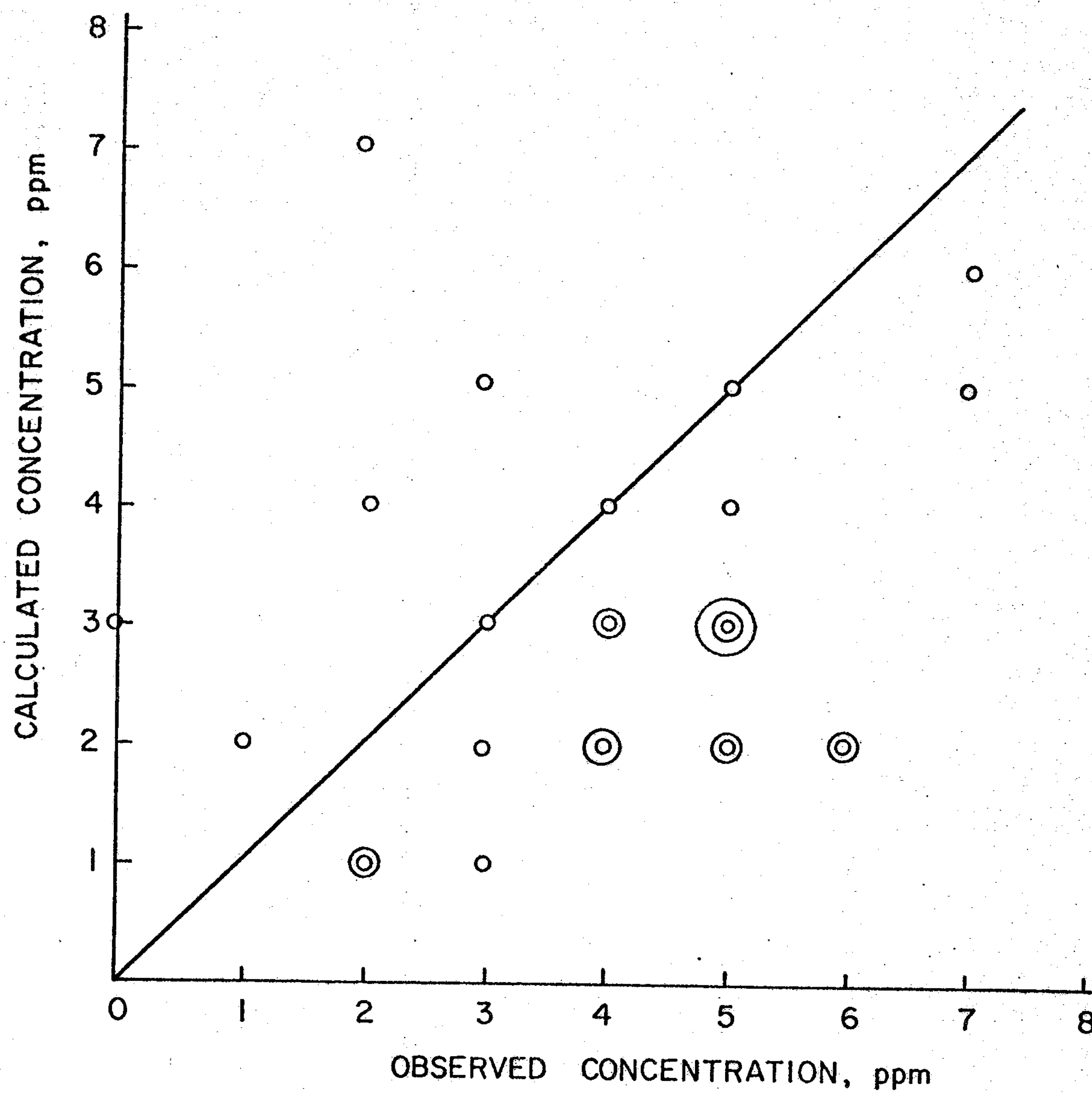


Figure 4. Calculated versus observed concentration of carbon monoxide for Patterson's study at Oakbrook (σ_{z_o} = 3.0m) [19].

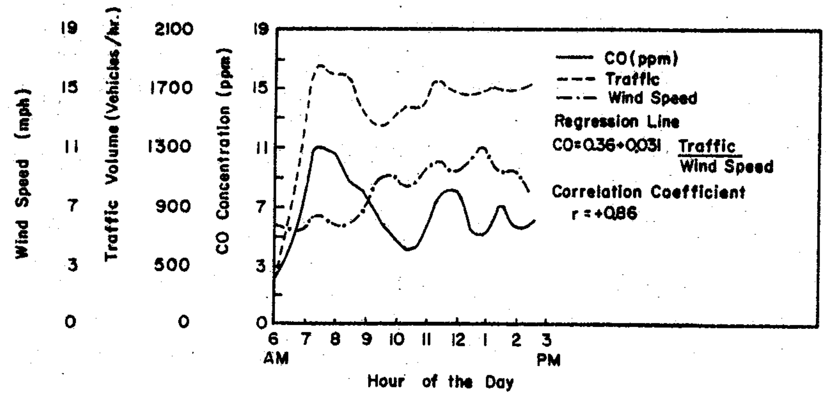
concentrations is 3.5 ppm versus 3.8 ppm for the average observed value with σ_{z_o} = 1.5 m (4.92 ft). The correlation coefficient, r, is 0.34 (r^2 = 0.11). The correlation coefficient obtained using σ_{zo} = 3.0 m (9.84 ft) is 0.29 (r^2 = 0.1). For σ_{zo} = 1.5 m (4.92 ft), twenty-two calculated values are a factor of two of those observed, five vary by more than a factor of two and six agree exactly. For σ_{zo} = 3.0 m (9.84 ft), twenty calculated values are within a factor of two, seven are not, and three agree exactly. The composite model exhibits a tendency to underpredict with fifteen of the calculated values being less than the observed values using σ_{zo} = 1.5 m (4.92 ft) (seventeen with σ_{zo} = 3.0 m (9.84 ft)), while only six are greater (for both values of σ_{zo}). The predicted concentrations tend to be overestimated at low wind speeds and underestimated at high wind speeds with the crossover occurring at wind speeds approximately equal to 3.5 m/s.

Cohen's Work

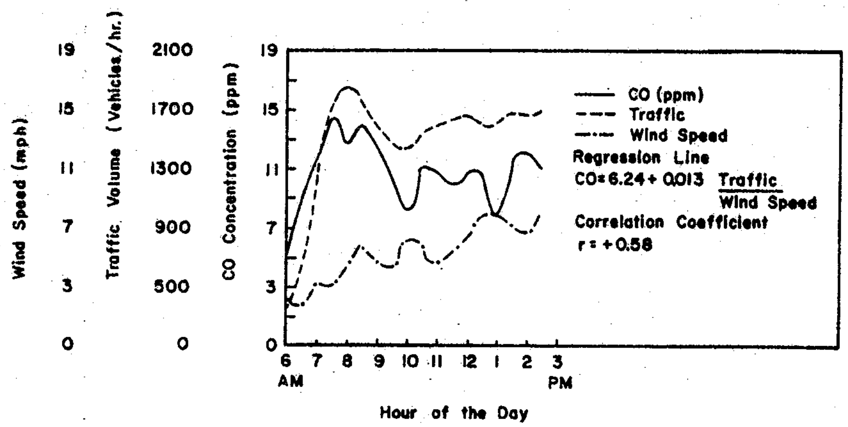
In a later study, Cohen [20] concluded that many of Patterson's assumptions were often violated in the field. Cohen developed a more comprehensive model incorporating the microscopic traffic simulation model, UTCS-1 [21] (a large, sophisticated model developed for the FHWA and currently known as NETSIM) and generated several emissions tables for HC, CO and NO_x using the Modal Analysis Model. The combination of these models enabled him to derive emission profiles for various traffic scenarios. He also modified the EPA HIWAY model to be compatible with these emission profiles. Using volume and turning movements provided by the District of Columbia Department of Highways and Transportation, Cohen ran 15 minutes of simulated time for Wisconsin Avenue between R and Q streets using his model. No comparison to actual experimental data was made, however. Cohen's model was never generalized for use on other intersections.

ERT Data

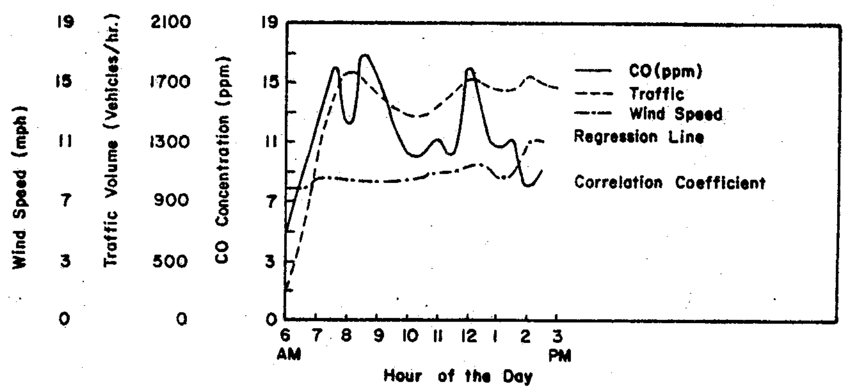
In 1974, Environmental Research and Technology, Inc. (ERT) performed a study for the District of Columbia with the purpose of quantifying air quality patterns in the vicinity of Wisconsin and Western Avenues, N.W. [22]. For a nine-hour period on each of three days, ERT performed a correlation analysis on the relationship between CO concentration and total traffic entering the intersection and on the relationship between CO levels, traffic and wind speed. The results of these regression analyses yielded site specific correlations of carbon monoxide concentrations as functions of traffic and wind speed. The hourly values of CO levels, traffic and wind speeds are presented graphically in Figure 5. These plots are indicative of the fluctuations of pollution, traffic and meteorology observed near intersections. However, no attempt was made by ERT to model the intersection using any of the emissions and dispersion estimating models previously mentioned.



(a) May 13, 1974



(b) May 21, 1974



(c) May 23, 1974

Figure 5. Hourly averages of carbon monoxide levels, wind speed and traffic volume at the intersection of Wisconsin and Western Avenue, NW [22].

CONNDEP DATA

In a paper published in 1978, Hanisch, et al. [23] presented the results of a study performed by the Connecticut Department of Enviromental Protection (CONNDEP). This study included a series of tests designed to evaluate the impact of idling vehicle emissions upon air quality under controlled conditions. These tests resulted in the development of an empirical equation for the CO concentration at a receptor site due to idling vehicles. By assuming that excess emissions are dominated by idling vehicles, Hanisch proposed a limited intersection model that was a combination of his empirical equation for excess emissions and the HIWAY Model for cruise emissions. However, no comparison with observed experimental data near an intersection was made. The data collected by CONNDEP was for an isolated row of queueing vehicles and are not applicable as a data base for intersection modelling.

Illinois Study

A study performed by the Illinois Enviromental Protection Agency and Enviro-Measures, Inc. in late 1978 [24] provides an analysis of carbon monoxide data collected near a signalized urban arterial intersection and a comparison of measured CO concentrations to those predicted by mathematical modelling. Two mathematical models were used to predict CO concentrations for the intersection. These were the original EPA HIWAY model (using MOBILE-1 emission factors and assuming vehicles traveling at an average route speed through the intersection) and the Indirect Source Guidelines using emission factors from the Modal Analysis Model.

Comparisons of measured and predicted one hour average CO concentrations were made only for those hours when the highest ambient CO concentrations were observed. Comparisons were made for twenty-eight periods, and the performance of the models were statistically evaluated. Figures 6 and 7 present scattergrams for the two models and Table 1 gives the statistical results. The correlation coefficient, r, was used as an index of model precision, and a second parameter, k, (the ratio of the mean predicted to the mean measured concentrations) was used as an index of model accuracy. The model accuracy is dependent on precision, thus rendering k values meaningless for low r values.

For the HIWAY model, a best fit of the data yielded a correlation coefficient of 0.42 ($r^2 = 0.18$) and an average k value of 0.65 (i.e., 35% underprediction). For the Indirect Source Guidelines, the best fit of the data yielded a correlation coefficient of 0.51 ($r^2 = 0.26$) and an average k value of 1.26 (26% overprediction). Since CO concentrations were taken for the east leg of the intersection only, the authors of the study separated the data into three categories: that collected in the queue zone (taken as the data collected at the stop line), that collected in the acceleration/deceleration zone (i.e. 40 meters east of the intersection), and that collected in the midblock zone (430

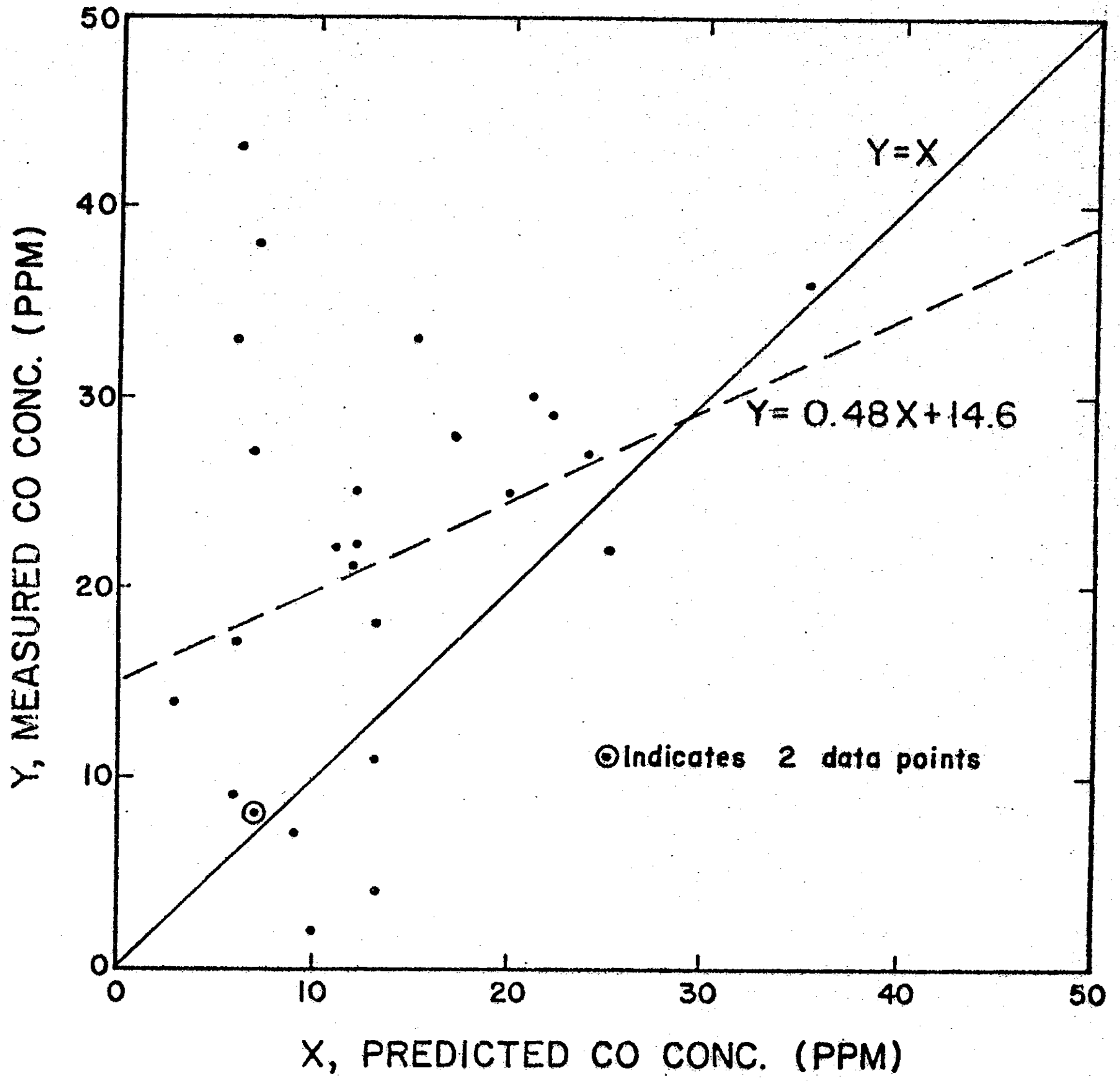


Figure 6. Scattergram of measured versus predicted carbon monoxide concentrations for HIWAY model using the Illinois data [24].

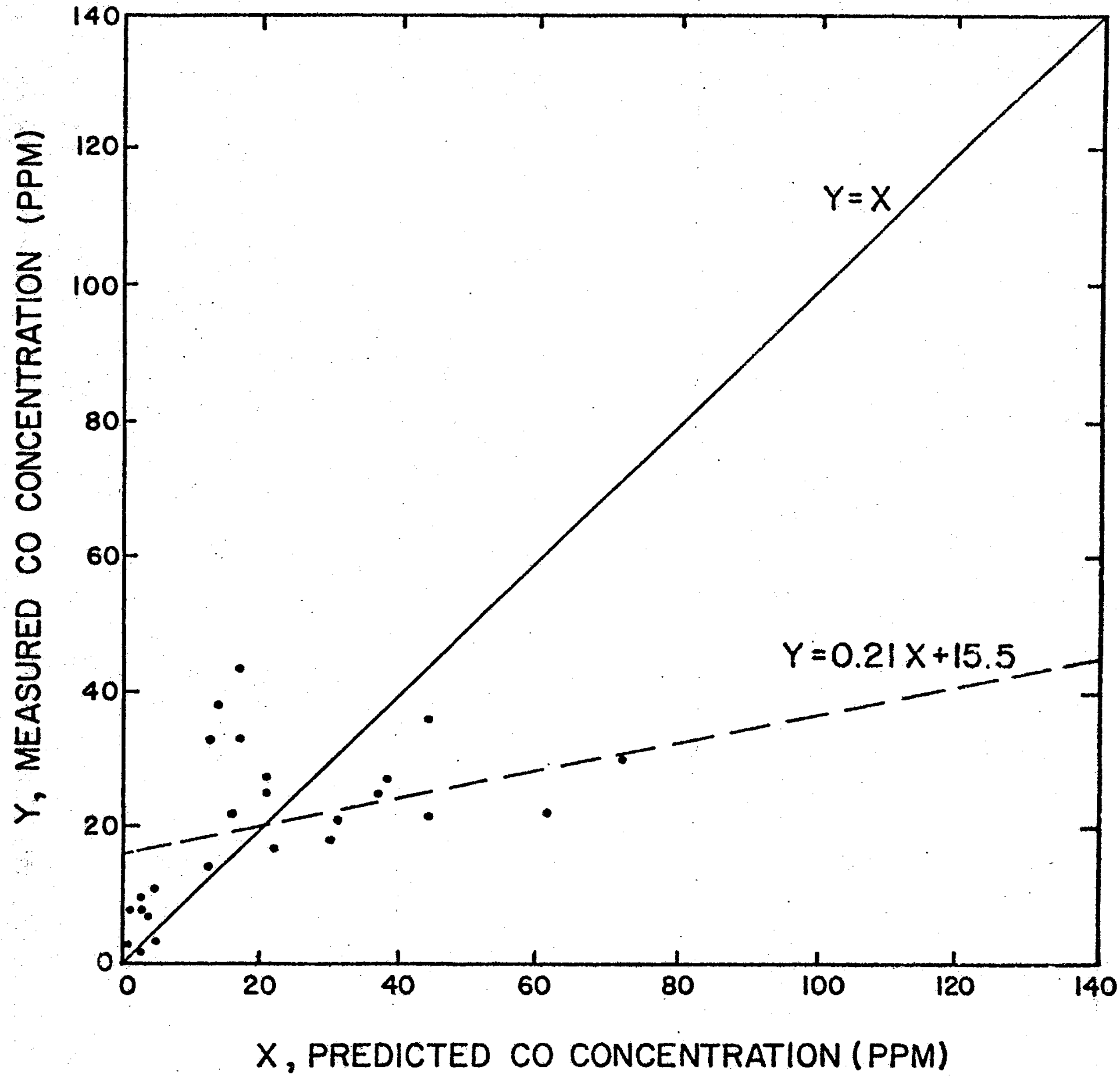


Figure 7. Scattergram of measured versus predicted carbon monoxide concentrations for the Indirect Source Guidelines procedure using the Illinois data [24].

Model	Data Set	N	$\bar{X}$ (ppm)	X_σ	X_{max} (ppm)	$\bar{Y}$ (ppm)	Y_σ	Y_{max} (ppm)	k_{mean}	k_{max}	r	m	b	CV%
HIWAY	All Data	28	13.8	9.8	46.2	21.2	11.5	43.2	0.65	1.07	0.416	0.483	14.6	54%
	Queue Zone	10	19.7	12.9	46.2	32.4	5.6	43.2	0.61	1.07	-0.304	-0.131	35.0	17%
	Accel/Decel Zone	10	12.1	6.6	24.9	21.8	4.7	30.3	0.56	0.82	0.526	0.377	17.2	22%
	Midblock Zone	8	8.4	3.5	12.9	6.6	3.0	10.7	1.27	1.21	0.197	0.169	5.2	45%
VOLUME 9	All Data	28	26.8	27.2	124.0	21.2	11.4	43.2	1.26	2.87	0.511	0.214	15.5	54%
	Queue Zone	10	37.9	34.0	124.0	32.4	5.6	43.2	1.17	2.87	-0.153	-0.025	33.3	17%
	Accel/Decel Zone	10	34.6	19.4	71.8	21.8	4.7	30.3	1.59	2.37	0.602	0.148	16.7	22%
	Midblock Zone	8	3.3	1.4	5.3	6.6	3.0	10.7	0.50	0.50	0.256	0.546	4.8	45%

TABLE 1. SUMMARY OF STATISTICAL RESULTS FOR HIWAY AND THE INDIRECT SOURCE GUIDELINES FROM THE ILLINOIS STUDY [26].

meters east of the intersection). Both the HIWAY and Indirect Source Guidelines exhibited poor precision for the queue zone and midblock zone, and better precision for the acceleration/deceleration zone (as reflected by the correlation coefficients). Based on a theoretical "worst case" scenario, the HIWAY model compared favorably to maximum concentrations observed in the field, while the Indirect Source Guidelines predicted a much higher CO concentration for the queue zone and acceleration/deceleration zone than those observed in the field.

<u>Minnesota Study</u>

In October, 1979, during a regional "Air Quality Symposium" [25] sponsored by the Minnesota Department of Transportation, Region V EPA, and the FHWA, data were collected near an intersection and used to test the performance of the CALINE-3 dispersion model. Emission factors and queue lengths were based on the methodologies presented by the Indirect Source Guidelines. The resulting scattergram is presented in Figure 8. When a best fit of the 92 data points was performed, the analysis yielded a correlation coefficient of 0.42 ($r^2 = 0.18$). The model exhibited a tendency to underpredict for low CO concentrations and overpredict for high values. The authors of the report concluded that the output of the model was influenced more by incorrect inputs than by the performance of the dispersion model.

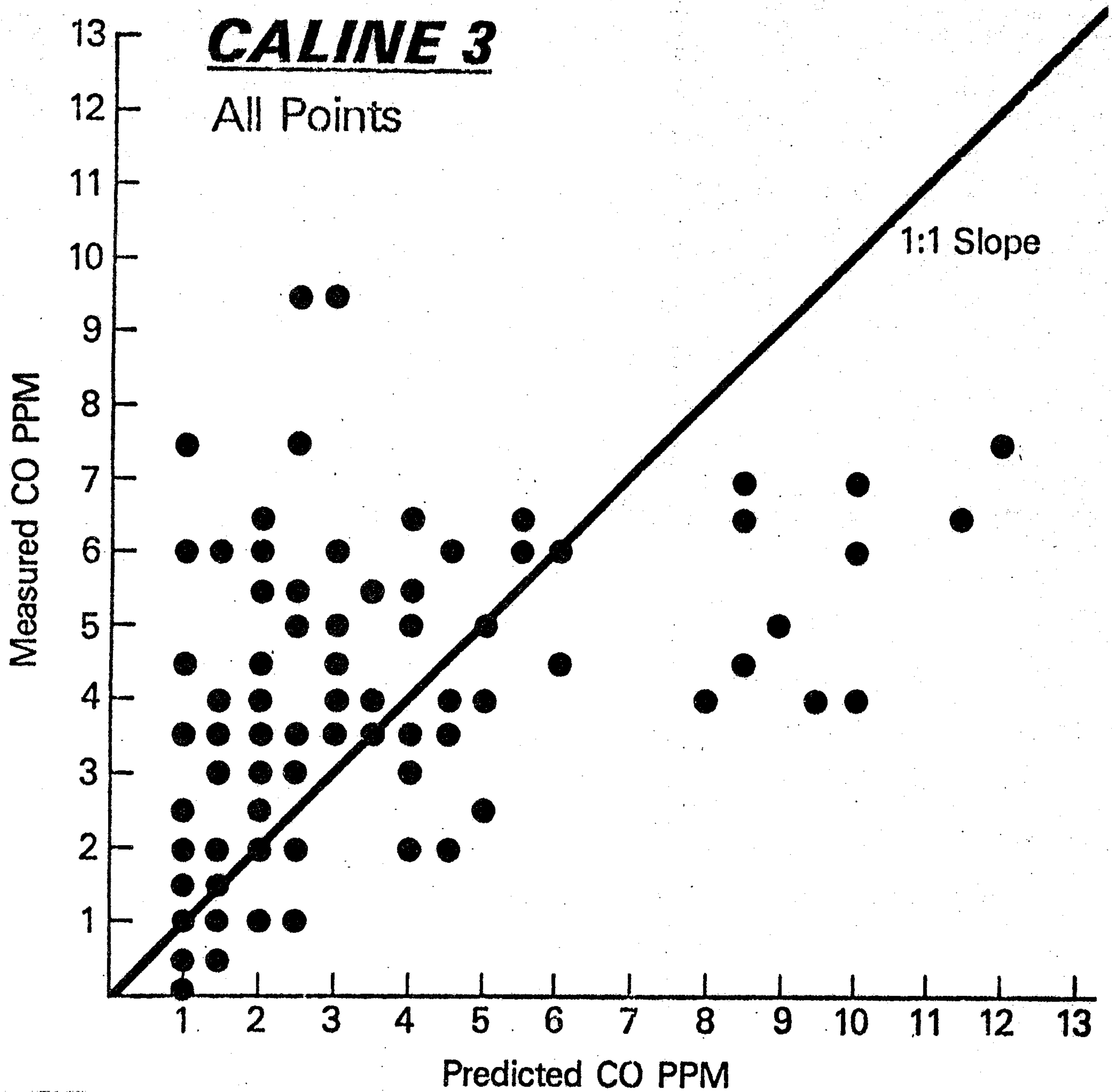


Figure 8. Scattergram of measured versus predicted carbon monoxide concentrations for the Minnesota study [25].

New York "Hot Spot" Study

From July, 1979, to September, 1980, Geomet Technologies, Inc. conducted the Upstate Carbon Monoxide Hot Spot Study for the New York State Department of Transportation [26]. Carbon monoxide, meteorological and traffic data were collected at four potential "hot spot" sites in the Capital District and four in the Rochester area for the purpose of calibrating a dispersion model. The model chosen was the Intersection Midblock Model, and as mentioned previously, it was soon modified by the NYSDOT to more realistically represent the conditions found at many intersections.

The NYSDOT study resulted in a data base of hourly average values for carbon monoxide, meteorological and traffic measurements. Using somewhat different hourly averages from this data base, two attempts were made to calibrate the IMM, one by Geomet Technologies and one by Zamurs of NYSDOT [27]. Both attempts at calibration met with unsuccessful results [14,26,27].

Each site had one (and only one) non-dispersive infra-red analyzer located adjacent to the roadway connecting the two intersections and approximately midway between the two (hence the term "mid-block"). Four of the eight sites had on-site meteorological instrumentation for measuring wind speed, wind direction and temperature. Directional traffic volumes were measured hourly at all sites, but only for the roadway adjacent to the CO probe.

Vehicle classification studies were taken at each site, and a radar speed gun was used to gather vehicular speed data at all eight sites. Other observations were made at each site to note traffic queue lengths, signal timing and congestion conditions.

The resulting data base consisted of the raw data sets (in hourly averages) from the eight monitoring sites. Due to the following reasons, the New York data base was not considered comprehensive enough to use in the present study.

(1) Only one carbon monoxide probe was used; thus there was no way to accurately determine the background CO concentrations.

(2) Many of the sites did not have on-site meteorological stations. Meteorological data for these sites had to be obtained from either a meteorological station at a different site or from a local airport.

(3) Traffic volumes were measured only on the roadway adjacent to the probe. These volume counts were not necessarily made during the same hours that CO concentrations were being measured. Traffic counts were not made on any of the other links in the dual intersection network. Since these traffic counts are essential in evaluating the operating characteristics of the intersections (as reflected by queue lengths, delay times, etc.), the lack of them points to the insufficiency of the data base.

The purpose of New York Study was primarily to screen many types of intersections for potential pollution hotspots. NYSDOT is aware of the inadequacy of such data for model development and is presently collecting data for a more comprehensive data base at several intersection sites in New York City [14].

Texas A&M Study

Experimental data were acquired as a part of an ongoing study of air quality near intersections. This study is being conducted by the Chemical Engineering Department and the Texas Transportation Institute at Texas A&M University (TTI Project No. 2-8-79-250) [28]. This project involved the computerized acquisition of pollutant, traffic and meteorological data at the Texas Avenue-Jersey Street intersection in College Station, Texas, during the period of October, 1980, to May, 1981, and at the Woodway Boulevard - South Post Oak Lane intersection in Houston, Texas, during the period of September to October, 1981. The College Station site and instrument layout are presented in Figure 9.

The terrain surrounding the intersection was generally flat. The northwest quadrant was a golf course of grass covered ground and individual, scattered trees. The northeast quadrant consisted of single family residences on wooded lots. A gas station was located at the intersection in the southwest quadrant, and a small community shopping center of one-story buildings ran along the western side of Texas Avenue in that quadrant. Single family residences were located at the intersection in the southeast quadrant

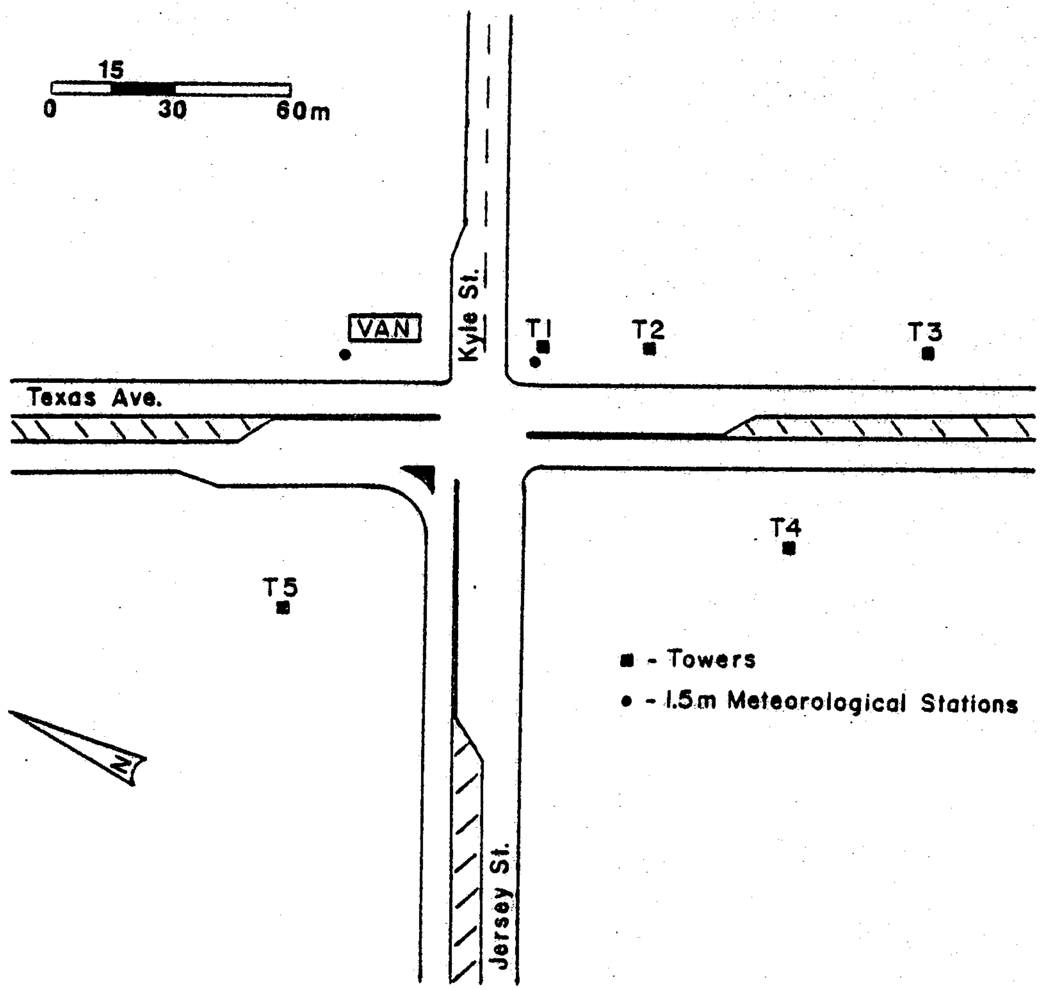


Figure 9. Site geometry for the Texas A&M - College Station data [28].

with another small one story shopping center along the eastern side of Texas Avenue about 75 metres (246 ft) from the intersection. Texas Avenue and Jersey Street were well-traveled, while Kyle Street had relatively low traffic flow.

Towers 1, 2 and 3 were located in the southeast quadrant. Tower 4 was located in the southwest quadrant, and Tower 5 was in the northwest. All instruments were interfaced to a Data General NOVA 1200 minicomputer located in a trailer in the northeast quadrant. The resulting data were logged on standard nine-track magnetic tape. The data were collected continuously with values recorded every four to eight seconds depending on the type of instrument. The advantage of instantaneous data measurements is that a better representation of actual conditions is obtained. Increased accuracy of averaged values over those obtained through bag or sequential measurements is thus insured. In addition, instantaneous data values allow the examination of the time variable patterns of traffic flow, pollutant levels, etc.

Traffic was monitored using 13 loop counters placed in the lanes approaching the intersection, as well as the exclusive left and right turn lanes. In conjunction with the NOVA computer, these loops allowed the following data to be collected: the number of vehicles and total time spent traversing the individual loops during the green and red phases of the signal; the total amount of delay encountered by vehicles passing over a loop while the light was red; and the percentage of vehicles making left and right turns. The time spent over the loops enabled the average vehicle speed for each lane to be calculated.

Carbon monoxide concentrations were monitored using Model 2600 CO Ecolyzers. Nine Ecolyzers in all were used, three each on Towers 1, 2 and 4. On each of these towers, the Ecolyzers were situated at heights of 5, 15 and 35 feet (1.52, 4.57, and 10.67 metres, respectively), and measurements were recorded every eight seconds.

Meteorological data were collected using vertical anemometers, horizontal anemometers, UVW anemometers, wind vanes, thermistors and a pyranometer. Tower 1 had a vertical anemometer, a horizontal anemometer, a wind vane and a thermistor at each of the three heights: 5, 15, and 35 feet (1.52, 4.57, and 10.67 m). A five foot (1.52 m) meteorological station at the trailer site had a vertical anemometer, horizontal anemometer, wind vane, and thermistor. Two additional thermistors were on Tower 5 at 5 and 50 foot (1.5 and 15.2 m) levels. The anemometer and thermistor measurements were recorded every eight seconds, while the wind vanes were recorded every four. The four UVW anemometers were situated at 15 and 35 foot (4.57 and 10.67 m) levels on Tower 4, and 5 and 50 foot (1.52 and 15.2 m) levels on Tower 5. The pyranometer was located at the trailer site at a height of 15 feet (4.57 m).

The raw data were edited (deleting any known bad data, etc.) and reduced to 15-minute averages. Standard deviations were also calculated for each 15-minute average.

The edited raw data are stored on standard nine-track tape in fixed-length, 80 byte records, and the 15 minute averages (and standard deviations) are available on magnetic tape. There are 153 15-minute cases which are deemed useable; e.g., 153 cases in which enough of the instruments were working correctly such that all necessary data for modelling the intersection are available.

Sulfur Hexafluoride (SF_6), a tracer gas, was released during approximately fifteen hours of the data. The gas was released at a constant, measured rate by a single vehicle passing back and forth through the intersection on Texas Avenue without stopping. Samples were collected using 15-minute sequential sampling syringes which were later analyzed for SF_6 concentration by gas chromatography.

As part of the Texas A&M study, data were also collected at the South Post Oak Lane - Woodway Boulevard intersection in Houston, Texas, during the months of September and October, 1981, and were available late in the study. Figure 10 shows the site and instrument layouts and a plan view of the site is given in Appendix B. In the northwest quadrant, a service station was located at the corner and the remainder of the quadrant was composed of two-story apartment buildings. The northeast quadrant was occupied by a seven-story apartment complex. The southeast quadrant contained three tall office buildings (one 18 story, and two 24-story buildings). In the southwest quadrant, there was a 14 story condominium complex.

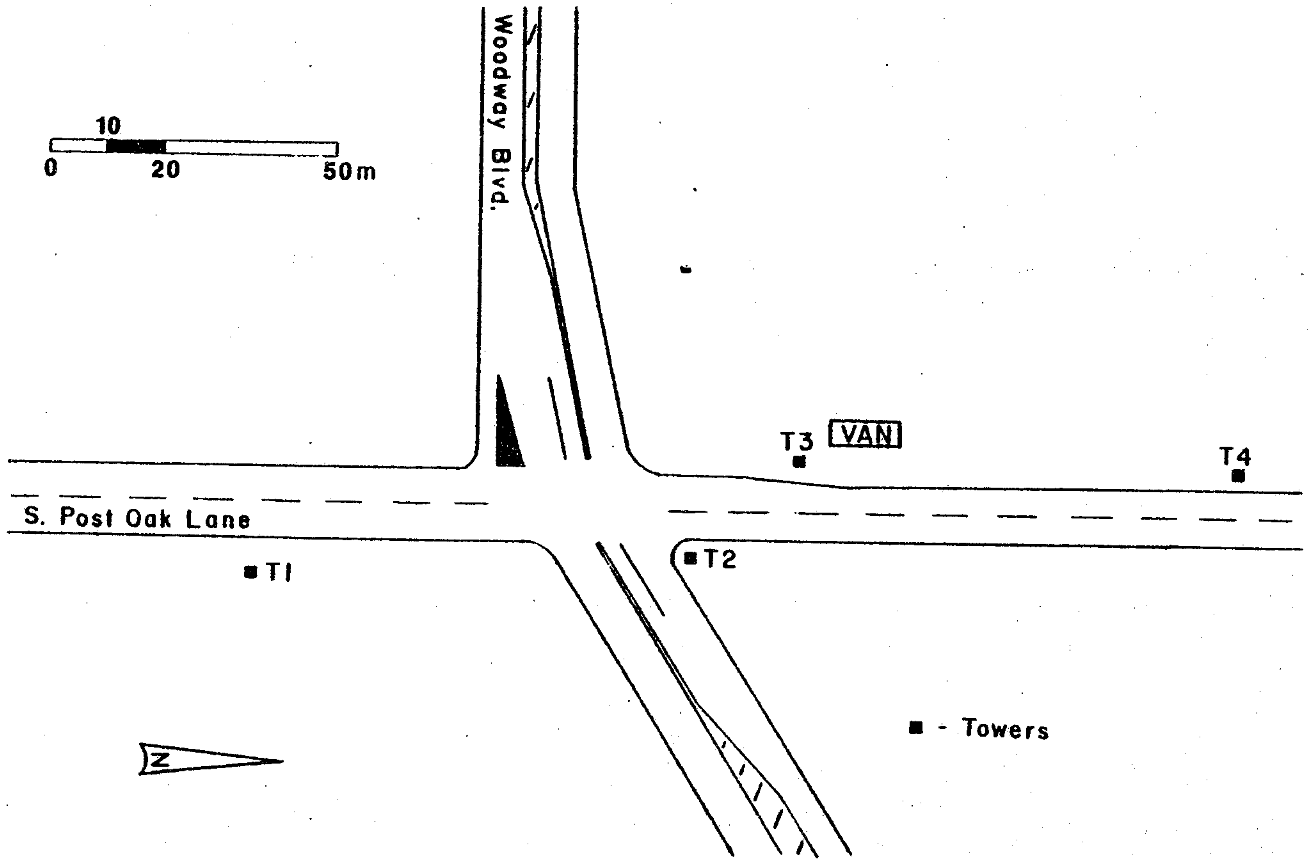


Figure 10. Site geometry for the Texas A&M - Houston data [28].

As at the College Station site, all instruments were interfaced to a Data General NOVA 1200 minicomputer. The measurements were taken essentially simultaneously allowing the dynamic responses of traffic, pollutant and meteorological conditions to be recorded. Tower 1 had UVW anemometers, thermistors and carbon monoxide Ecolyzers at the 5 and 35 foot (1.52 and 10.67 m) levels. Tower 2 had UVW anemometers at the 20 and 35 foot (6.10 and 10.67 m) levels, a cup anemometer and wind vane at the 5 foot (1.52 m) level, and CO ecolyzers at all three levels. Tower 3 had cup anemometers, wind vanes, thermistors and Ecolyzers at the 5, 20 and 35 foot (1.52, 6.10, and 10.67 m) levels. Tower 4 had a cup anemometer, wind vane and thermistor at the 20 foot (6.10 m) level, and an Ecolyzer at the 5 and 35 foot (1.52 and 10.67 m) level. In addition, a pyranometer at the trailer measured incoming solar radiation, and the barometric pressure and relative humidity were also recorded. Loop counters, placed in the approach and turn lanes, were used to obtain traffic counts and speeds. The raw data were edited (deleting any known bad data, etc.) and reduced to 5, 15, and 60-minute averages. Standard deviations were also calculated for the averages. The edited raw data are stored on standard nine-track tape in fixed-length, 80 byte records, and the averaged data (and standard deviations) are available as well. There are 97 60-minute cases, and a corresponding number of 15 and 5-minute cases available.

Sulfur Hexaflouride (SF_6) tracer was also released during approximately half of the Houston data cases. The gas was released at a constant, measured rate by a single vehicle passing back and forth without stopping through the intersection on Woodway Boulevard. Samples were collected using 15-minute sampling sequential syringes which were later manually analyzed for SF_6 concentration by gas chromatography.

CALTRANS Sacramento Study

During the months of February, March and April, 1980, The California Department of Transportation (CALTRANS) collected pollutant, traffic and meteorological data at the intersection of Florin Road and Freeport Boulevard in Sacramento [29]. Measurements were taken around the clock for a continuous period of forty days. The site and instrument layouts are presented in Figure 11.

The site surroundings consisted of bare or grass covered ground on all four quadrants for a distance of at least 50 metres from the travelled way. The terrain was level and occupied by scattered single story residential developments. A small community shopping center was also located well back from the intersection in the northwest quadrant. The site offered a reasonably high traffic flow without the interfering background sources of gas stations and parking lots normally associated with busy intersections.

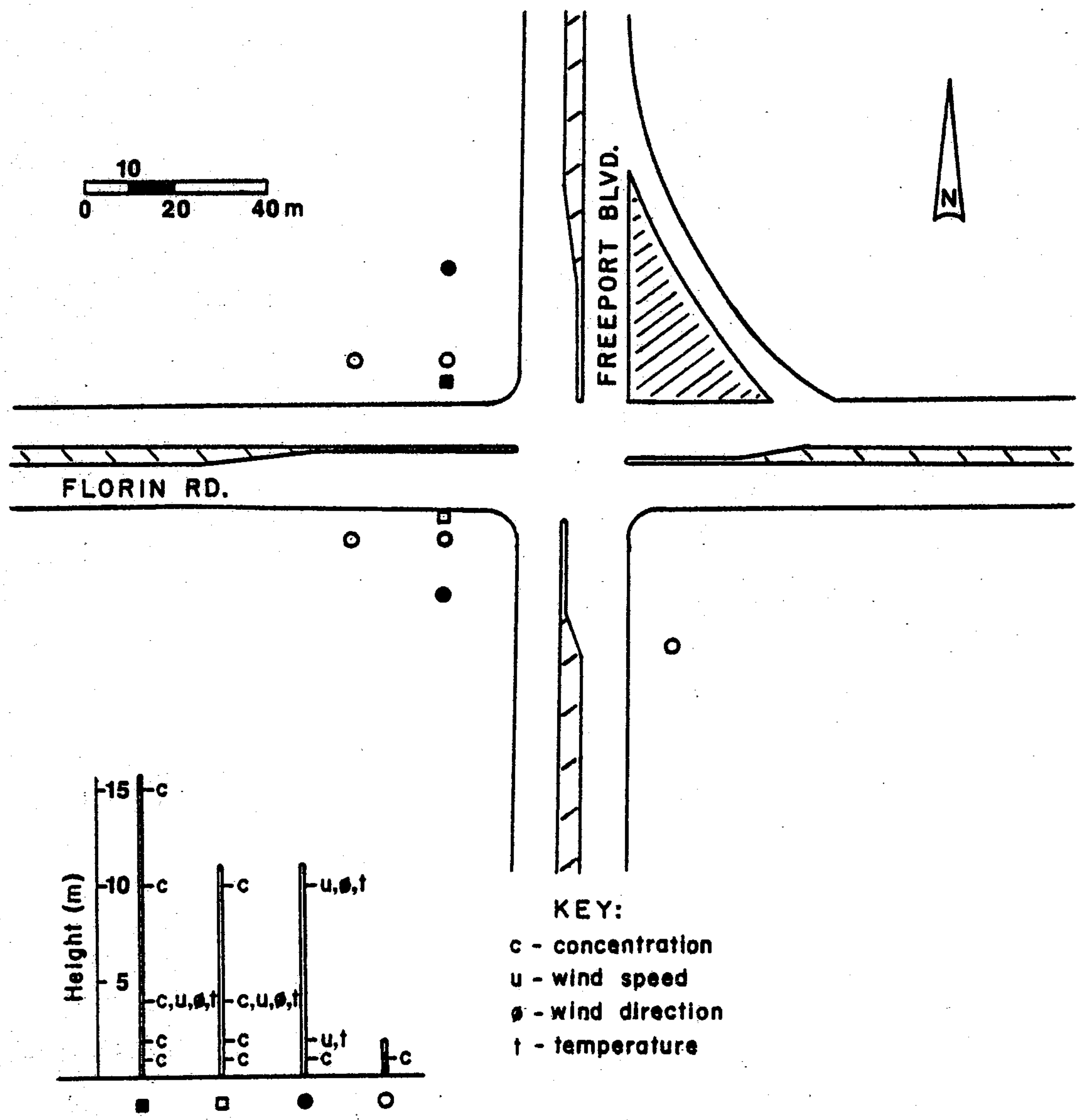


Figure 11. Site geometry for the California data [29].

Fifteen carbon monoxide probe locations were chosen. Eight of these were in the northwest quadrant and seven in the southwest quadrant. Also a sequential bag sampler was placed in the southeast quadrant. The two towers innermost to Florin Road contained vertical probe arrays with four probes on the southern tower at 1, 2, 4 and 10 metre (3.28, 6.56, 13.12, and 32.81 ft) heights, and five probes on the northern tower at the 1, 2, 4, 10 and 15 metre (3.28, 6.56, 13.12, 32.81, and 49.21 ft) levels. Three additional probes were placed in both the northwest and southwest quadrants at a height of one metre (3.28 ft). Sampling of the carbon monoxide levels was accomplished using two separate systems: Non-dispersive Infra-red (NDIR) analyzers and gas chromatographs with flame ionization detectors. Three NDIR analyzers were utilized with each coupled to five probe lines. An on-board minicomputer performed switching at one minute intervals so that each line was sampled one minute out of every five by an NDIR analyzer at line velocities of 10 ft/s (3.05 m/s). Gas chromatograph samples were taken as bag samples over the first 15 minutes of each hour, thus providing an integrated concentration measurement rather than the temporally stratified sample taken by the NDIR analyzers. The gas chromatography analyses were run only for the nine probes on the two towers innermost to Florin Road.

The outermost meteorological towers had cup anemometers and temperature probes at the 2 and 10 metre (6.56 and 32.81 ft) heights to provide wind speeds and temperatures, as well as wind shear temperature profile estimates. Wind direction was measured with wind vanes mounted at the 10 metre (32.81 ft) level on these same towers. Wind speed and direction readings were recorded every 0.1 seconds and temperature readings every 60 seconds. Bivane anemometer - fast response thermistor units were also mounted at the four meter level on the two innermost towers to Florin Road.

Traffic counts were obtained using pneumatic counters for inflow and outflow on each leg of the intersection. No measurement of the percentage of vehicles turning was made, nor was any attempt made to measure vehicle speeds.

The data base made available by CALTRANS consists of hourly averages (and standard deviations) for all of the recorded variables mentioned above. Additionally, hourly averages for the calculated variables, Richardson Number and Bulk Richardson number were provided. These data are stored on standard nine-track tape in the form of fixed-length 68 byte binary records.

Chapter III

MODEL DEVELOPMENT

As with many of the previous intersection studies, the development of the TEXIN Model required the performance of three major tasks: (1) estimation of various traffic parameters (queue length, time in queue, etc.); (2) estimation of vehicle emissions and their distribution; and (3) modelling of pollutant dispersion downwind of the intersection. Considerable emphasis was placed on developing a model that facilitated user application, yet achieved accuracy equal to or surpassing that of existing intersection models. Also, an effort was made to minimize the amount of computer time required.

A. OVERVIEW OF THE MODEL

The general flow diagram for the TEXIN Model is presented in Figure 12. The model requires a minimal set of four types of geometrical, meteorological, and traffic-related inputs, as shown in the figure. Initially, the Level of Service for the intersection and the stopped delay associated with this level of service are determined using a method known as "Critical Movement Analysis" for signalized intersections (a corresponding procedure is used for unsignalized intersections). The stopped delay is then used to calculate several other traffic parameters of interest, including approach delay, time in queue, percent

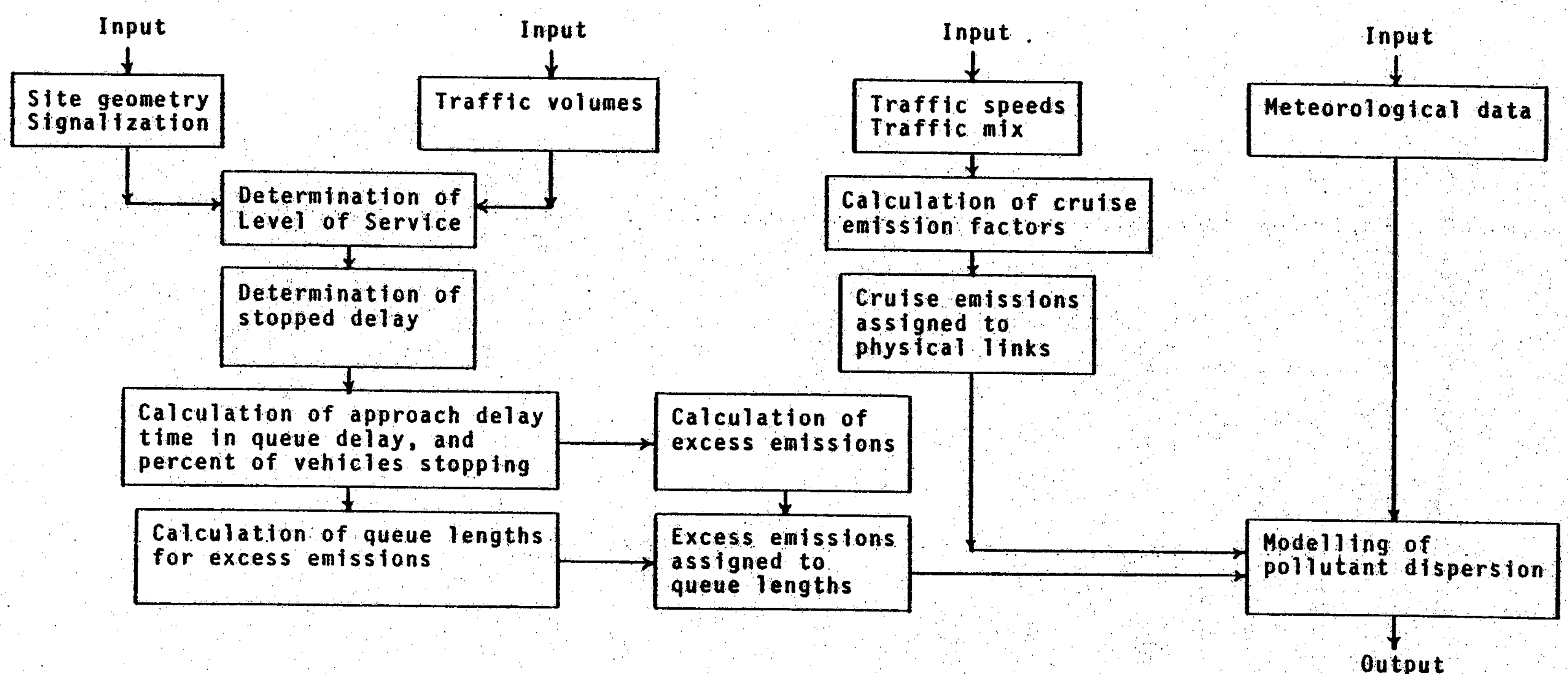


Figure 12. General flow diagram for the TEXIN Model.

of vehicles stopping, and queue length. Cruise emissions and excess emissions due to vehicles slowing, stopping, and idling are then estimated. Cruise emissions are assigned to physical links within the intersection and the excess emissions are assigned to pseudolinks formed from the queue lengths. The dispersion of pollutants downwind of the intersection is subsequently modelled for the specific meteorological scenario, and the results are output in a convenient format. The detailed mechanics of each aspect of the model are described in greater detail below.

The TEXIN Model is flexible enough to handle most intersection configurations which would realistically be encountered by highway engineers. The program can model the basic case of a simple intersection (signalized or unsignalized) with four straight legs, as well as more complex situations where the legs of the intersection may be curved. In addition to modelling the major intersection, the program has the flexibility to concurrently model several minor intersections (controlled by stop or yield signs) arising from nearby side streets. It should be noted that the dispersion routines in the TEXIN Model are not intended for use with "street canyon" configurations between tall buildings in highly urban areas.

B. TRAFFIC PARAMETER ESTIMATION

The first function performed by the program is that of traffic flow analysis. Initially, the traffic flow on the major intersection is evaluated and afterwards any minor intersections are handled. A complete description of the methodologies used in the TEXIN Model to perform the traffic flow analysis follows.

The primary factor normally considered by traffic engineers in determining the operating characteristics of an intersection is the "Level of Service" involved. The Level of Service is a measure of the mobility of an intersection and is stratified into the following six levels:

A - Free flow, low volume; high operating speed, high manueverability.

B - Stable flow, moderate volume; speed somewhat restricted by traffic conditions, high manueverability.

C - Stable flow, high volume; speed and manueverability determined by traffic conditions.

D - Unstable flow, high volume; tolerable but fluctuating operating speeds and manueverability.

E - Unstable flow, high volume approaching roadway capacity; limited speed (ca. 30 mph/48.3 kph), intermittent vehicle queueing.

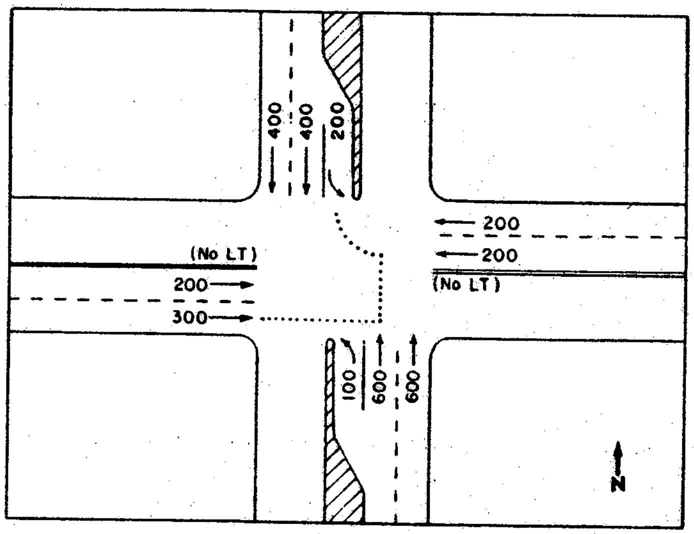
F - Forced flow, volume lower than capacity due to very low speeds; heavy queueing of vehicles, frequent stoppages.

The Critical Movement Analysis technique (as presented in Development of an Improved Highway Capacity Manual, NHCRP 3-28 [30]) was incorporated into the TEXIN Model to estimate the Level of Service for signalized intersections. Critical Movement Analysis is a procedure which permits the analysis of a signalized intersection as an entire unit. The basis of the analysis is the principle that at each signalized intersection a combination of conflicting movements (lane volumes) must be accommodated. The sum of these volumes is termed the "critical volume."

Figure 13 shows an example of critical movement combinations. The critical volumes are the volumes of travel represented by the highest lane volumes of opposing travel (through and left turn) for both the north-south and east-west directions. Once the critical volumes are determined for both directions, they are summed to give the "sum of critical volumes" which is compared to a benchmark intersection capacity to determine the Level of Service and volume to capacity ratio (V/C) for the intersection.

A number of elements can be considered in the calculation of the sum of critical volumes. These are: (1) lane width, (2) bus and truck volume, (3) bus stop operations, (4) left turns, (5) right turns with pedestrian activity, (6) parking activity and (7) peaking characteristics. Research has been conducted on these elements and has resulted in individual adjustment factors for each.

To minimize user input for the TEXIN Model only one adjustment factor of prime importance (that for left turns) was utilized. Left turning vehicles are treated in more detail for the simple reason that left turns (unless removed from through traffic by use of exclusive turn lanes) have a large impact on capacity. In the model, the effect of left



- Two and Three Lane Approaches
- Five Phase Actuated Signal
- Note: For the east-west street, the critical volume is 300 vph. For the north-south street the greatest demand for green time will occur with the conflicting movement totaling 800 vph (600 + 200 LT). The conflicting movement totaling 500 vph (400 + 100 LT) would require less green time and will be satisfied if the 800 vph critical volume is satisfied.
- Sum of Critical Volumes:
  300 + 800 = 1100 vph.

Figure 13. An example of critical movement summation [30].

turn vehicles is treated by using passenger car equivalency (PCE) values. PCE values are multiplicative adjustment factors applied to the left turning traffic volumes. Table 2 gives PCE values for left turns from both left-through lanes and exclusive turn lanes [30].

Critical Movement Analysis is based on per-lane volumes; thus, it is desirable for the user to supply volumes for each lane. However, this is not always possible and adds to the complexity of user inputs. For this reason, a table of adjustment factors was incorporated into the model. These factors were taken from a document on "Quick Response Techniques" published under the National Cooperative Highway Research Program (NCHRP) [31]. Table 3 presents lane-use factors to convert total directional movement into a lane volume. The lane-use factors exceed the inverse of the number of lanes in order to account for the unequal distribution of travel between lanes.

As part of the Critical Movement Analysis technique presented in NCHRP 3-28 [30], a set of guidelines on Levels of Service, volume/capacity (V/C) ratios, average delay values and sums of critical volumes was recently published. Table 4 gives recommended thresholds for the maximum sum of critical volumes for Levels of Service A through E. Table 5 shows the correlation between the volume/capacity ratio and delay values. These delay values relate to the mean stopped delay incurred by all vehicles entering the intersection. By linearly interpolating the volume/capacity ratio within

Table 2: Passenger car equivalency (PCE) values for left turn effects [30].

Left Turns Allowed from Left-Through Lanes						
1.	No Turn Phase	Opposing Volume (vph):	000-299	300-599	600-999	1000+
		1 Left Turn Equals:	1.0 PCE	2.0 PCE	4.0 PCE	6.0 PCE
2.	With Turn Phase	1 Left Turn Equals:	1.2 PCE			
Left Turns Allowed from Left Turn Bays Only						
3.	No Turn Phase	Opposing Volume (vph):	000-299	300-599	600-999	1000+
		1 Left Turn Equals:	1.0 PCE	2.0 PCE	4.0 PCE	6.0 PCE
4.	With Turn Phase	1 Left Turn Equals:	1.05 PCE			

Table 3. Lane-use factors [31].

Approach Lanes	Lane-Use Factor
1	1.00
2	0.55
3	0.40
4	0.30

Table 4. Level of Service ranges [30].

Level of Service	Maximum Sum of Critical Volumes		
	Two Phase	Three Phase	Four or More Phases
A	1000	950	900
B	1200	1140	1080
C	1400	1340	1270
D	1600	1530	1460
E	1800	1720	1650
F	---- Not Applicable ----		

Table 5. Delay and Level of Service [30].

Level of Service	Typical V/C Ratio*	Delay Range** (s/veh)
A	0.00-0.60	0.0 - 16.0
B	0.61-0.70	16.1 - 22.0
C	0.71-0.80	22.1 - 28.0
D	0.81-0.90	28.1 - 35.0
E	0.91-1.00	35.1 - 40.0
F	varies	40.1 or more

*Volume to capacity ratio.

**Measured as "stopped delay" as described in reference 32. Delay values relate to the mean stopped delay incurred by <u>all</u> vehicles entering the intersection. Note that traffic signal coordination effects are not considered and could drastically alter the delay range for a given V/C ratio.

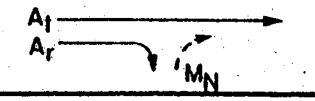
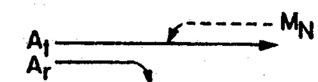
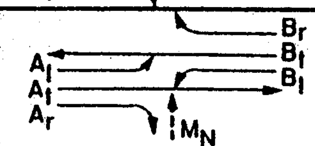
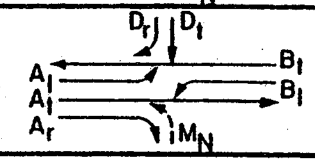
the delay range for the given Level of Service, the stopped delay for any volume/capacity ratio can be determined. This stopped delay per vehicle is the basis for determining other traffic parameters in the TEXIN Model.

When the demand volume exceeds the capacity of the intersection (V/C > 1) breakdown conditions exist (Level of Service - F). Under such conditions Critical Movement Analysis is not completely applicable and cannot accurately describe the traffic flow conditions under such circumstances (heavy queueing of vehicles, frequent stoppages, etc.). The model handles these situations by simply linearly extrapolating the stopped delay value beyond the applicable volume/capacity region (0.00 - 1.00). This gives stopped delay values above 40 seconds as is expected for breakdown conditions. However, the user is cautioned that the actual stopped delay value may not be the same as the value calculated, thus placing the model's results in question under these circumstances. The TEXIN program prints out a warning message when such situations occur.

The above methodology was applied for the traffic flow analysis of simple signalized intersections. A different procedure was necessary for unsignalized intersections because Critical Movement Analysis is only applicable to signalized intersections. The procedure incorporated into the TEXIN Model is the methodology presented in NCHRP 3-28 [30]. Only intersections controlled by two-way stop signs or yield signs can be treated by this analysis, thus limiting the TEXIN Model's applicability to these situations. Uncontrolled and four-way stop sign controlled intersections are therefore not within the scope of the model.

The methodology for unsignalized intersections is based on potential capacities for the minor approach movements which are compared to the existing demand for each movement to determine a Level of Service. The major street traffic is assumed to be unaffected by the minor street. Only left turning traffic on the major road is assumed to incur delay, and this is due to the opposing major street through traffic. Minor street flows, on the other hand, are impeded by all conflicting movements. It is necessary to deal with the individual traffic movements to treat all the potential impedances. These traffic movements are: (1) right turns into the major road; (2) left turns from the major road; (3) through traffic crossing the major road; and (4) left turns into the major road. These individual traffic streams are shown in Figure 14.

The conflicting traffic streams, M_H, are used to determine the maximum capacity, M_{No}, for a given movement. For vehicles emerging from the minor road (or turning left off the major road), the available gaps in the conflicting streams must be long enough to accommodate the desired maneuver. Table 6 gives critical gaps dependent upon the intended manuever, the type of control, the major road prevailing speed, and the number of lanes on the major road.

Step 1	Right turns into major street:	$M_H = 1/2A_r + A_t$	
Step 2	Left turns from major street:	$M_H = A_r + A_t$	
Step 3	Crossing major street:	$M_H = 1/2A_r + A_t + A_l + B_r + B_t + B_l$	
Step 4	Left turns into major street:	$M_H = 1/2A_r + A_t + A_l + B_r + B_t + D_r + D_t$	

Note: In Step 1, if there is more than one lane on the major street, A_t is the flow in the curb lane only.
In Steps 1, 3, 4, if a turning lane is present for major street right turns, A_r can be omitted.
In Steps 2 and 3, large radius turning areas for right turns off the major street and/or STOP or YIELD control of these turns reduce or eliminate the effect of A_r and B_r.
For complementary movements, reverse the major street movements (A and B) and minor street movements (C and D).

Figure 14. Definition of conflicting traffic schemes for an unsignalized intersection [30].

Table 6. Critical gap for passenger cars (s) [30].

Vehicle Maneuver and Type of Control	Prevailing Speed			
	30 mph (50 kph)		55 mph (90 kph)	
	Major Road		Major Road	
	2 lanes	4 lanes	2 lanes	4 lanes
Right Turn from Minor Road:				
YIELD Control	5.0	5.0	6.0	6.0
STOP Control	6.0	6.0	7.0	7.0
Left Turn from Major Road:				
No Control	5.0	5.5	5.5	6.0
Crossing Major Road:				
YIELD Control	6.0	6.5	7.0	8.0
STOP Control	7.0	7.5	8.0	9.0
Left Turn from Minor Road:				
YIELD Control	6.5	7.0	8.0	9.0
STOP Control	7.5	8.0	9.0	10.0

These critical gaps, T_g, are the minimum time gaps in the conflicting streams necessary to execute the desired manuever. The maximum capacity is determined from Figure 15 using the relevant conflicting volume and critical gaps.

This maximum capacity is the largest flow that can be achieved from the minor movement into the intersection, and is equal to the actual capacity for right turns from the minor road and left turns off the major road. However, additional adjustments are necessary for left turning and through traffic from the minor road to account for congestion interference. This is due to the possibility that traffic turning off the major road (and opposing minor road through traffic) may become congested and interfere with minor road traffic. To compensate for this, the maximum capacity is reduced through the use of an impedance factor, P, which defines the probability that the minor road movement will remain unaffected. Figure 16 gives the impedance factor as a function of the percent of capacity used (i.e., the ratio between the existing demand, B_L, of a potentially congesting flow and the maximum capacity, M_{No}, of that stream expressed as a percentage, $100[B_L/M_{No}]$). Figure 17 shows the manner by which maximum capacities for each movement are reduced.

One final adjustment is necessary to account for shared lane conditions. If each minor flow does not have an exclusive lane for that particular movement, there will be interference between those movements sharing the lane. The

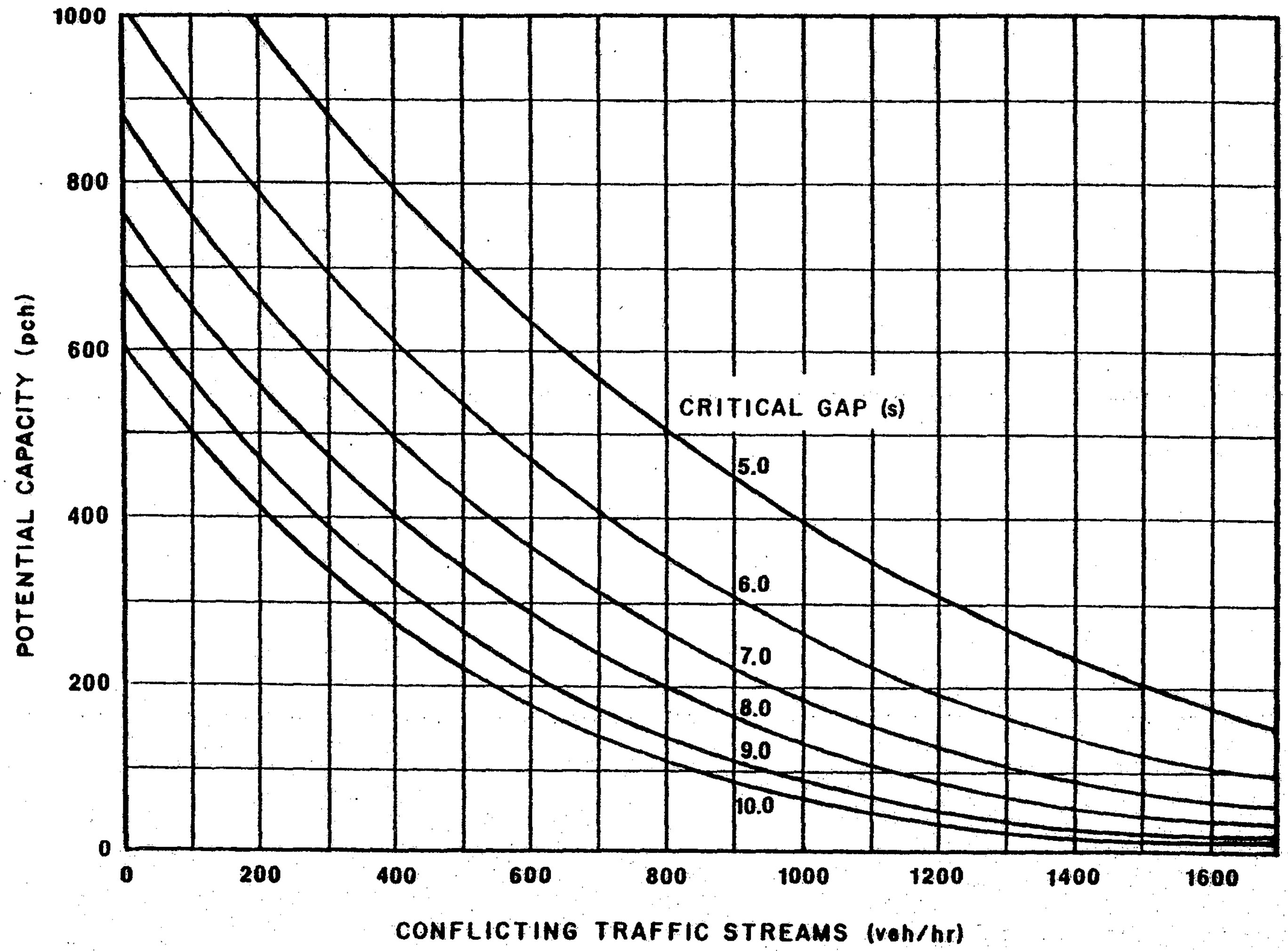


Figure 15. Maximum capacity based on conflicting volume and critical gap [30].

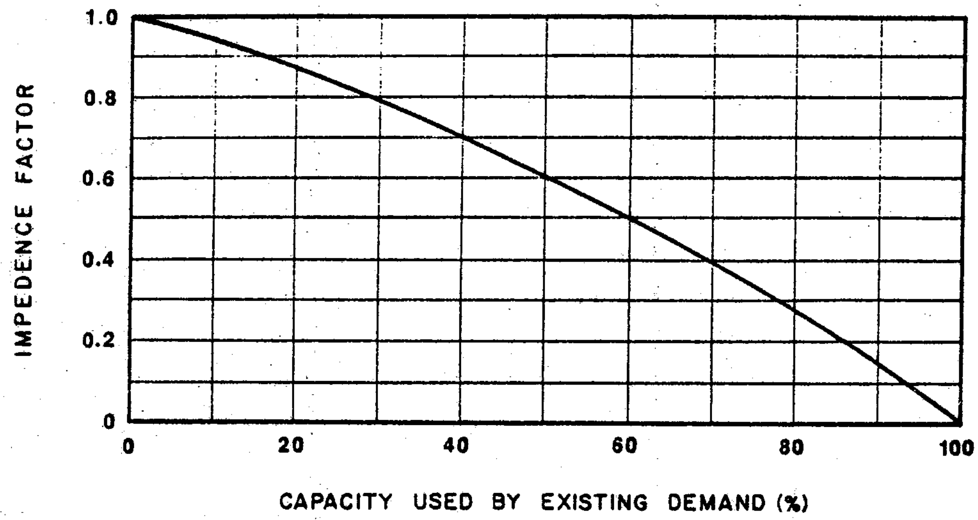


Figure 16. Capacity reduction caused by congestion [30].

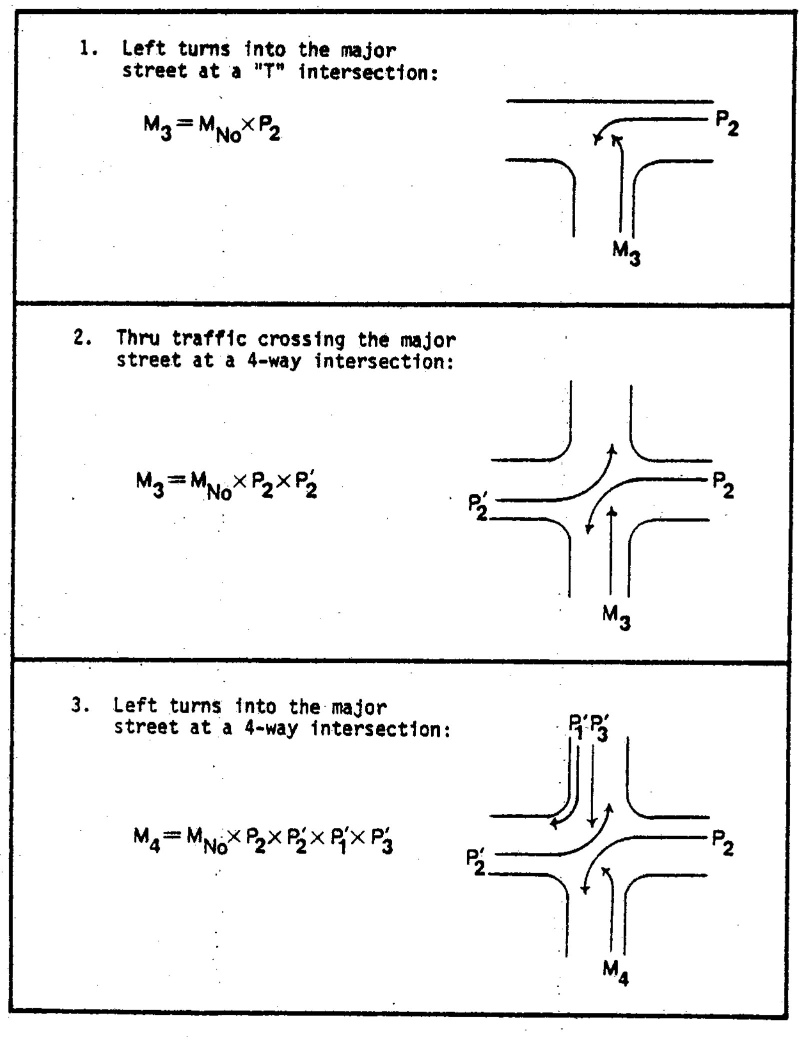


Figure 17. Application of impedance factors [30].

capacity of the shared lane can be determined by the following equation from NCHRP 3-28 [30]:

$$\frac{1}{M_{134}} = \frac{X}{M_1} + \frac{Y}{M_3} + \frac{Z}{M_4} \qquad \text{(III-1)}$$

M_{134} = capacity of all streams using the shared lane

X,Y,Z = proportion of right, through, and left movements, respectively

M_1, M_3, M_4 = capacity of the right, through, and left individual streams, respectively

Note that only those movements included in the shared lane are included in the computation.

Once the calculated capacity has been determined, a comparison is made with the existing demand. The difference between the calculated capacity and the existing demand is defined as the reserve capacity. The Level of Service and traffic delay are directly related to the reserve capacity as shown in Table 7. The suggested ranges of reserve capacities for the various Levels of Service are given in this table. Since a reserve capacity is calculated for each individual movement (unless shared lane conditions exist), the reserve capacity for each roadway is taken as the weighted average of the reserve capacities for the indiviual movements on the roadway. As in the case of signalized intersections, Table 5 is used to relate the Level of Service to stopped delay. By linearly interpolating the

Table 7. Level of Service and expected delay for reserve capacity ranges [30].

Reserve Capacity	Level of Service	Expected Traffic Delay
400 or more	A	Little or no delay
300 to 399	B	Short traffic delays
200 to 299	C	Average traffic delays
100 to 199	D	Long traffic delays
0 to 99	E	Very long traffic delays
less than 0	E	Failure - extreme congestion
(any value)	F	Intersection blocked by external causes

reserve capacity within the delay range for the given Level of Service, the stopped delay for any reserve capacity can be determined. Thus, a stopped delay per vehicle is determined for each leg of the intersection, and this value is the basis for determining other traffic parameters in the TEXIN Model.

A typical vehicle encountering delay at an intersection will normally experience one of three types of movement through the intersection. The vehicle may be forced to slow down, but not stop, on the way through the intersection; the vehicle may be forced to stop and then proceed through the intersection; or, if the intersection is extremely congested, the vehicle may come to a stop several times on the approach to the intersection. Figure 18 is taken from a study by Reilly, et al. [32] and shows the time-space relationship for a vehicle with multiple stops. Reilly also considered non-stopping vehicles which may be forced to slow down during the approach. Figure 19 depicts the movement of such a vehicle encountering delay but not actually stopping.

Several definitions relating to characteristics of vehicle delay (as defined by Reilly, et al. [32]) should be introduced at this point. They are:

(1) <u>Approach Delay Section</u>--The approach delay section is a section of roadway of fixed length on the approach to a signalized intersection. This distance is the length over which all delay associated with an intersection will occur.

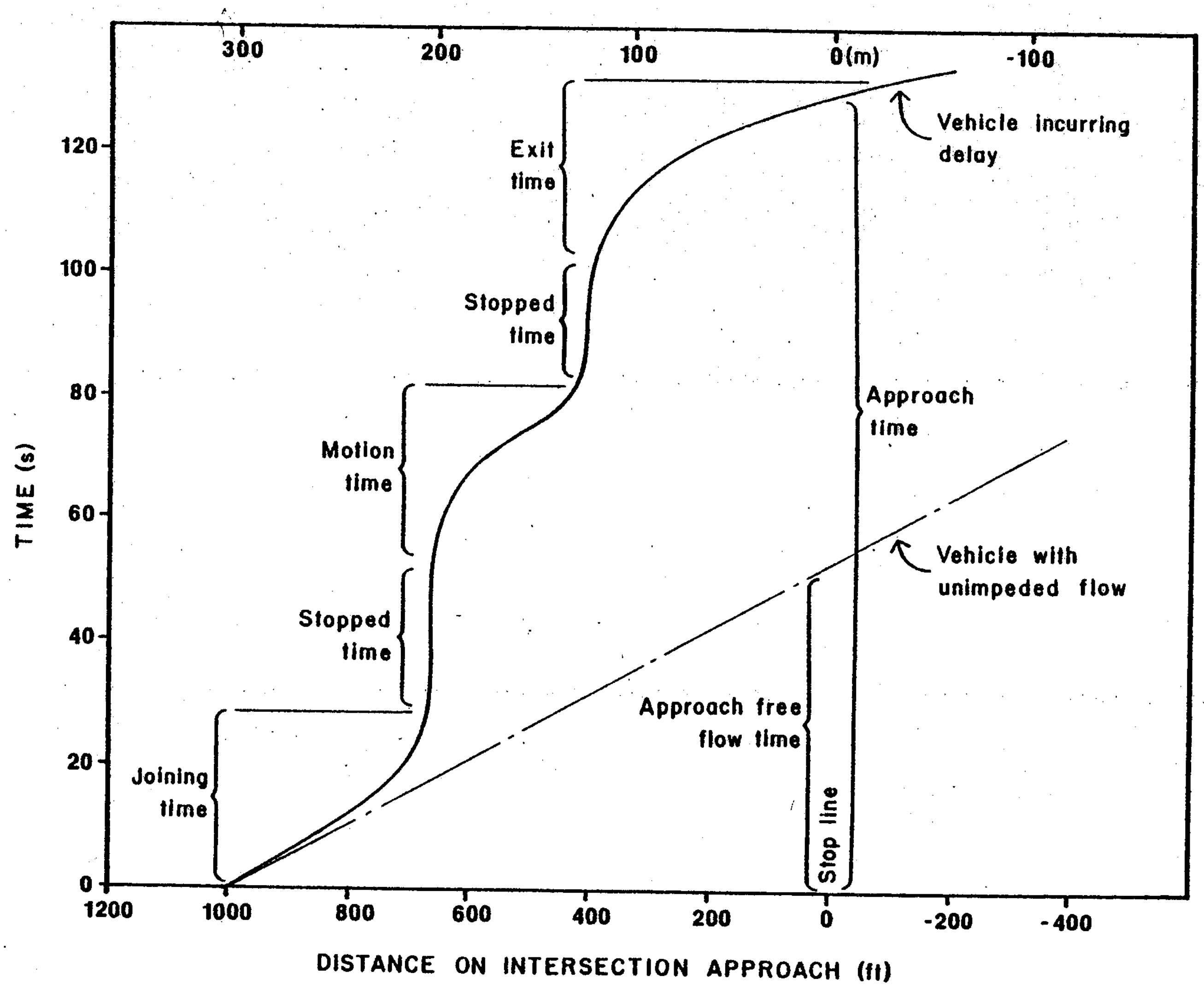


Figure 18. Time-space relationship for a vehicle with multiple stops [32].

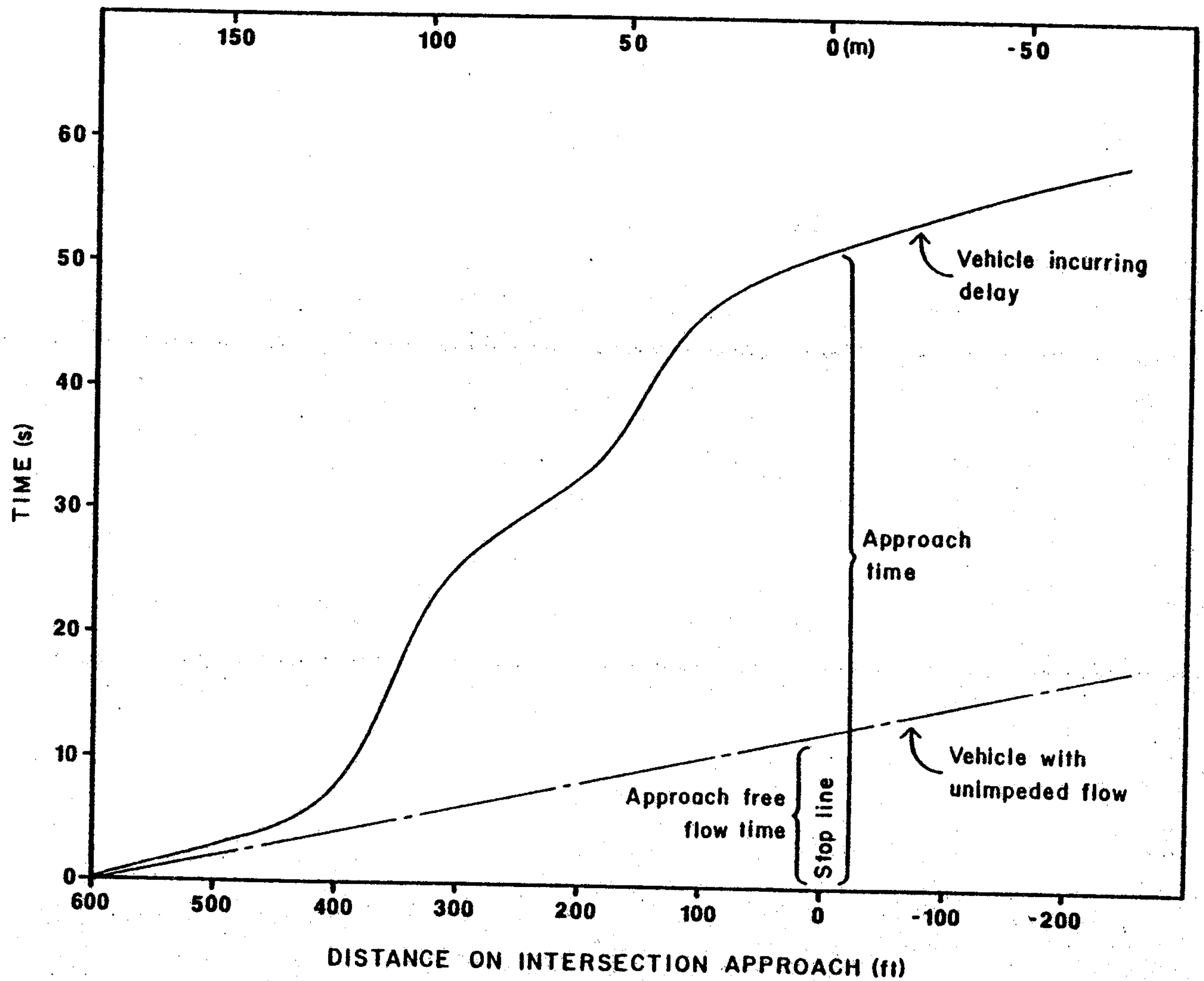


Figure 19. Time-space relationship for a vehicle incurring delay but no stops [32].

(2) Approach Free Flow Time--The time required by a vehicle to traverse the approach delay section when the vehicle incurs no delay due to the intersection, and the vehicle is travelling at free flow speed.

(3) Approach Time--The time used by a vehicle in traversing the approach delay section. This time includes all signal-related delay incurred by the vehicle.

(4) Approach Delay--The approach time for a vehicle minus the approach free flow time.

(5) Stopped Time--That portion of approach time during which the vehicle is stopped due to signal related activity.

(6) Stopped Delay--Equal to stopped time.

(7) Motion Time--That portion of approach time which occurs between two periods of stopped time.

(8) Exit Time--That portion of approach time which occurs between the end of the final stopped time segment and the departure of the vehicle from the approach delay section.

(9) Time in Queue--The sum of stopped time, motion time and exit time. This measure applies only to those vehicles stopping.

(10) Time in Queue Delay--Equal to time in queue.

(11) Percent of Vehicles Stopping--The number of vehicles incurring stopped delay divided by the total volume of vehicles exiting the approach delay section.

To determine the inter-relationships between stopped delay, approach delay, time in queue and percent of vehicles stopping, Reilly, et al. [32] conducted a study of ten urban intersections from the Boston, MA.; Washington D.C.; Oklahoma City, OK. and Tucson, AZ. areas. The ten selected intersections represented a wide range of conditions and the results of the research were intended to be generally applicable throughout the United States. Using time-lapse photography, time values for the above mentioned measures were obtained, and statistical analyses of the various correlations were performed. Figures 20 through 22 show the regressions relating these four measures as well as the statistical results of these correlations. Of particular interest is the strong linear relationships ($R^2 > 0.94$) between the measures suggesting that accurate estimates for approach delay, time in queue, and percent of vehicles stopping can be based on the stopped delay (as determined from Critical Movement Analysis or the corresponding analysis for unsignalized intersections). For this reason, these relationships were incorporated into the TEXIN Model.

Once the percent of vehicles stopping has been determined, the queue length, QL, can be calculated. The following equation was developed to calculate the queue length:

$$QL = \frac{PCST*TTEI*8*Cy}{3600} \qquad \text{(III-2)}$$

where: PCST = the percent of vehicles stopping

TTEI = the total number of vehicles entering the intersection on a per lane basis, veh/hr

CY = cycle time, s

8 = the distance occupied by a queued vehicle, m

This is the total queue length at the intersection (e.g., the sum of the individual queue lengths for all approach legs). For individual legs of the intersection, the queue length is

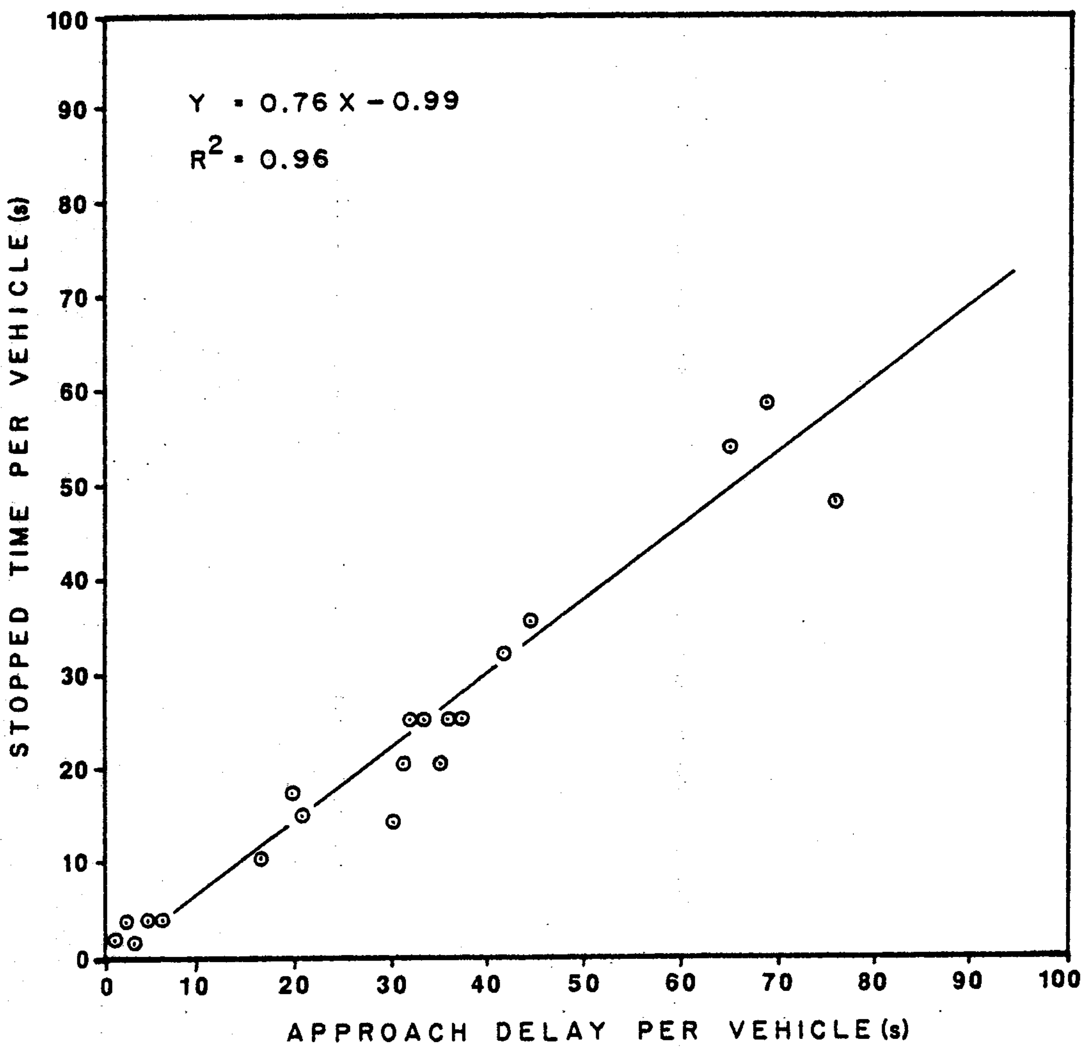


Figure 20. Stopped time per vehicle versus approach delay per vehicle [32].

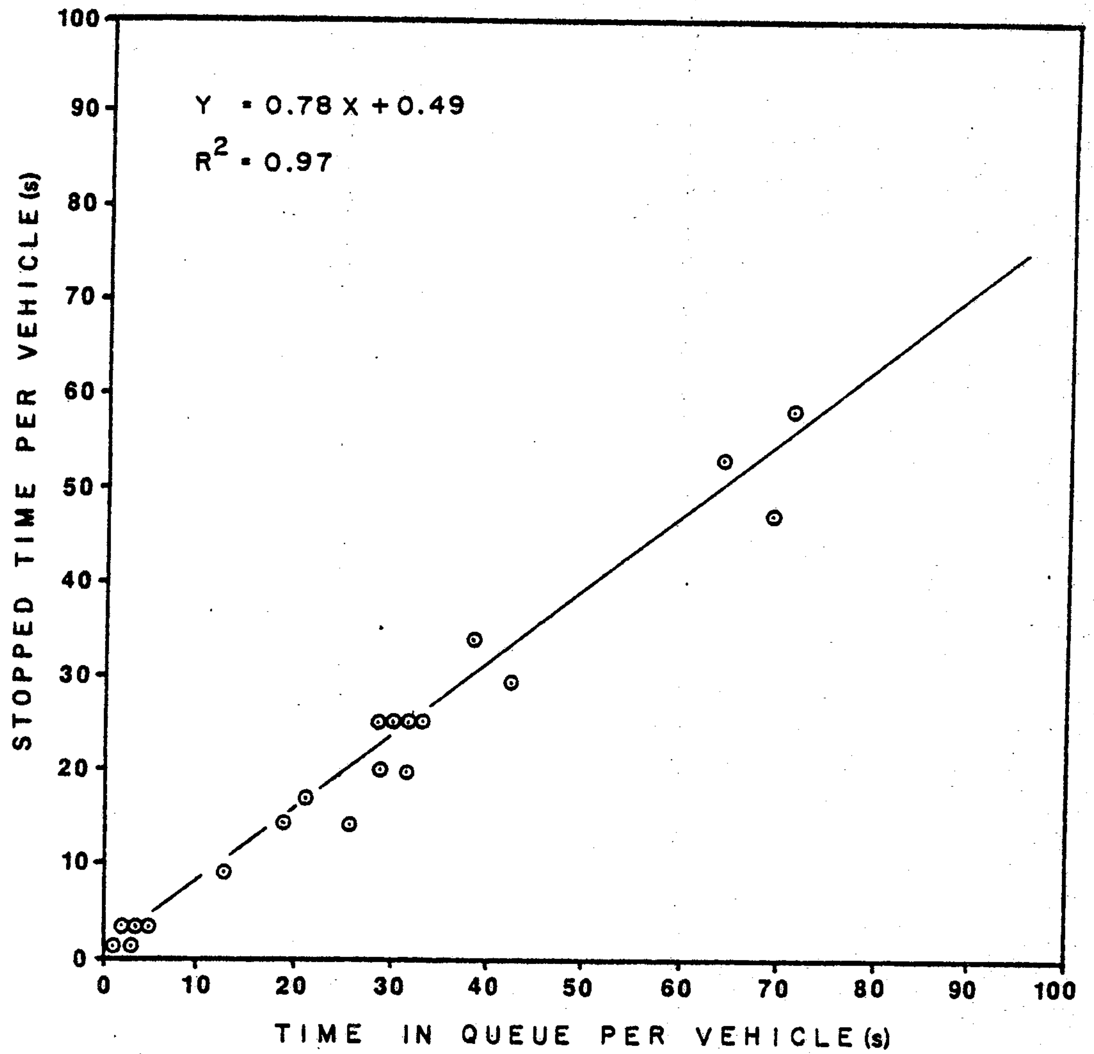


Figure 21. Stopped time per vehicle versus time in queue per vehicle [32].

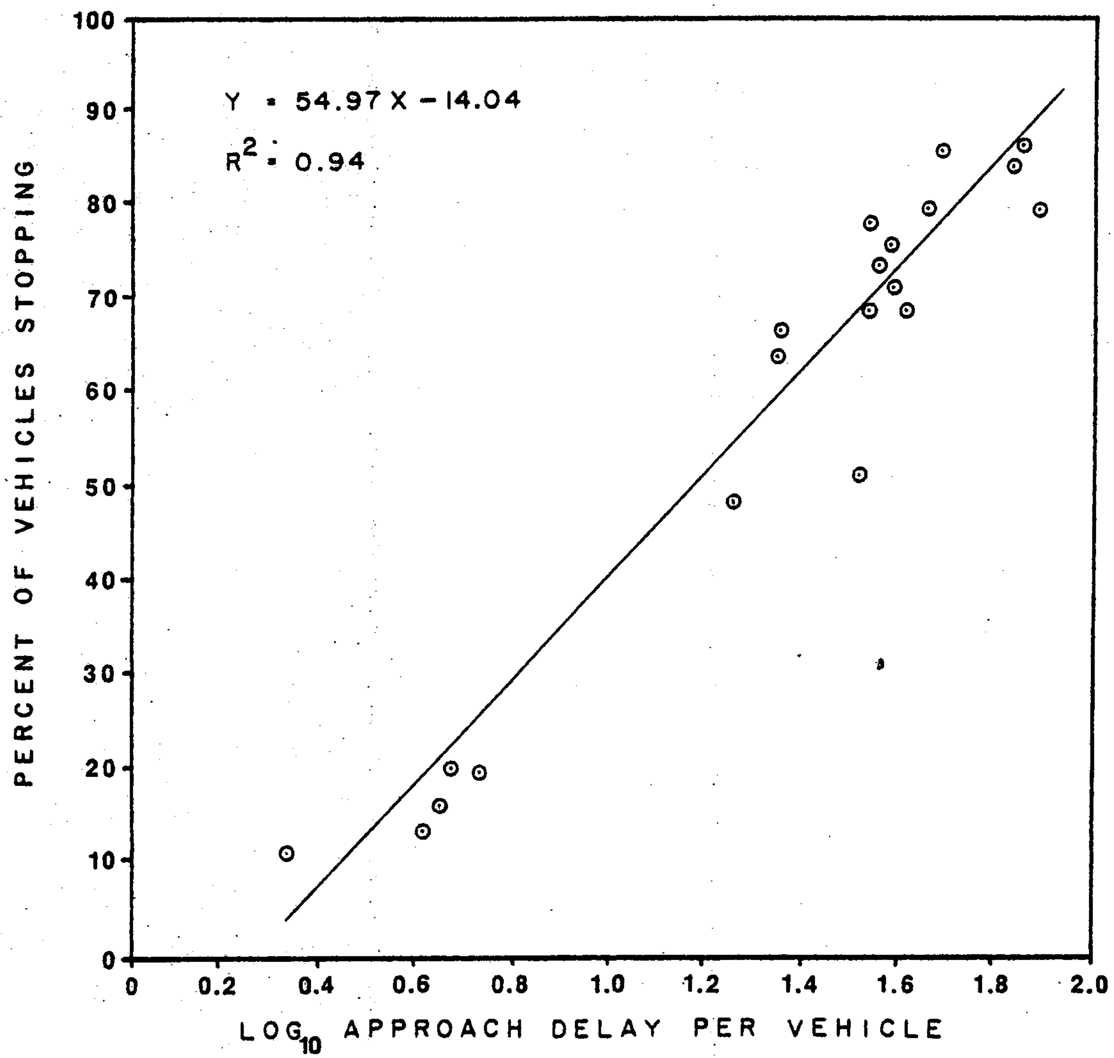


Figure 22. Percent of vehicles stopping versus $\log_{10}$ approach delay per vehicle [32].

determined by replacing TTEI with the individual approach leg volumes in equation (III-2) above. For an unsignalized intersection, the following equation was developed to calculate the queue length for the individual legs of the intersection:

$$QL = 8* \frac{\text{Existing Demand}}{\text{Reserve Capacity}} \quad \text{(III-3)}$$

For minor intersections (controlled by stop or yield signs) arising from nearby side streets, the methodologies for unsignalized intersections presented above are utilized with certain simplifying assumptions to facilitate user application and keep the analyses tractable.

C. VEHICLE EMISSIONS ESTIMATION

The second function performed by the model is the estimation of vehicle emissions. The emissions are modelled as the sum of two components: cruise emissions from free flowing traffic and excess emissions emitted by vehicles incurring delay (either slowing, stopping or idling). The cruise emissions are assumed to be uniformly distributed along the entire length of the roadway, while the excess emissions are taken to be emitted only over the queue length. The MOBILE-2 program was incorporated into the model to estimate the cruise emissions of free flowing vehicles. These are the most recent emissions rates available, and allow the user to either specify the specific scenario (VMT mix, cold/hot start fractions, etc.) or to use the default national average values.

To conserve computer time, sizeable portions of the extremely large MOBILE-2 were deleted program which were not needed by the TEXIN Model. These deletions included the nitrogen oxides and hydrocarbon emission factors, optional correction factors for inspection/maintenance programs, air conditioning and extra-load towing, and most of the input/output processing. These modifications resulted in an approximate two-thirds decrease in storage space as well as a similar decrease in the compilation and execution time required to process the MOBILE-2 program. It should be noted that the MOBILE-2 emissions model is merely a subroutine of the TEXIN Model. Users of the model who are familiar with FORTRAN can easily modify the model to include future versions of MOBILE-2 or of any cruise emissions estimation routines.

Since MOBILE-2 will only estimate average emissions for vehicles at an average route speed, a method for estimating excess emissions due to vehicles slowing and stopping had to be adopted. The method incorporated into the TEXIN Model utilized the traffic parameters determined above and nomographs relating excess emissions to speed changes, as suggested by Ismart [33]. Excess emissions are calculated as the sum of three components: emissions due to vehicles stopping and returning to an initial speed, emissions due to vehicles slowing (but not stopping) and returning to an initial speed, and emissions due to vehicles idling.

The carbon monoxide emissions due to vehicles stopping is determined by the following equation from Ismart [33]:

where: COST = total amount of excess CO emitted due to vehicles stopping, lbs/hr

ER = pounds of CO emitted per 1000 speed changes

1000 = factor to convert ER to pounds per speed change

The emission rate, ER, is determined using Figure 23 by considering the vehicle as going from the initial speed to zero speed and then returning to the initial speed. These emission rates are based on the most recent rates available (from work completed by Kearis in 1980 [34]). The rates were derived using at-grade data obtained in St. Louis, Missouri, and the 1977 Modal Analysis Model. They pertain to 100% light-duty, 100% hot stabilized, low-altitude, non-California vehicles for a base year of 1975. For the study, Kearis assumed an average acceleration/deceleration rate of 3 miles/hr/sec (1.3 m/s^2).

To account for the difference between the emission rates under the actual vehicle scenario and under the Modal Analysis Model vehicle scenario, a correction factor must be applied to these rates. This correction factor is calculated as the ratio of the MOBILE-2 composite emission factor for the inputted vehicle scenario to the MOBILE-2 composite emission factor for the Modal Analysis Model vehicle scenario. The emission rate obtained from Figure 23 is multiplied by this correction factor to give the correct emission rate for use in equation (III-4).

To determine the carbon monoxide emissions due to vehicles slowing, the following equation from Ismart [33] is used to calculate the time lost by vehicles slowing down but not stopping:

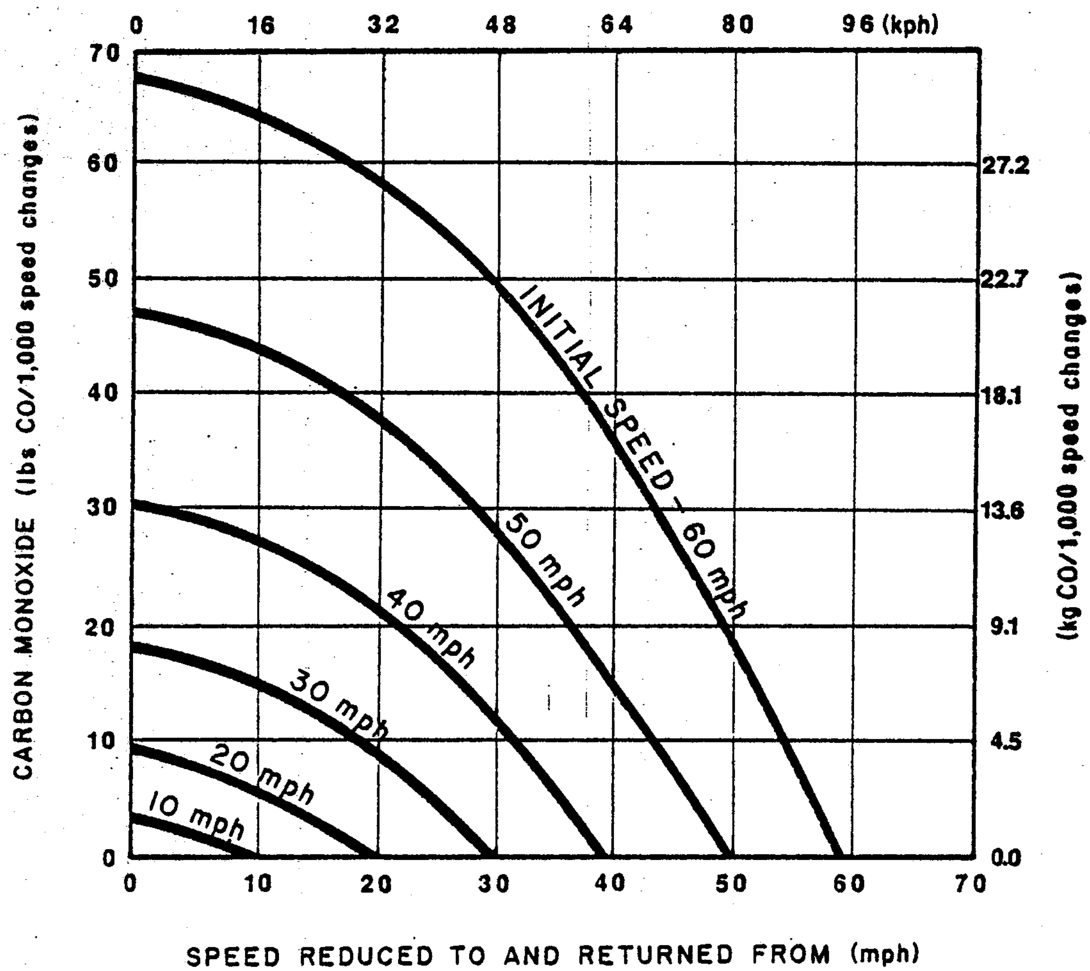


Figure 23. Carbon monoxide emissions for vehicular speed changes [34].

$$\text{Slowdown Delay} = \text{ADPV} - \text{TIQPV} \qquad \text{(III-5)}$$

where: ADPV = approach delay, s/veh
TIQPV = time in queue delay, s/veh

Once the slowdown delay per vehicle is determined, the excess emissions due to vehicles slowing, COSD, is estimated from an equation by Ismart [33]:

$$\text{COSD} = \frac{(\text{ADPV} - \text{TIQPV})*\text{TTEI}*\text{ER}}{3600*\text{HRS}} \qquad \text{(III-6)}$$

where: ER = pounds of CO emitted per 1000 speed changes
HRS = the excess hours consumed per 1000 speed changes

The value for HRS is obtained from Table 8 [35] using the initial speed and the speed reduced from and returned to. The emission rate, ER, is obtained from Figure 23 using the initial speed and the speed to which the vehicle slows. Once again, the correction factor is applied to the rate obtained from Figure 23.

Ismart suggests that for simplifying purposes this slowdown speed should be assumed equal to one-half the initial speed. Since this was an arbitrary assumption, its accuracy was checked using actual data from the Texas A&M College Station data. For this purpose, the initial speed was taken as the weighted average of the vehicle speeds obtained from the seven traffic loops located in the approach lanes (well upstream of the

Table 8. Excess hours consumed for vehicular speed changes (hr/1000 speed changes) [35].

Initial Speed (mph)	Speed Reduced To and Returned From											
	Stop	5 8	10 16	15 24	20 32	25 40	30 48	35 56	40 64	45 72	50 80	(mph) (kph)
5	1.02											
10	1.51	0.62										
15	2.00	1.12	0.46									
20	2.49	1.62	0.93	0.35								
25	2.98	2.11	1.40	0.80	0.28							
30	3.46	2.60	1.87	1.24	0.70	0.23						
35	3.94	3.09	2.34	1.69	1.11	0.60	0.19					
40	4.42	3.58	2.81	2.13	1.52	0.97	0.51	0.16				
45	4.90	4.06	3.28	2.57	1.93	1.34	0.83	0.42	0.13			
50	5.37	4.54	3.75	3.01	2.34	1.71	1.15	0.68	0.35	0.11		
55	5.84	5.02	4.21	3.45	2.74	2.08	1.47	0.94	0.57	0.28	0.09	

intersection), and the slow-down speed was taken as the weighted average of the speeds obtained from the six traffic loops internal to the intersection (in the right and left turn lanes). Initially, it was assumed that there would be a strong relationship between the percent reduction in the initial speed and stopped delay per vehicle. However, when a regression analysis was performed little correlation between the two variables was found. Therefore, the relationship between the initial speed and the slow-down speed was examined. A regression analysis of these variables gave the equation:

$$\text{Slowdown speed} = 0.45(\text{Initial speed}) \qquad \text{(III-7)}$$

with good correlation ($r^2 = 0.90$). Since the value of 0.45 is in close agreement with Ismart's suggestion of 0.5, the 0.50 value was incorporated into the model.

Excess emissions due to vehicles idling are calculated from the stopped delay per vehicle and the idling emission rate using the following equation from Ismart [33]

$$\text{COID} = \text{SDPV*TTEI*ER}/(60*453.6) \qquad \text{(III-8)}$$

where: COID = total amount of CO emitted due to vehicles idling, lbs/hr

SDPV = stopped delay per vehicle, s/veh

ER = idling emission rate, gm/veh-min

453.6 = conversion factor from grams to pounds

60 = conversion factor from minutes to seconds

The idling emission rate, ER, is determined using the MOBILE-2 program.

The total excess emission factor is then calculated using the values for COST, COSD and COID and the total queue length. The following equation was developed to calculate the total excess emission factor:

$$EF = \frac{(COST + COSD + COID)*453.6}{QL*3600} \qquad \text{(III-9)}$$

where the emission factor, EF, is in gm/m-s. Since Critical Movement Analysis treats the entire (signalized) intersection as a whole, the values for COST, COSD, and COID as calcuated in equations (III-4) through (III-8) represent the total excess emissions due to vehicular delay at the intersection; and thus, the value for the queue length must be the value described by equation (III-1). Therefore, the model does not distinguish between the various approach legs when determining the excess emissions. One excess emission factor is calculated for the entire intersection, and it applies to all legs. However, the method of distributing the excess emissions along the links treats each approach leg individually. The queue length for each separate approach leg is used as the length of roadway over which the excess emissions are emitted for that leg.

For unsignalized intersections, the individual queue lengths for each leg of the intersection are used in equation (III-9) yielding a different emission factor for each leg. Additionally, the values used in equation (III-4) through (III-8) are those values for the individual legs of the intersection (e.g., as stopped delay, percent stopping, approach delay, etc.). This results from determining a different Level of Service for each leg of an unsignalized intersection.

D. POLLUTANT DISPERSION MODELLING

The Gaussian dispersion model, CALINE-3, was incorporated into the TEXIN Model to calculate the dispersion of pollutants downwind of the intersection. CALINE-3 requires less input than other models (i.e., HIWAY-2), and its performance in predicting concentrations for cases where experimental values are available has been shown by Rodden, et al. [36] to be the best among pollution dispersion models capable of handling intersection situations. CALINE-3 treats each leg of an intersection (both incoming and outgoing traffic lanes) as a separate link, rather than treating each individual lane as a link. This not only greatly simplifies the necessary input, but also complements the Critical Movement Analysis technique and the rest of the analysis of traffic flow incorporated in the TEXIN Model.

Several minor modifications were made to CALINE-3, mainly to the input/output routines, so that it could handle the pseudolinks over which the excess emissions occur (and in the units calculated above). However, all the normal capabilities of CALINE-3 remain the same. As incorporated into the TEXIN model, it will still handle depressed, fill or bridge sections, curved roadways, various receptors, raised source heights, and all related situations for which it was designed. CALINE-3 is not applicable to street canyon configurations, however. In addition to modifications made to input/output routines, an attempt was made to make CALINE-3 applicable for lower wind speeds. The User's Guide for CALINE-3 states that the model has not been verified for wind speeds less than 1 m/s, and that assumptions of negligible along-wind dispersion and steady state conditions are questionable at such low wind speeds.

Examination of the Texas A&M data from the College Station site at extremely low wind speeds (less than 1 m/s, approximately 10% of the cases) showed that the measured concentration gradient between the low (5 ft.) receptors and the high (35 ft.) receptors was substantially less than for those cases corresponding to high winds. This suggests that at low wind speeds there is an increased rise of pollutants. This phenomena has also been researched by Chock [37]. In studying the effect of plume rise at low wind speeds, Chock developed a line source model that allowed for plume rise. However, such a method would require substantial modification to the CALINE-3 model. Consequently, a simpler approach was adopted to account for plume rise by merely raising the source height. Chock reports an ambient plume rise speed of 0.15 m/sec for a crosswind road speed of 0 m/s. Using this value and the value for residence time as calculated by CALINE-3, the following equation was developed to calculate the height that the source is raised (above the inputted source emission height):

$$\Delta H = 0.15\ (TR)$$

This additional height, ΔH, can be thought of as the height that a pollutant emitted at the roadway centerline would rise by the time it reached the roadway edge. TR is the residence time calculated by CALINE-3. The result of this modification on model performance is discussed in Chapter IV.

E. SUMMARY OF MODEL INPUTS AND OUTPUTS

To summarize the input data required by the TEXIN Model and the output from the same, the procedure for modelling a sample intersection is presented. For a simple, signalized intersection with four right-angle corners, an X-Y Cartesian coordinate system is mapped onto the intersection with the axes lying coincident with the two perpendicular roadways. This places the center of the intersection approximately at the origin of the Cartesian coordinate system.

The first input required by the model is the geometry of the four links (approaches) representing the intersection. These inputs are data that are easily obtained and normally available, and consist of: (1) the upstream and downstream coordinates of each link, (2) the width of each link, (3) traffic volume for each link, (4) average vehicular speed for each link, (5) estimated percentage of cars turning right and left for each link, (6) the number of approach and turning lanes for each link, (7) the source (link) height, and (8) the link type (i.e., at-grade, fill, etc.). Next, the Cartesian coordinates (including the height) of the receptors must be specified. The meteorological conditions are required next and consist of wind speed, wind direction (measured clockwise with respect to the positive y-axis), the stability class, temperature, and the mixing height. In addition, the surface roughness and averaging time are required by the CALINE-3 program incorporated into the model. As an option, the user may specify the VMT mix and the percentage of hot starts/cold starts for use in the MOBILE-2 program. Otherwise, the national default values for these parameters are used. In addition, information on the signalization is required (e.g., number of phases, left turn phases and cycle length).

The primary output of the TEXIN Model is, of course, the predicted carbon monoxide concentrations at the receptors. Additional optional outputs can also be printed. These include a summary of the input data, the composite emission factors and idling emission rates (from MOBILE-2), the excess emission factors, the queue lengths and other traffic parameters of interest (stopped delay, etc.), as well as the CO concentration contribution from each individual link and psuedolink at the receptors.

Copies of the complete input and output files for three specific cases are included in the User's Guide in the appendix. For a more detailed explanation of model inputs and outputs, the reader is also referred to this User's Guide.

CHAPTER IV

RESULTS AND DISCUSSION OF RESULTS

The primary objectives of the project were to identify and evaluate pollution estimation procedures for simple signalized intersections and to calibrate and/or otherwise improve these models. Owing to the complex nature of the intersection problem, the only valid criterion for these evaluations was comparison to experimental data. Two other important, but secondary, considerations were ease of use and economy of computer time. With these objectives in mind, the initial phases of the project involved extensive literature search and review, as summarized in Chapter II. Evaluation of the literature pinpointed only a few models and data bases suitable for continued study under the project.

The Texas A&M College Station data were chosen as the principal basis for the work. The TAMU data were found to be the most comprehensive available due to the simultaneous nature of the traffic, pollution, and meteorological measurements. Also, the TAMU data were acquired by the principal investigators and therefore were readily available and well understood. In later stages of the study, the Sacramento, California, data base was received and was also used for comparison purposes. Near the end of the study, the Texas A&M Houston data also became available and were utilized. Analysis of the raw data available in these three data bases is described below. The rationale for the elimination of the New York and other data bases was outlined in Chapter II.

Three predictive models were found to be worthy of detailed study. These were the Intersection Midblock Model (IMM) (as modified by Piracci, et al. [14]); the Colorado Model, MICRO; and the Indirect Source Guidelines - Volume 9 (Revised). As discussed in detail below, each of these methods was applied to all or part of the TAMU College Station data and the resulting statistics were analyzed. All of the models were found to be very approximate in nature and all required considerable effort to use.

Attempts were made to calibrate the emission factors and dispersion estimates for these models using the TAMU data. However, considering the accuracy of the results obtained, as well as the degree of effort and computation time necessary for use of these methods in the field, it was decided to attempt the development of a simpler technique of comparable value.

Making use of established "short-cut" traffic and emissions estimation techniques as described in Chapter III, the TEXIN Model was thus developed. The techniques in the TEXIN Model were those which appeared to best model the Texas A&M - College Station data. Subsequent changes and adjustments to the TEXIN Model (e.g., raising the source height for low wind speeds) were also inspired by comparison to the College Station data. This practice of best fitting the College Station data could thus be considered as biasing the TEXIN Model to that data; however, no empirical correlations based on the College Station data were used. All the techniques, correlations, etc. in the TEXIN Model were derived from the literature (e.g., the plume rise relationship from Chock) and were independent of the College Station data. In addition, the California and Houston data bases are completely unbiased since they were not available until after the TEXIN Model had been developed.

The TEXIN Model was found to have superior accuracy to the three models cited above for simple signalized intersections. The model is also very simple to use and requires less than one-tenth of the total computer time required by the IMM.

A detailed discussion of these comparisons is included below with a description of the input parameters involved. The results of the TEXIN simulation of the California and Houston data are also presented. A discussion of model applications and "worst case" considerations follows and the chapter is concluded with a summary of other more qualitative project results.

A. COMPARISON OF MODEL PREDICTIONS TO THE COLLEGE STATION DATA

The methods by which the input parameters were specified for each of the models were made as consistent as possible to properly compare the results. It was also observed that minimizing the number and complexity of the required inputs would be a strong advantage for a new model. For these reasons, a detailed description of the input parameters for each model's simulation of the Texas A&M - College Station data is given below. The inputs which were common to all models are summarized first and the input data particular to each model are discussed afterwards.

Inputs Common to All Models

The wind speed and wind direction were required by all models, and the ambient temperature was required by all but MICRO. Stability class was also a primary requirement for all four models in question. The average wind speed and the incoming solar radiation (as a measurement of insolation) were used to determine stability class. The average wind speed was taken as the arithmetic mean of the four anemometers at a given height for the 15-minute sampling period, and the incoming solar radiation was measured by the pyranometer. Figure 24 was then used to determine the stability class from an analysis by Pasquill [38]. The average wind direction and temperature were also taken as the arithmetic mean of the wind vanes and thermistors, respectively.

A value of 1000 meters (3281 ft) was used as the mixing layer height in all cases as there were no special nocturnal inversion situations in the College Station data. The roughness height was determined using Myrup and Ranzieri's table of suggested surface roughness values as given in the

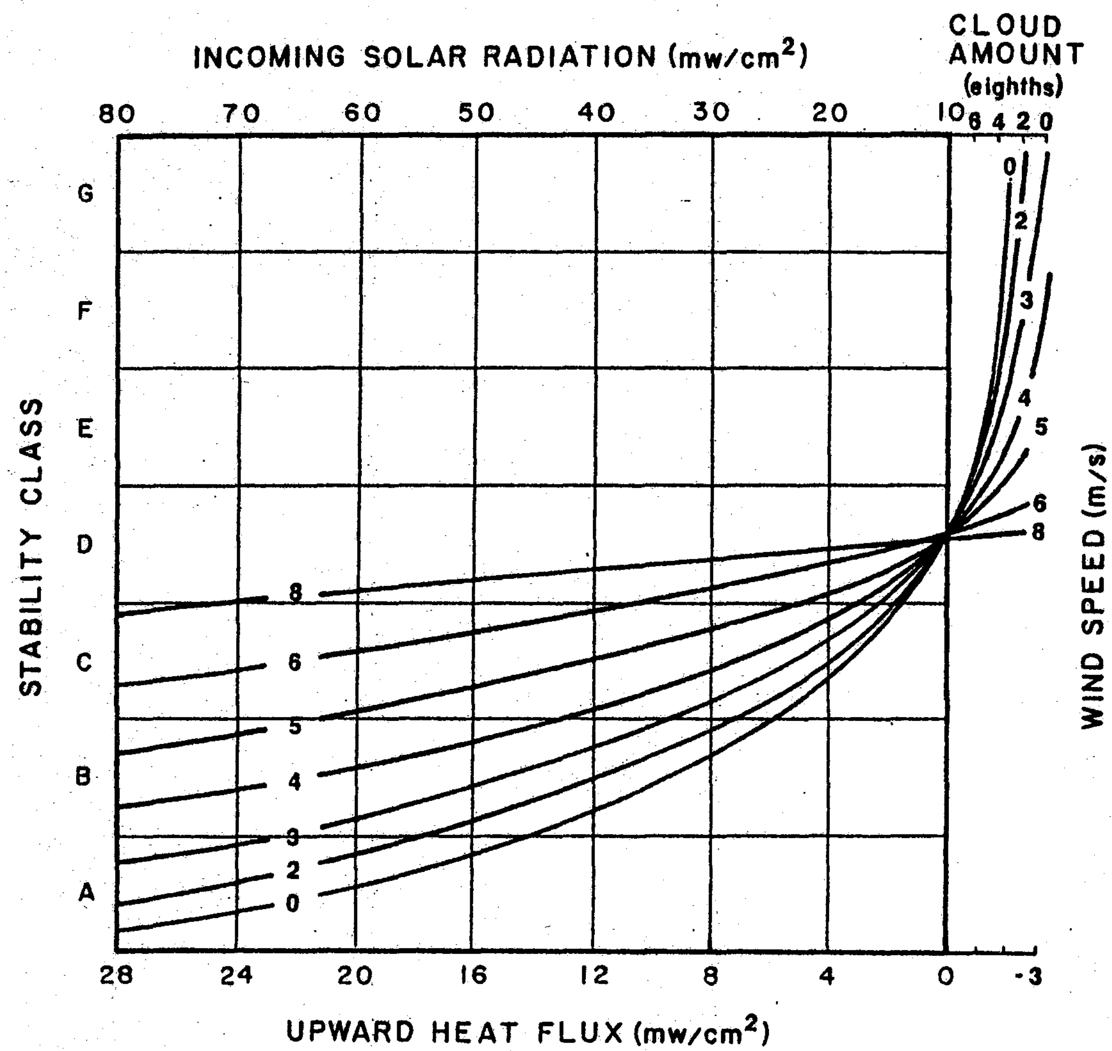


Figure 24. Pasquill stability classes, A-G, as related to wind speed and incoming solar radiation [38].

CALINE-3 User's Guide [8]. Since the majority of the College Station data involved a wind blowing out of the southwest quadrant which contained a shopping center with one-story buildings, a roughness height of 1.5 meters (4.92 ft) was chosen. (This value was not required by the IMM).

The input variables pertaining to the VMT mix and the operating mix (% cold starts, hot starts, etc.) were county-wide values obtained from the Texas State Department of Highways and Public Transportation [39] and are given in Tables 9 and 10. (These values were not required by MICRO).

The length of the links (as measured from the intersection to the upstream end of the link) used in the IMM, MICRO, and the TEXIN Model were as follows: 650 metres (2133 ft) for the northern leg of Texas Avenue, 450 metres (1476 ft) for the southern leg of Texas Avenue, 450 metres (1476 ft) for Jersey Street, and 250 metres (820 ft) for Kyle Street. For Texas Avenue these distances were the lengths of roadway to the intersections north and south of the intersection under study (minus approximately 75 metres to account for delay at these intersections). For Jersey and Kyle Streets, these distances were the length of roadway to major curves in the streets. These distances are not critical since the majority of emissions are emitted in the vicinity of the intersection by vehicles slowing, stopping, accelerating and idling. The width of the roadway and the source emission height (assumed to be zero) were required by all the models except MICRO.

Table 9. VMT mix for Brazos County [39].

Year	LDGV	LDGT1	LDGT2	HDGV	HDDV	MC
1980	0.590	0.224	0.108	0.038	0.036	0.004

Table 10. Percentage cold starts/hot starts (1980) for Bryan/College Station, Brazos County area [39].

Time of Day	PCCN	PCHC	PCCC
00-02	44	11	54
03-05	54	7	59
06-08	46	13	57
09-11	24	32	52
12-14	18	33	37
15-17	27	27	39
18-20	16	29	40
21-23	27	18	48

Observed Concentration Convention

The observed carbon monoxide concentration values were calculated as the measured downwind CO concentration minus the average measured upwind CO concentration. Since Tower 4 was set up as the primary upwind tower, theoretically the only cases for which true background concentration values could be obtained were those with a wind out of the southwest quadrant (winds blowing from any angle between the southern leg of Texas Avenue and the western leg of Jersey Street, as shown in Figure 9). For winds blowing from the northwest quadrant, pollution from vehicles on Jersey Street could alter the background value. However, most emissions are emitted near the intersection and Tower 4 was located at a considerable distance from Jersey Street. Consequently, it was assumed that for winds blowing from the northwest quadrant, Tower 4 concentrations were valid background values for wind angles less than 45 degrees (as measured from Jersey Street). For wind angles greater than 45 degrees, the Tower 4 receptors were affected by vehicles encountering delay on Jersey Street and thus these data were omitted from the analyses.

Of the 153 15-minute sampling periods chosen from the College Station data, approximately one-third were in the less than 45 degree segment of the northwest quadrant. Exclusion of these data did not significantly improve or detract from the performance of any of the models tested. Therefore, the assumption appeared to be valid, and the data were included in the analyses.

Additional Inputs For The Intersection Midblock Model (IMM)

The IMM requires by far the most extensive input data of all models considered. The model treats each lane of traffic as a separate finite line source (or link). Consequently, the signalization for each lane (type of control, number, and length of phases, etc.) must be determined and supplied to the model. For each phase of the cycle, a description of each lane approaching the intersection must also be specified. Along with the geometry of each link, the volume, velocity into and out of the intersection, and the deceleration into and acceleration out of the intersection must also be supplied. Velocity and acceleration data were not collected in the College Station study. Therefore, these values had to be estimated. This was done using the equation:

$$V_f^2 = V_o^2 + 2a\ (x_o - x) \qquad \text{(IV-1)}$$

For vehicles approaching the intersection, the final speed, V_f, was assumed to be zero; and for vehicles leaving the intersection the initial speed, V_o, was assumed to be zero. The distance over which acceleration/deceleration occurs, (x_o-x), was assumed to be 200 feet (61.0 m) for both accelerating and decelerating vehicles. This is approximately the distance from the intersection that vehicles will begin to incur delay due to signal activity. Using these values, the acceleration (deceleration), a, was calculated from equation (IV-1). The velocities into and out of the intersection were taken as the average route speed for the respective lanes.

The lane capacity for each approach link must also be supplied to the model and this value was obtained from Table 4 as 1650 veh/hr. The geometry of the links leaving the intersection must be specified, but only the volume and velocity on these links need to be input in addition. The fractional volumes per lane for all links are also required and would need to be estimated by the average user. However, since the College Station data contain the necessary volumes by lane, actual values of these fractions were used.

Minor modifications to the input/output routines of the IMM program were necessary to enable the simulation of all sampling periods in one run. (The IMM is an extremely long program and the compilation time would have been excessive if it had been recompiled for each simulation.) Major debugging of the program was also necessary since the developmental version supplied by the NYSDOT was not completely compatible with the Amdahl 470 FORTRAN H (Extended) compiler at Texas A&M.

Additional Inputs for MICRO

The MICRO program required little input due to the fact that a vast majority of the required variables are set internally to "reasonable" values. The only input data required are volume counts for the through and turning traffic on the four approach links and the type of signalization involved (type of control, number, and length of phases). The remaining variables, such as vehicle speeds, link geometry, wind speed, wind direction, receptor locations, etc., are generated internally. Minor modifications to the input/output routines allowed the actual measured values for these variables to be used and for the simulation of all the cases to be performed in one run. Minor debugging was also necessary since the program was written on a CDC computer for an interactive mode and would not compile on the Amdahl 470.

One point of confusion (on which the User's Guide gave no information) concerned the source and receptor heights. One of the namelist variables set internally is the height of the individual links. However, no value for the receptor or source height is mentioned in either the User's Guide or the program listing.

By examining the program listing, the height of the link was determined to be the height difference (or sum), z-h, (or z+h), of the source, h, and the receptor, z. By using a source height of zero (as was used for all cases studied), the sum and difference are equal; thus, the various receptor heights were input as the height of the links in order to get predicted CO concentrations for the different receptors.

Additional Inputs for the TEXIN Model

In addition to the common inputs, the TEXIN Model required only the approach volumes and fractions turning on the four approach links, the number of phases and the total cycle length of the signal, as described in Chapter III. It should be noted that the other inputs required (which were common to all models) are generally those inputs required by the CALINE-3 and MOBILE-2 programs. The TEXIN Model requires a minimal set of inputs which can be easily specified by the average user.

Statistical Comparison of Models

The Intersection Midblock Model (IMM), the program MICRO, and the TEXIN Model were each used to simulate the 153 15-minute average sampling periods of the Texas A&M - College Station data. Scattergrams of predicted versus observed values are presented in Figures 25-27 and a comparison summary of the regressions is shown in Table 11. Figure 28 presents a comparison of these regressions in graphical form.

With respect to these figures, note that a perfect fit would yield a slope of 1.00, an intercept of 0.00, and a regression coefficient of 1.00. The large degree of scatter present in all of the models is due to the difficult nature of the intersection pollution problem and explains the reluctance of many highway design engineers to place confidence in such simulations.

Examination of these statistics indicates that the TEXIN Model is somewhat better than the IMM and much better than MICRO for the simple signalized case under consideration. MICRO exhibits by far the worst performance of the three models. MICRO consistently underpredicts with

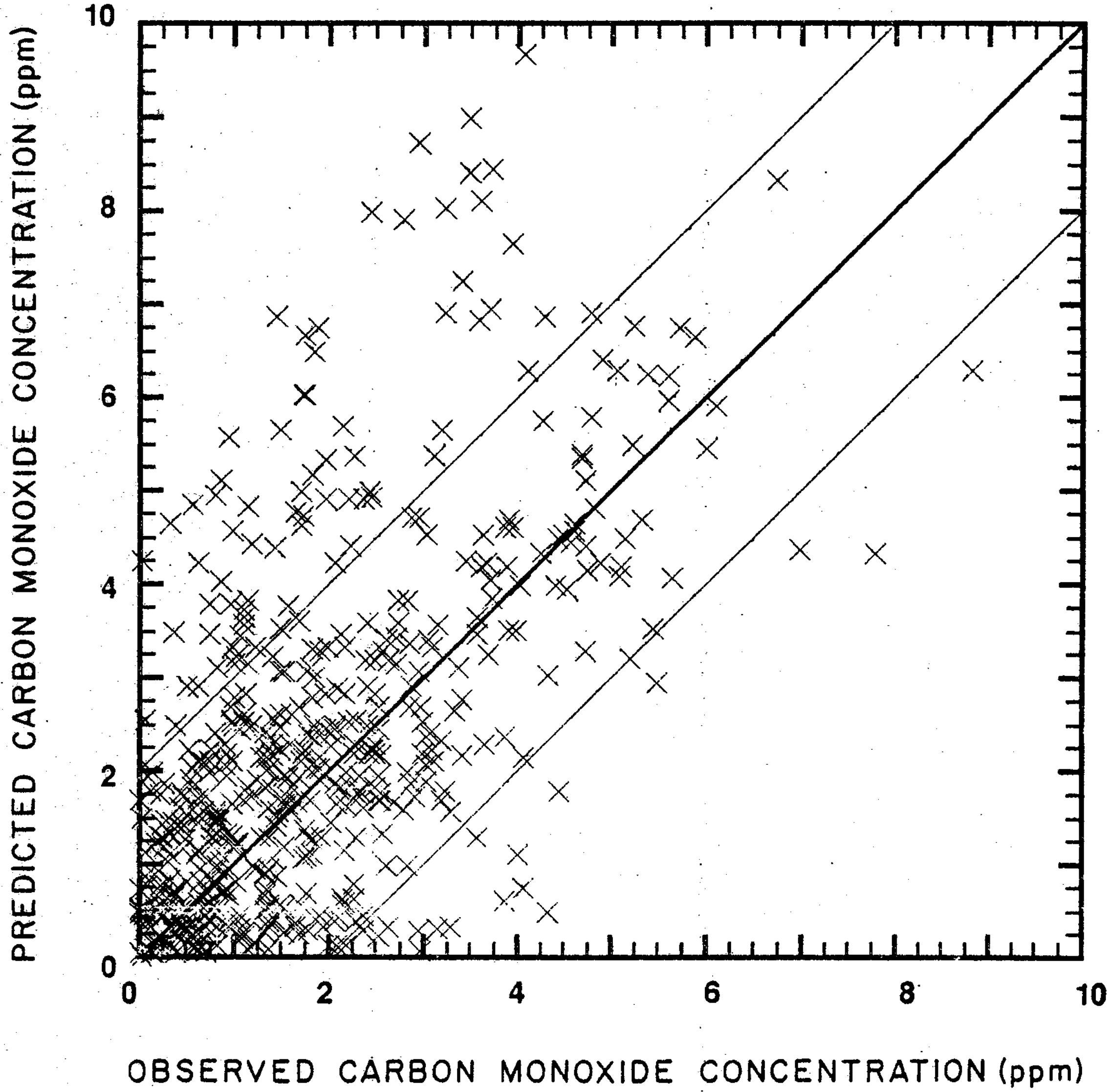


Figure 25. Scattergram of predicted versus observed CO concentrations for the IMM using the Texas A&M - College Station data [28].

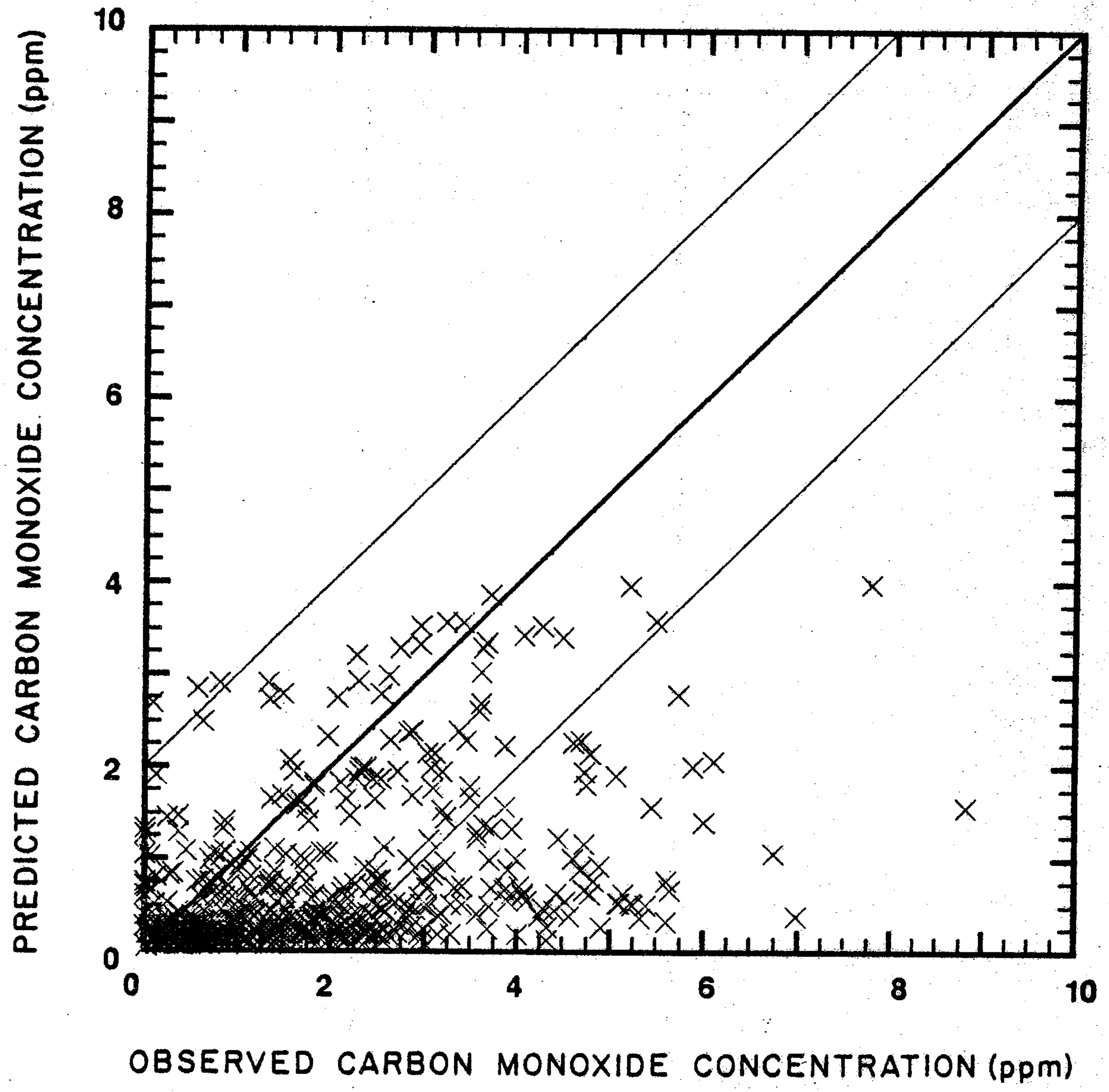


Figure 26 Scattergram of predicted versus observed CO concentrations for MICRO using the Texas A&M - College Station data [28].

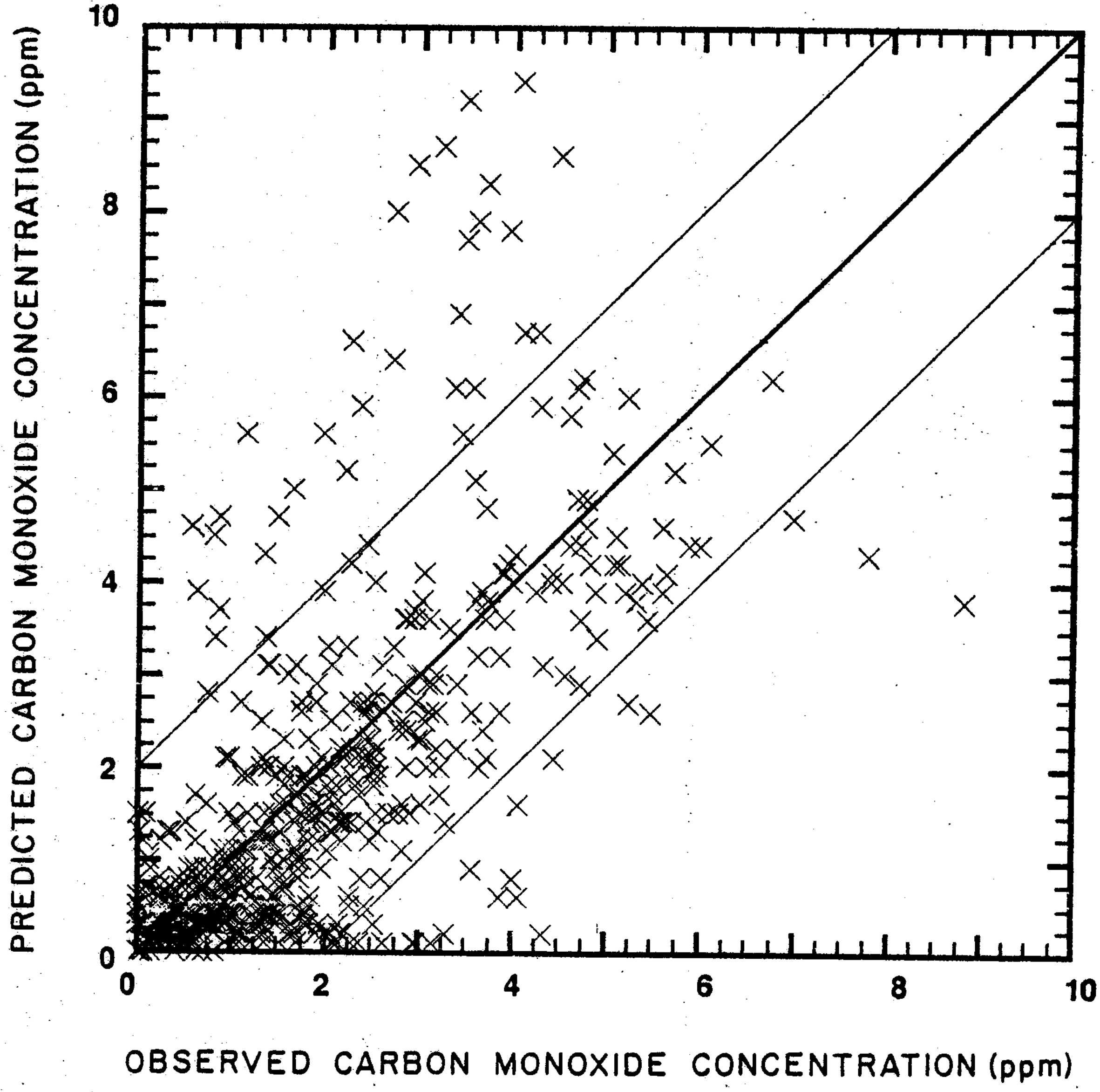


Figure 27. Scattergram of predicted versus observed CO concentrations for the TEXIN Model using the Texas A&M - College Station data [28].

Table 11. Statistical comparison of the TEXIN Model, the IMM and MICRO predictions for the College Station data [28].

Statistic	TEXIN	IMM	MICRO
Slope	0.85±0.04	0.81±0.04	0.23±0.02
Intercept (ppm)	0.14±0.09	0.80±0.10	0.26±0.05
r^2	0.469	0.373	0.182
Avg. Error (ppm)	-0.14	0.47	-1.16
Avg. Sq. Err. (ppm^2)	1.80	2.67	3.12
No. of Points:			
Total	539	539	539
Within 2 ppm	482(89%)	446(83%)	418(78%)
Within 1 ppm	380(71%)	327(61%)	277(51%)

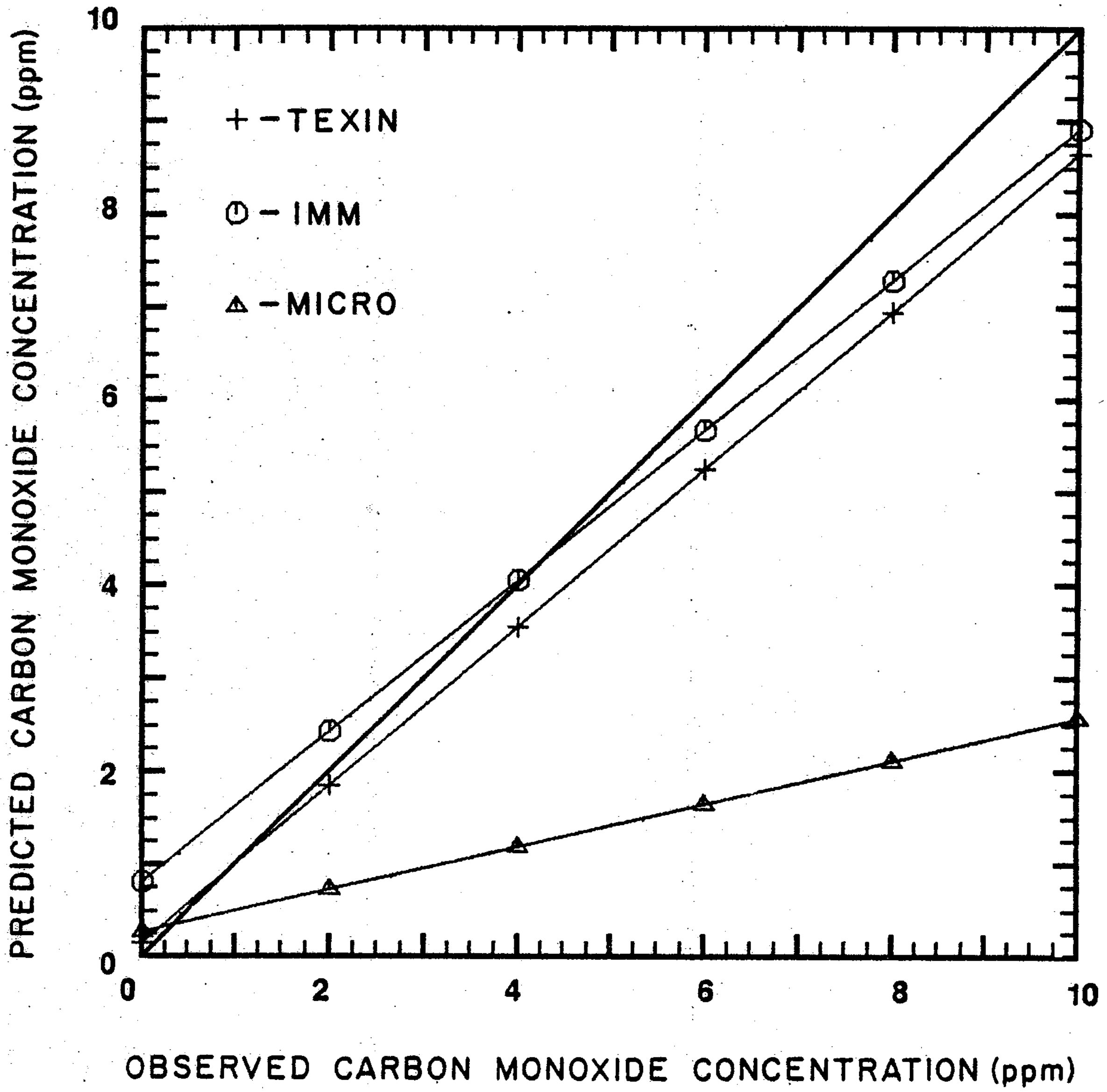


Figure 28. Regression lines for the TEXIN Model, the IMM and MICRO using the Texas A&M - College Station data [28].

an average error of -1.16 ppm. The slope of the regression line for MICRO is relatively flat (0.234) indicating that over the range of actual CO concentration values no strong trend of predicted values exists. MICRO also has the lowest regression coefficient and highest average squared error indicating a considerable amount of scatter about the regression line.

The TEXIN Model and the IMM regression lines have similar slopes (with the TEXIN being slightly closer to the desired value of unity). The IMM generally tends to overpredict with an average error of 0.474 ppm while the TEXIN model has a tendency to slightly underpredict (average error of -0.140 ppm). The TEXIN Model has both a higher correlation coefficient and a lower average squared error than the IMM indicating less scatter about the regression line.

Another important comparison is the amount of computer time required to implement the three models. The programs were run on an a computer with a Fortran H (Extended) compiler. Table 12 gives the core space and time required to compile and execute the three models for a single simulation run. These values are for a representative run and will vary somewhat for different scenarios. As can be seen from the table, the IMM requires by far the most time to execute. The ratio of the IMM's execution time to the TEXIN Model's execution time is 11.6.

Table 12. Computer requirements for the TEXIN Model, the IMM and MICRO (single simulation).

	TEXIN	IMM	MICRO
<u>Compile</u>:			
Core Space (bytes)	184 K	252 K	132 K
Time (C.P.U. sec)	5.13	7.28	1.64
<u>Execute</u>:			
Core space (bytes)	160 K	288 K	120 K
Time (C.P.U. sec)	0.58	6.74	0.60

Table 13. Computer execution times required by the TEXIN Model and the IMM (multiple simulation runs).

	Number of Simulations			
	1	3	10	100
<u>TEXIN</u>:				
Total time (C.P.U. sec)	0.58	0.77	1.46	15.0
Time per simulation	0.58	0.26	0.15	0.15
<u>IMM</u>:				
Total time (C.P.U. sec)	6.74	21.0	63.1	----
Time per simulation	6.74	7.01	6.31	----
Ratio (IMM/TEXIN)	11.6	27.3	43.2	----

This ratio increases dramatically as the number of simulations is increased. Table 13 shows the execution times for the TEXIN Model and the IMM for multiple simulations. The execution time per simulation required by the IMM remains essentially constant as the number of simulations is increased, while it decreases dramatically for the TEXIN Model. For example, where the TEXIN Model requires slightly less than a tenth of the computer time required by the IMM for a single simulation, it requires less than a fortieth of the computer time when more than ten simulations are run.

Indirect Source Guidelines

As mentioned previously, a subset of the College Station data was modelled using the procedures outlined in the Indirect Source Guidelines. These procedures must be performed manually, and thus it was not feasible to model all 153 cases. Several 15-minute sampling periods were chosen to represent a wide spectrum of wind speeds and directions. The cases selected had been accurately modelled by both the IMM and TEXIN Model. The results of these selected cases are presented in Table 14.

The Guidelines consistently overpredicted the CO concentrations by a factor of three to five for the receptors at the 5 and 15 foot (1.52 and 4.57 m) levels. For receptors at the 35 foot (10.67 m) level, the Guidelines consistently underpredicted CO levels. In fact, a value near zero (0.1 ppm) will practically always be predicted by

Table 14. Statistical comparison of the Indirect Source Guidelines predictions for selected College Station data cases [28].

Sampling Period	Receptor:	Tower 1			Tower 2		
	Level (ft):	5.00	15.0	35.0	5.00	15.0	35.0
	(m):	1.52	4.57	10.7	1.52	4.57	10.7
03/11/80@1430	Predicted:*	16.8	4.5	0.1	13.0	4.1	0.1
	Observed:	5.0	3.2	1.9	3.1	2.1	1.4
03/11/80@1445	Predicted:	21.5	6.2	0.1	17.1	5.8	0.0
	Observed:	3.9	2.3	1.5	4.5	3.3	1.6
03/11/80@1500	Predicted:	29.9	8.6	0.1	22.0	7.4	0.1
	Observed:	3.6	2.2	1.5	3.9	2.8	1.4
05/12/80@0945	Predicted:	5.8	3.2	0.1	4.9	2.9	0.1
	Observed:	1.7	0.9	0.4	1.8	1.3	1.1
05/12/80@1000	Predicted:	6.3	3.4	0.1	5.0	2.9	0.1
	Observed:	1.7	0.9	0.5	1.7	1.3	1.1
08/05/81@1430	Predicted:	12.1	4.2	0.1	12.8	4.3	0.1
	Observed:	4.7	2.8	1.4	3.0	1.4	1.7
08/05/81@1445	Predicted:	12.7	3.9	0.1	13.5	4.3	0.1
	Observed:	4.0	2.5	---	2.8	1.2	1.9
18/05/81@1412	Predicted:	18.2	4.9	0.1	12.8	4.1	0.1
	Observed:	5.6	2.6	1.5	2.7	0.9	0.7
18/05/81@1427	Predicted:	15.7	4.3	0.1	11.1	3.5	0.1
	Observed:	4.4	2.2	0.9	2.4	0.6	0.3

*Concentration in parts per million.

the Guidelines for a receptor at this height and the given distance from the roadway.

The major reason for the general overprediction of the Indirect Source Guidelines involves the philosophy of the guidelines. The predictions are conservative in nature due to the fact that the purpose of the guidelines was to present a screening procedure for initial testing of intersections to determine whether or not a more detailed analysis was necessary. The Guidelines therefore should not be generally used as a predictive tool.

<u>Further Comparisons of the TEXIN Model and the IMM</u>

To further evaluate the models' performance and to determine what improvements or calibrations might be made to either model, the effects of wind speed and wind direction on the models' accuracy were analyzed. This was accomplished by stratifying the data by wind speed and wind angle. Three wind speed classes were chosen: low (0 to 2 m/s), medium (2 to 4 m/s), and high (above 4 m/s); and three wind angle classes were chosen: near-parallel (0^{o} to 30^{o}) to the roadway, near-forty-five (30^{o} to 60^{o}) to the roadway, and near-perpendicular (60^{o} to 90^{o}) to the roadway. These categories yield nine distinct wind speed - wind angle combinations.

Obviously, when the wind is nearly perpendicular to one street in a single intersection, it is nearly parallel to the cross-street. This makes categorization by wind angle rather ambiguous. To avoid confusion, the wind/roadway angle was taken to be the wind angle with respect to the leg of the intersection that is the largest contributor to the pollutant at the receptors. Although the high wind category includes all wind speeds above 4 m/s, no wind speeds above 6.5 m/s were observed in the data.

Scattergrams of predicted versus observed CO concentrations for the nine wind speed/wind angle categories were produced for both the IMM and the TEXIN Model. These scattergrams are presented in Figures 29-34 and provide for more detailed analysis of the models. No plots were made for MICRO or the Indirect Source Guidelines due to their poor overall performances.

Figures 29-31 show scattergrams for the various wind speed/wind angle categories as simulated by the TEXIN Model. Figure 29 differentiates between low, medium, and high wind speeds for the near-parallel wind situations. Figure 30 presents the same comparison for the near-forty-five degree cases and Figure 31 depicts the near-perpendicular wind cases.

In comparing these figures, the first point of interest is that the model's accuracy does not appear to depend upon wind angle. It predicts as well for near-parallel winds as it does for near-forty-five or near-perpendicular winds.

For high wind speeds, at all wind angles, the model predicts best with practically all of the points falling within 2 ppm. For medium wind speeds, though, there is more scatter with more points lying outside the 2 ppm line (although for the near-parallel case only one point is

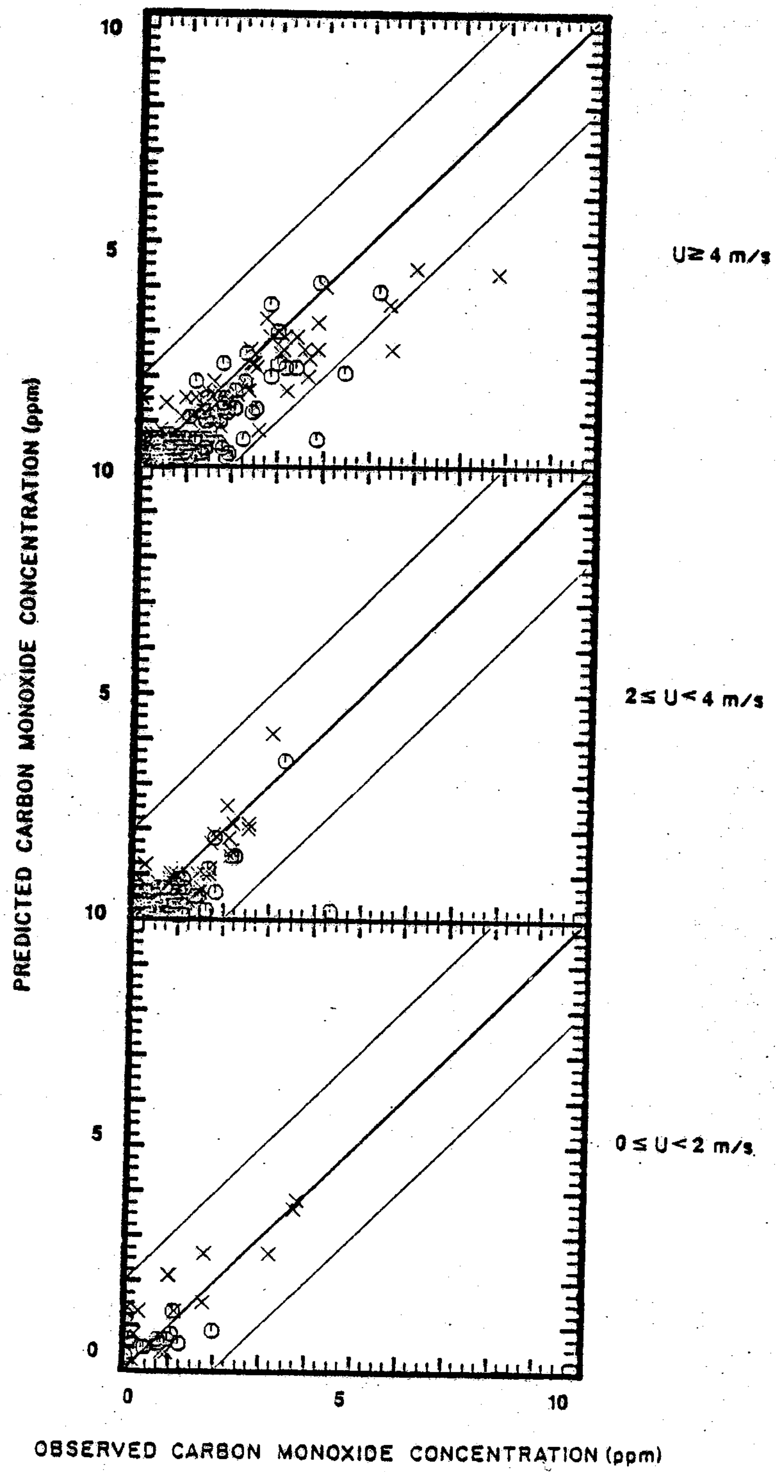


Figure 29. Scattergrams for near-parallel wind cases from the TEXIN Model using the Texas A&M - College Station data (X-Tower 1, O-Tower 2) [28].

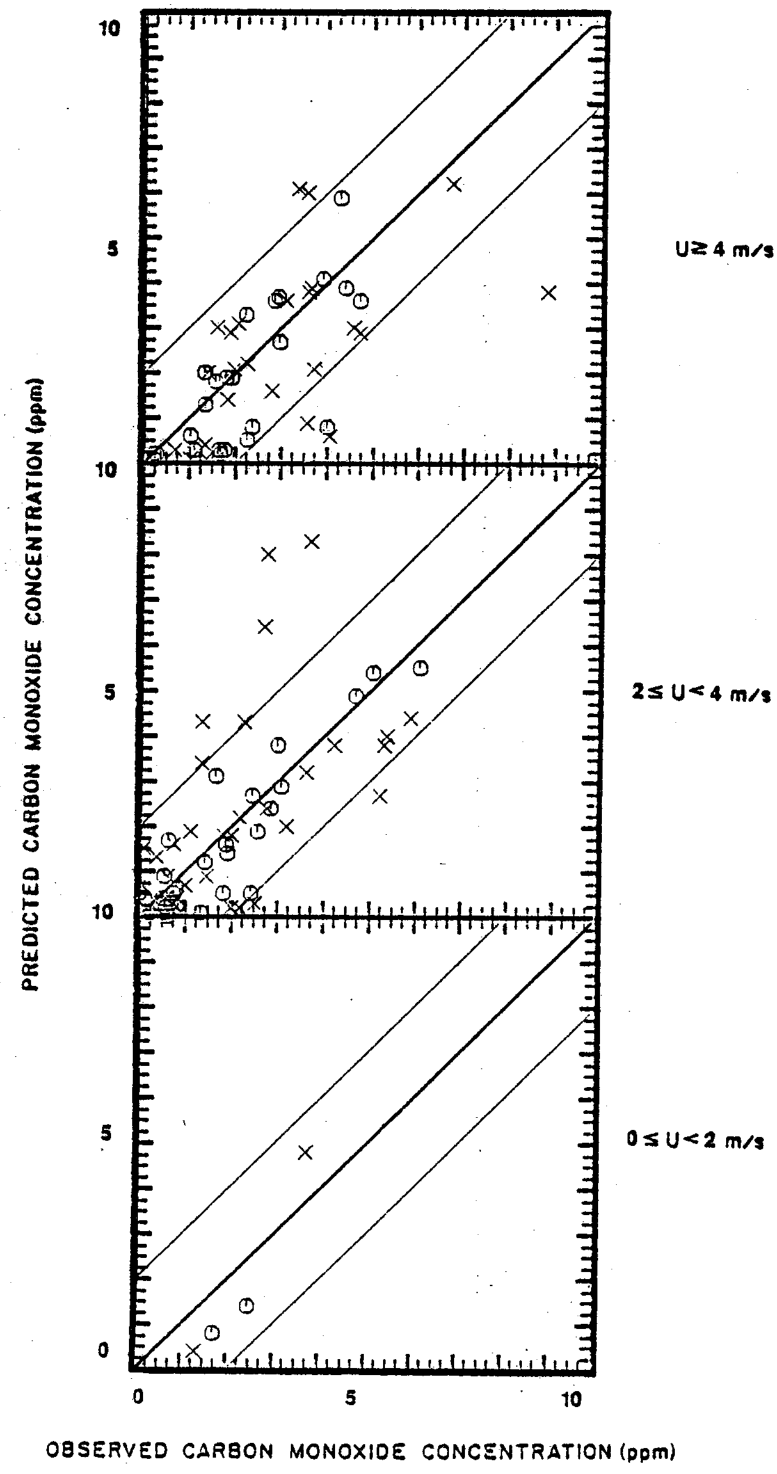


Figure 30. Scattergrams for near-forty-five degree wind cases from the TEXIN Model using the Texas A&M - College Station data (X-Tower 1, 0-Tower 2) [28].

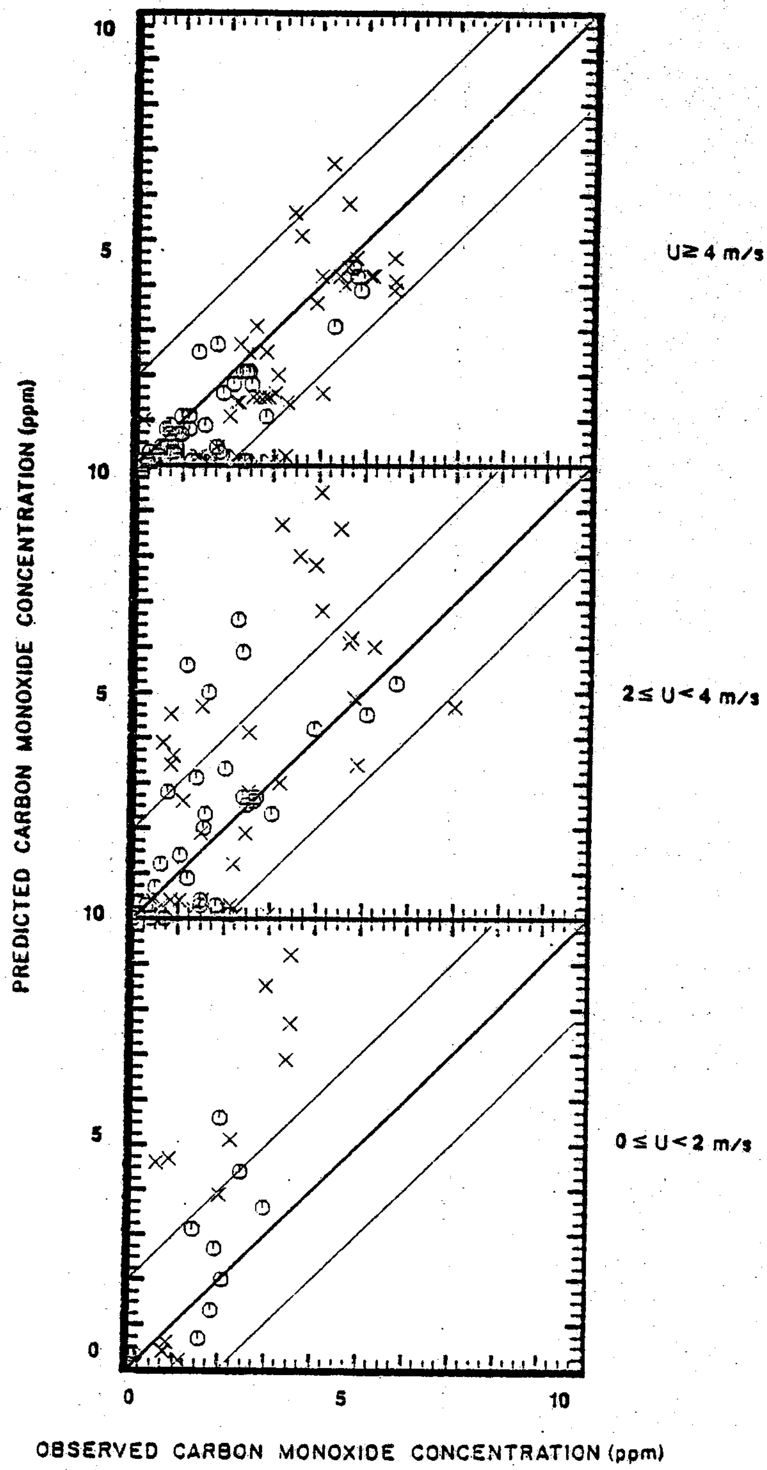


Figure 31. Scattergrams for near-perpendicular wind cases from the TEXIN Model using the Texas A&M - College Station data (X-Tower 1, O-Tower 2) [28].

outside the 2 ppm line). For low wind speeds, the model overpredicts a number of points for near-perpendicular winds only. There are not many points in the other wind angle classes for comparison.

While the TEXIN Model does overpredict for some points at low and medium wind speeds, it does not exhibit a general tendency to overpredict. Rather, increased scatter in the comparisons is observed. The points in the high wind speed categories fall within a rather tight band between the 2 ppm lines, while the points for low and medium wind speeds, although exhibiting more scatter, fall equally above and below the forty-five degree line.

Figures 32-34 present similar scattergrams for the wind speed/wind angle categories using the IMM simulations. Once again, there appears to be little dependence on wind angle. Like the TEXIN Model, the IMM predicts best for high wind speeds with few points falling outside the 2 ppm range. For low and medium wind speeds, however, the IMM exhibits both overprediction and increased scatter. Only two points are below the forty-five degree line for low wind speed cases, and the majority of the points are above the 2 ppm line. Also for medium wind speeds, many points are above the 2 ppm line, and a majority fall above the forty-five degree line.

Neither model varies significantly in accuracy with respect to the tower being modelled. The model predicts the CO concentration levels at both Towers 1 and 2 equally well. This suggests that both models perform equally well in estimating CO levels at receptors near the intersection

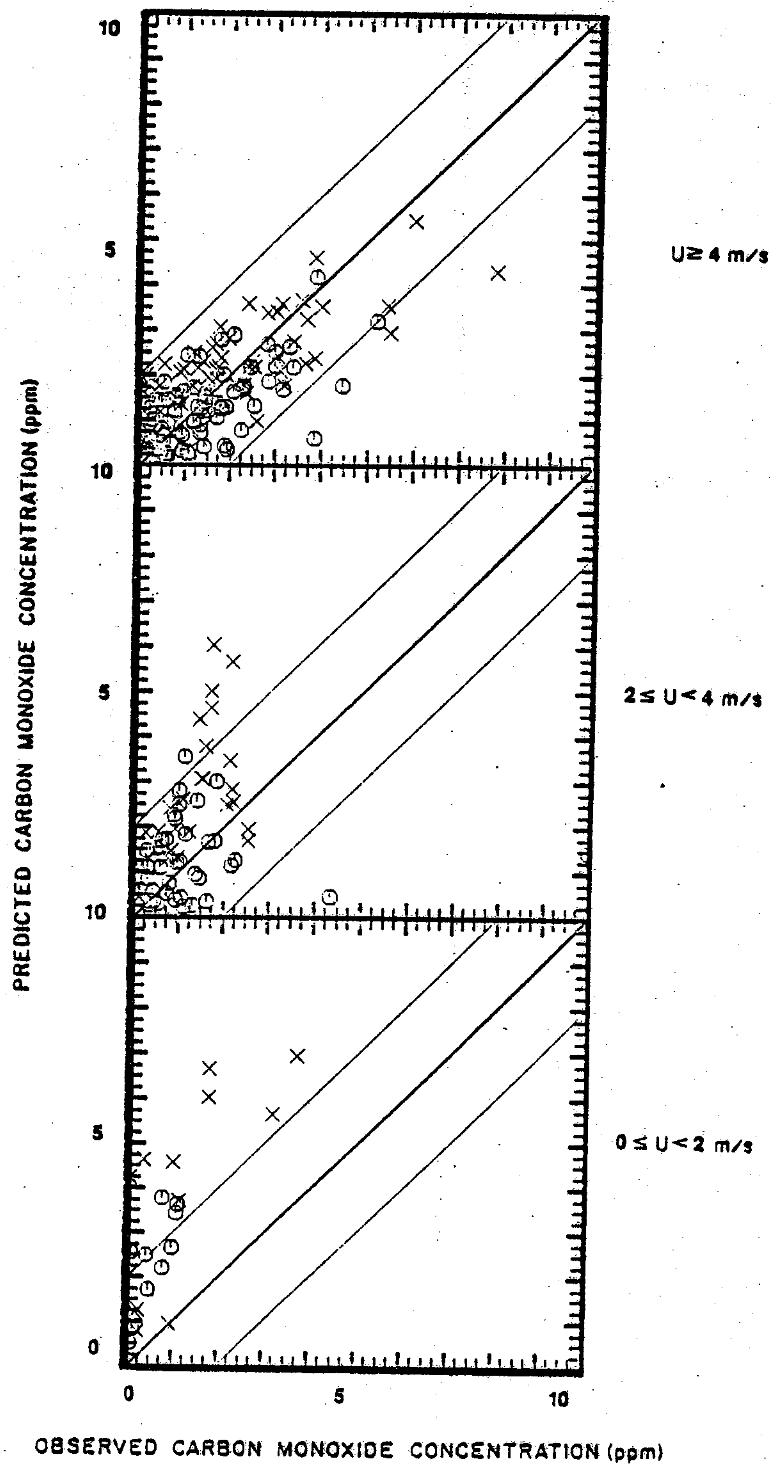


Figure 32. Scattergrams for near-parallel wind cases from the IMM using the Texas A&M - College Station data (X-Tower 1, O-Tower 2) [28].

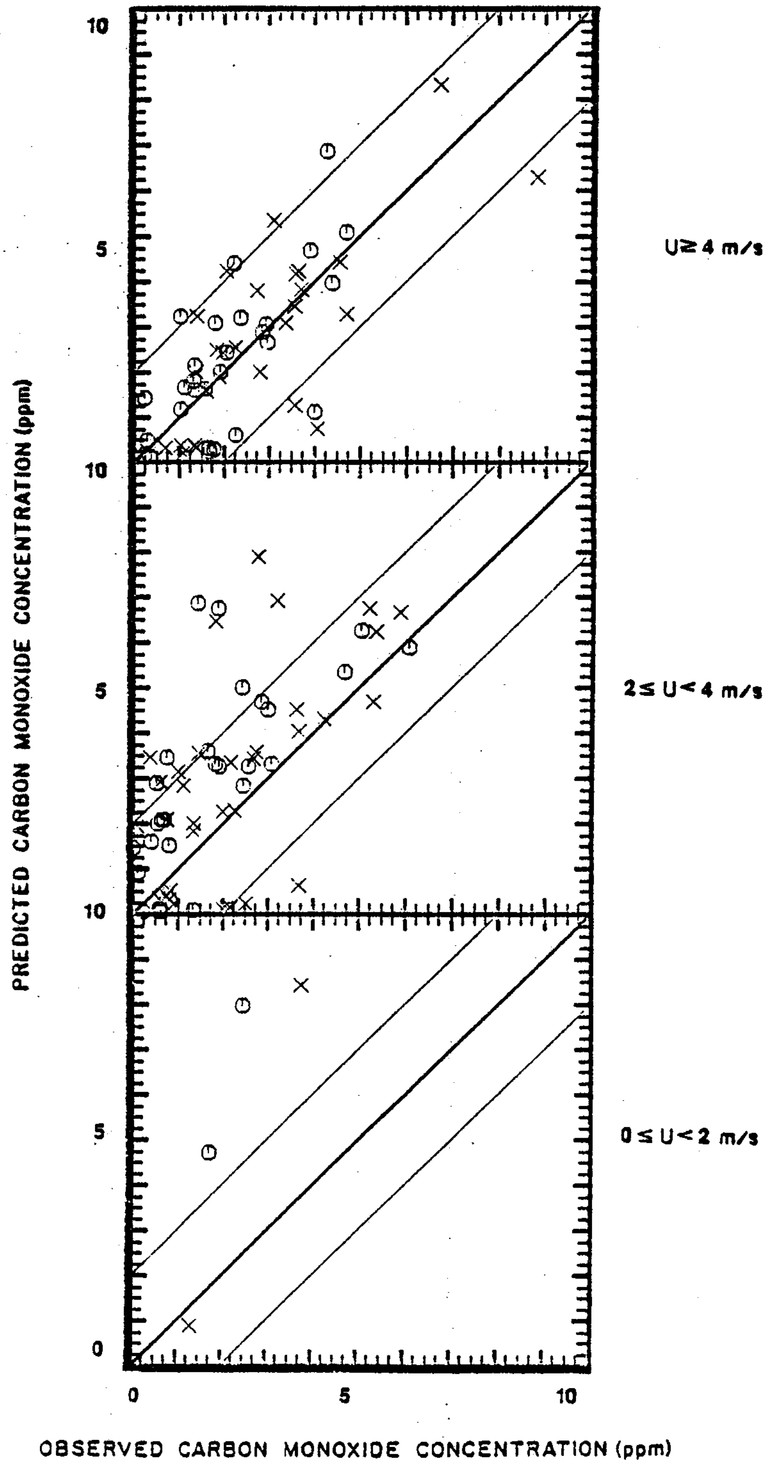


Figure 33. Scattergrams for near-forty-five degree wind cases from the IMM using the Texas A&M - College Station data (X-Tower 1, O-Tower 2) [28].

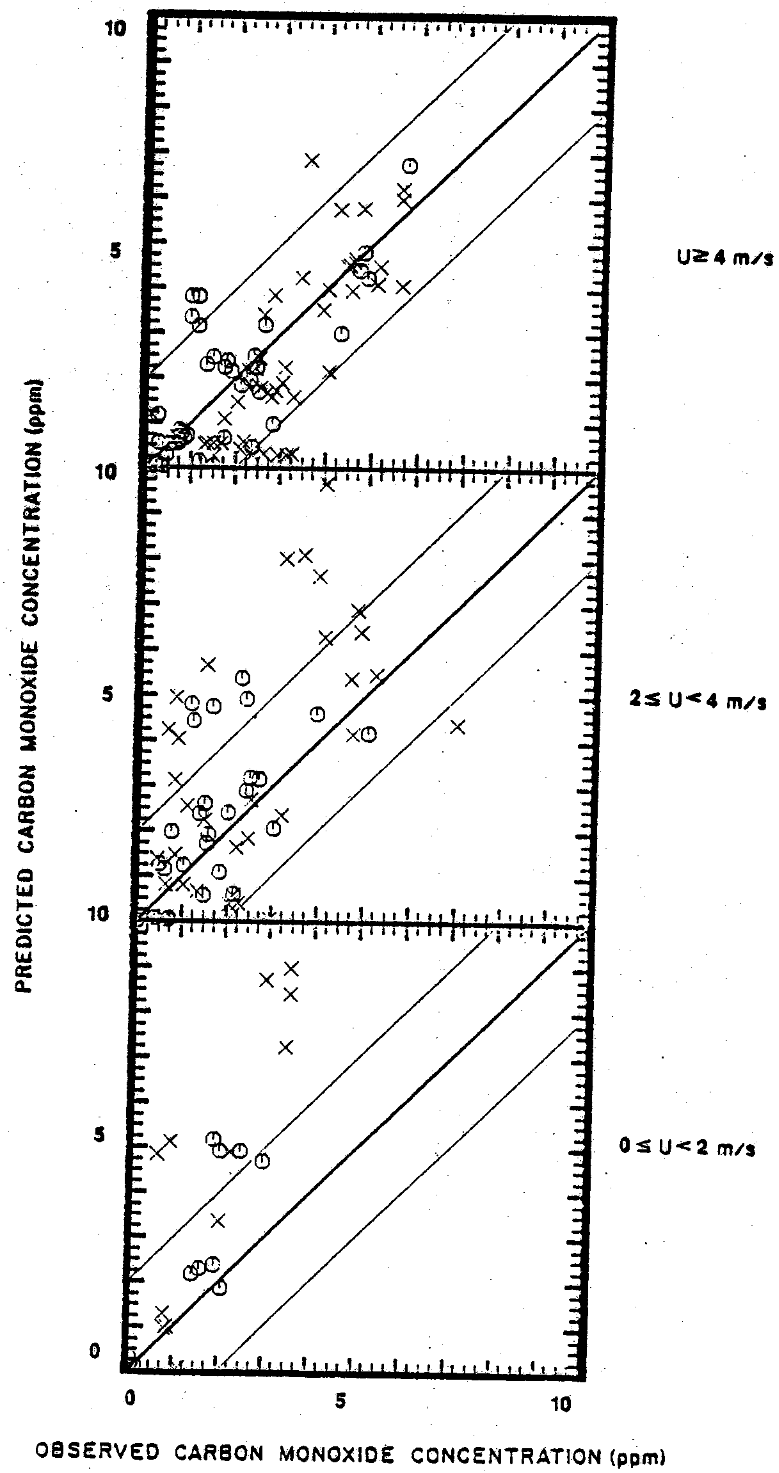


Figure 34. Scattergrams for near-perpendicular wind cases from the IMM using the Texas A&M - College Station data (X-Tower 1, O-Tower 2) [28].

(Tower 1) as at receptors near midblock (Tower 2). This finding is particularly useful in determining realistic receptors for simulation of worst case conditions.

The TEXIN Model includes elevation of the source height for extremely low wind speeds (below 1 m/s) as described in Chapter III. Without this correction, the model tended to overpredict by a factor of approximately two at low wind speeds. The correction brought these points more in line with the observed values; however, there were only a few cases of wind speeds below 1 m/s and the results are inconclusive. If this source height correction factor, as expressed by equation (III-8), is applied to all wind speeds, little or no difference in predicted CO concentrations for wind speeds above 1 m/s is observed. This is due primarily to the negligible amount by which the source height is raised. These results also suggest that the IMM might be improved by a similar adjustment for wind speeds below 1 m/s.

Another interesting performance comparison between the two models was their accuracy at the various receptor heights. Figure 35 presents separate scattergrams of predicted versus observed values for the 5, 15, and 35 foot (1.52, 4.57, and 10.67 m) level receptors for the TEXIN Model. The TEXIN Model adequately (to the accuracy of the model) predicts the CO concentrations for the 5 and 15 foot (1.52 and 4.57 m) level receptors, although there is a little more scatter for the 5 foot (1.52 m) level. For receptors at the 35 foot (10.67 m) level the TEXIN Model

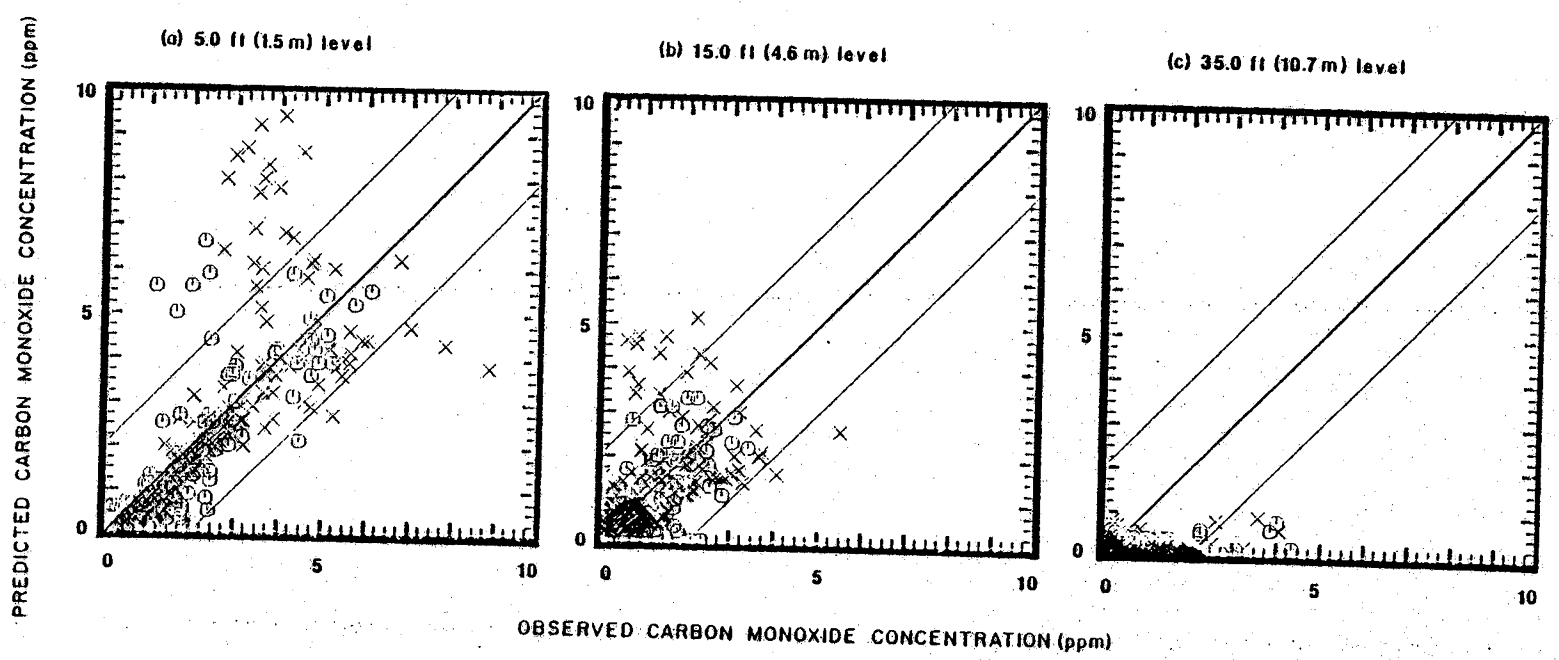


Figure 35. Scattergrams for receptors at the various levels from the TEXIN Model using the Texas A&M - College Station data (X-Tower 1, O-Tower 2) [28].

vastly underpredicts. In fact, the regression line for these points has a negative slope indicating that the TEXIN Model predicts lower values as the observed CO concentrations increase. Figure 36 shows corresponding scattergrams for the IMM with similar results.

As previously noted by Rodden, et al. [36], the inability to accurately predict the CO concentrations at high receptor heights appears to be a function of the dispersion models used (CALINE-3 and HIWAY-2 in the TEXIN Model and the IMM, respectively). Attempts to calibate and/or improve this performance in the TEXIN Model were not successful. Two approaches were tried: elevating the source height and increasing the initial vertical dispersion parameter. To improve the model's performance for the 35 foot (10.67 m) level receptor, the source must be raised to such a height that the accuracy for the 5 and 15 foot (1.52 and 4.57 m) levels, as well as the overall accuracy, were significantly decreased. Since CO concentrations for the lower heights would normally be of more interest for pedestrians and other common receptors this approach was abandoned. Attempts to increase the initial vertical dispersion parameter failed to better the model's performance for the 35 foot (10.67 m) level receptors.

B. COMPARISON OF MODEL PREDICTIONS TO THE CALIFORNIA DATA

The TEXIN Model was the only model used to simulate the CALTRANS Sacramento data. MICRO and the Indirect Source

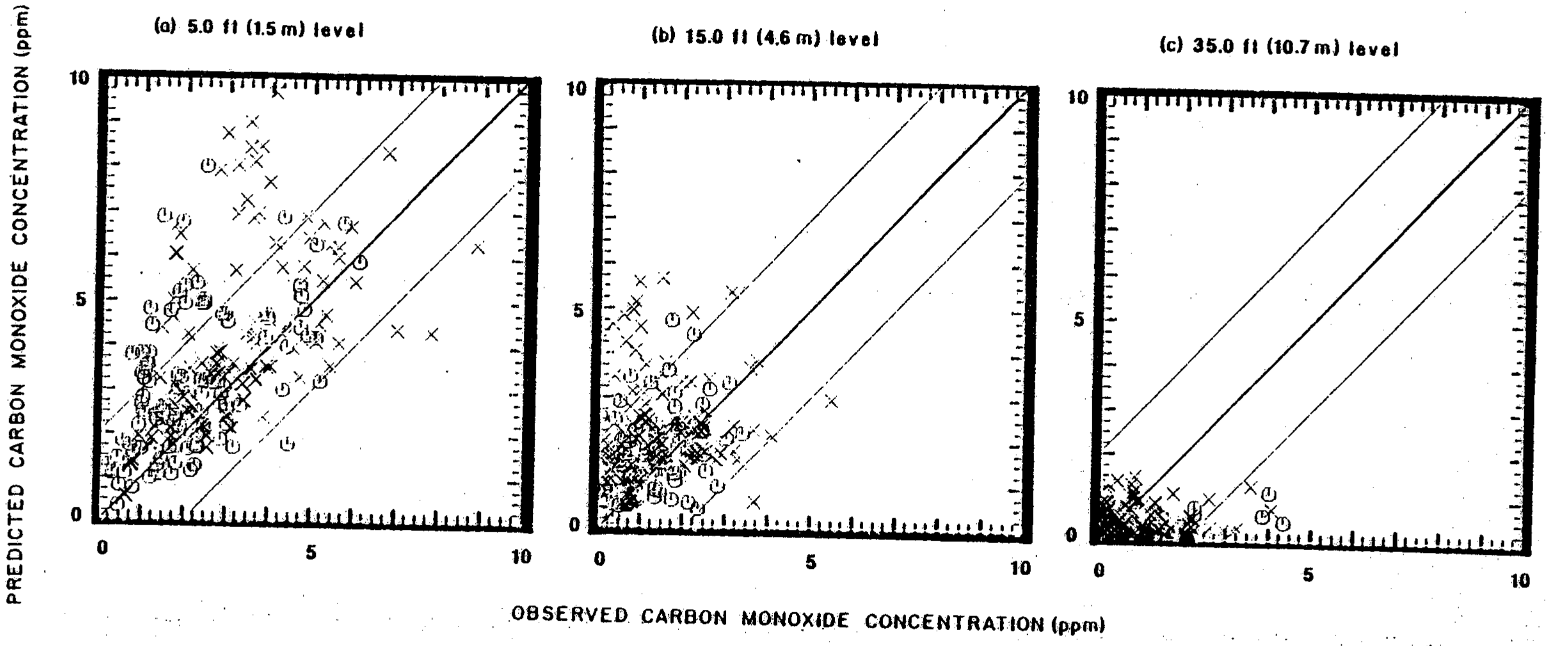


Figure 36. Scattergrams for receptors at the various levels from the IMM using the Texas A&M - College Station data (X-Tower 1, 0-Tower 2) [28].

Guidelines were not used due to their poor performance in modelling the College Station data, and the Intersection Midblock Model was not used due to the prohibitive computer cost of applying if to the large California data base of 6164 total points.

Input Parameter Discussion

Since there were no measurements of vehicle speeds made at the Florin Road-Freeport Boulevard intersection, an estimated average speed had to be used. This speed was taken to be 30 mph (48.3 kph) for all legs as suggested by CALTRANS [40]. The default national average values of the MOBILE-2 program for the vehicle mix were used.

From the site description provided by CALTRANS and the table of suggested roughness heights given by Myrup and Ranzeiri [8], a surface roughness of 1.0 meter (3.28 ft) was chosen. A value of 1000 meters (3281 ft) was used as the mixing layer height.

Since no measure of incoming solar radiation was made, the stability class for each sampling period was determined using the Richardson Number, Ri, as suggested by Slade [41]. The stability was classified as unstable (Pasquill type A-B) for $Ri < 0.0$, slightly stable (Pasquill type C-D) for $0.0 < Ri < 0.08$ and stable (Pasquill type E-F) for $Ri > 0.08$. These were for assumed typical wind speeds. The average wind speed was used to differentiate between the individual Pasquill stability classes in the above categories.

Observed Concentration Convention

The observed carbon monoxide concentration values were calculated as the measured downwind CO concentration minus the average upwind CO concentration. Since the Florin - Freeport intersection site had carbon monoxide monitors in three quadrants, a background concentration could be obtained for winds blowing from any quadrant except for the one without a CO monitor (the northeast quadrant). The majority of the data did have winds blowing from one of these three quadrants.

Statistical Comparisons

A scattergram of predicted versus observed CO concentrations (for the 60-minute average sampling periods) as simulated by the TEXIN Model is presented in Figure 37 and the statistical results of the regression analysis are given in Table 15. The regression line is also shown graphically in Figure 38.

The TEXIN Model's performance for the California data was similar to that for College Station. Statistically, the slopes of the regression lines were near unity and the intercepts were near zero for both comparisons. The regression coefficients and the average squared errors were also approximately equal for the two comparisions. The average error was negative for the Texas A&M data and positive for California, however, both were near zero. Likewise, the percentage of points within one and two ppm

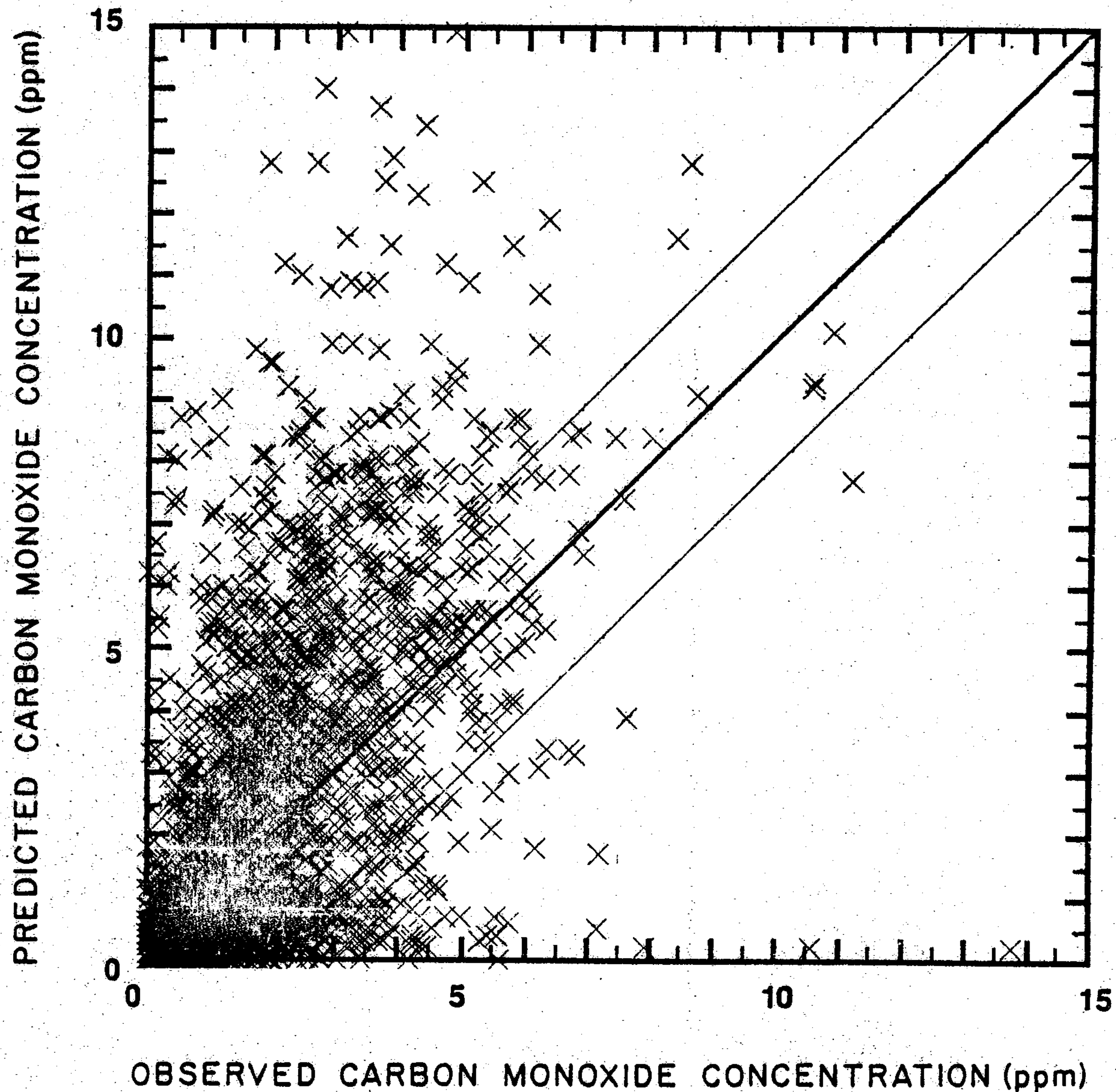


Figure 37. Scattergram of predicted versus observed CO concentrations for the TEXIN Model using the California data [29].

Table 15. Statistical comparison of the TEXIN Model predictions for the CALTRANS Sacramento data [29].

Statistic	TEXIN Model
Slope	1.11 ± 0.01
Intercept (ppm)	-0.01 ± 0.02
r^2	0.495
Average Error (ppm)	0.08
Avg. Sq. Error (ppm^2)	1.99
Number of Points:	
Total	6164
Within 2 ppm	5549 (90%)
Within 1 ppm	4851 (79%)

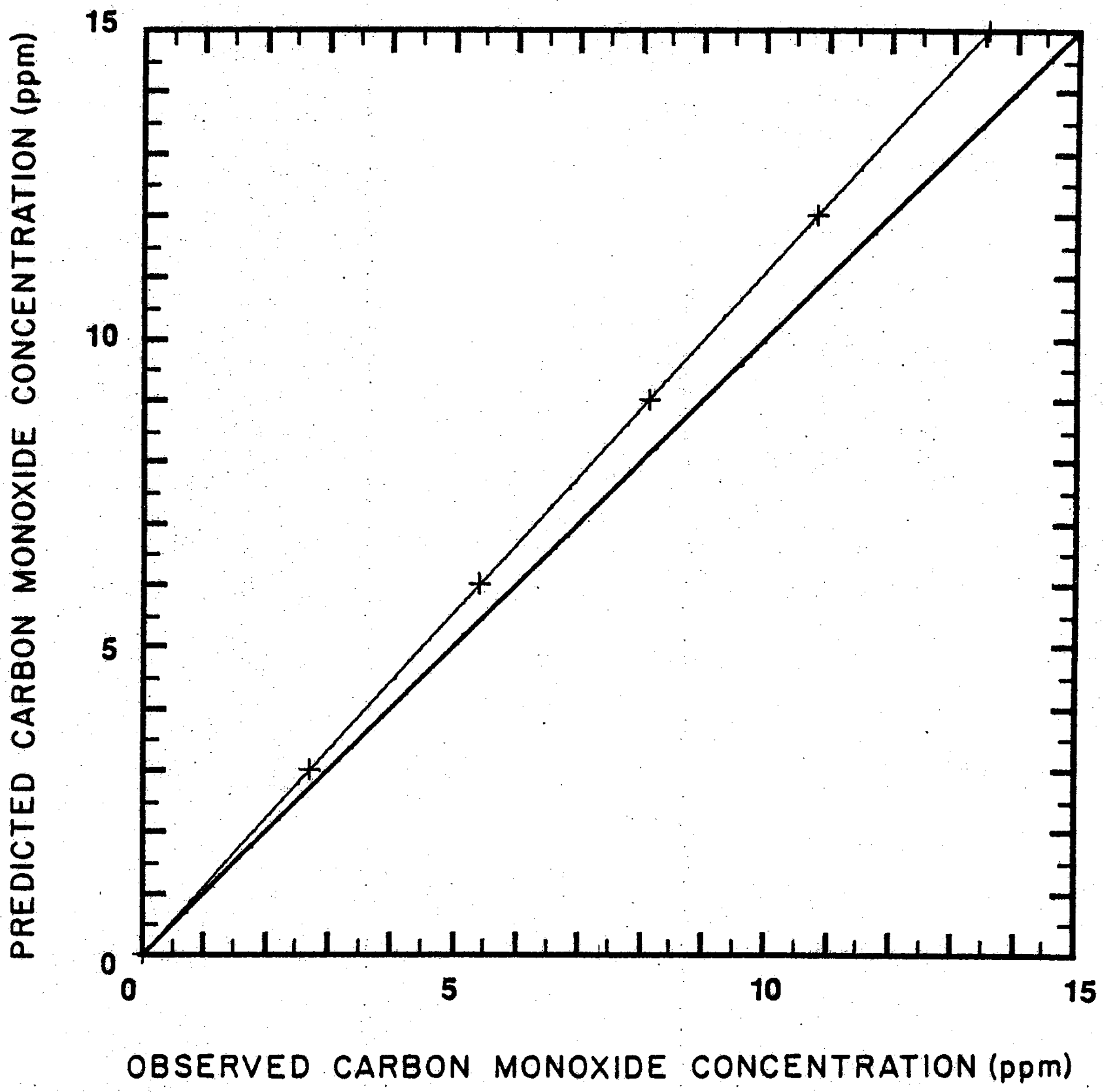


Figure 38 . Regression line for the TEXIN Model using the California data [29].

were about the same for both cases. The general appearances of the two scattergrams were also very similar.

Separating the data into the nine wind speed/wind angle combinations as was done for the TAMU data, one can glean more information from the comparisons. These plots are displayed in Figures 39-41. Once again there was no dependence on wind angle as far as accuracy was concerned, and the model again predicted best at high wind speeds. With the large number of points in the California data, the low wind speed scatter is more readily apparent. Although there does appear to be overprediction for lower wind speeds, this effect is actually only increased scatter in the results. To verify this conclusion, the relationship between wind speed and predicted CO concentration may be examined.

From the Gaussian dispersion equations (equations II-5 and II-6) used by CALINE-3, it is apparent that the major effect of wind speed is its inverse proportionality to predicted CO concentration. The only other computation involving wind speed is in the determination of the initial vertical dispersion parameter. If the TEXIN Model tended to overpredict for lower wind speeds, it should be possible to calibrate the model since the wind speed is simply related inversely to the predicted CO concentration.

This calibration was attempted by determining a virtual wind speed which gave the best fit for each case. This was accomplished by minimizing the function:

$$f = \sum_{1}^{N} \left(\frac{u \cdot PR}{u^*} - OB \right)^2 \qquad \text{(IV-2)}$$

where: PR = predicted concentration, ppm
OB = observed concentration, ppm
u = actual wind speed, m/s
u^* = virtual wind speed, m/s
N = number of receptors

The virtual wind speed was varied incrementally from one-fifth of the actual wind speed to five times the wind speed, and the virtual wind speed that produced the minimum value for the function, f, was taken as the best-fit for that case. Once a best-fit virtual wind speed had been determined for each case, an attempt was made to correlate the virtual wind speed and the actual wind speed. This attempt met with no success. No correlation, either linear or non-linear, could be found, signifying that more random scatter exists at lower wind speeds and that no net overprediction by the model is present.

Statistical analyses were conducted on only those data at extremely low wind speeds (less than 1 m/s), and the slope of the resulting regression line was 1.17. However, when these same cases are modelled without the source height correction factor described previously, the slope of the regression line was 1.89 indicating a tendency to overpredict by almost a factor of two for wind speeds below one meter per second. Therefore, the addition of the source height correction factor to the TEXIN Model extends the

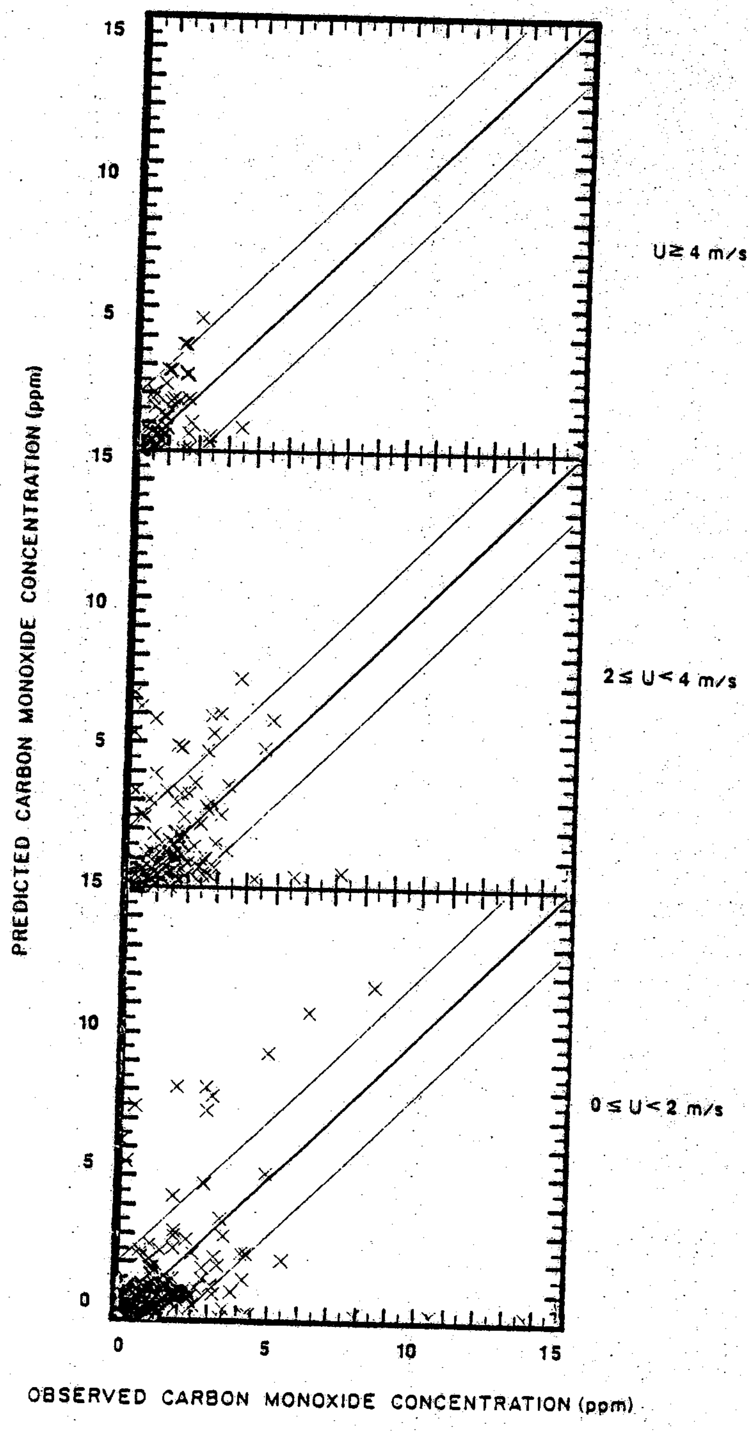


Figure 39. Scattergrams for near-parallel wind cases from the TEXIN Model using the California data [29].

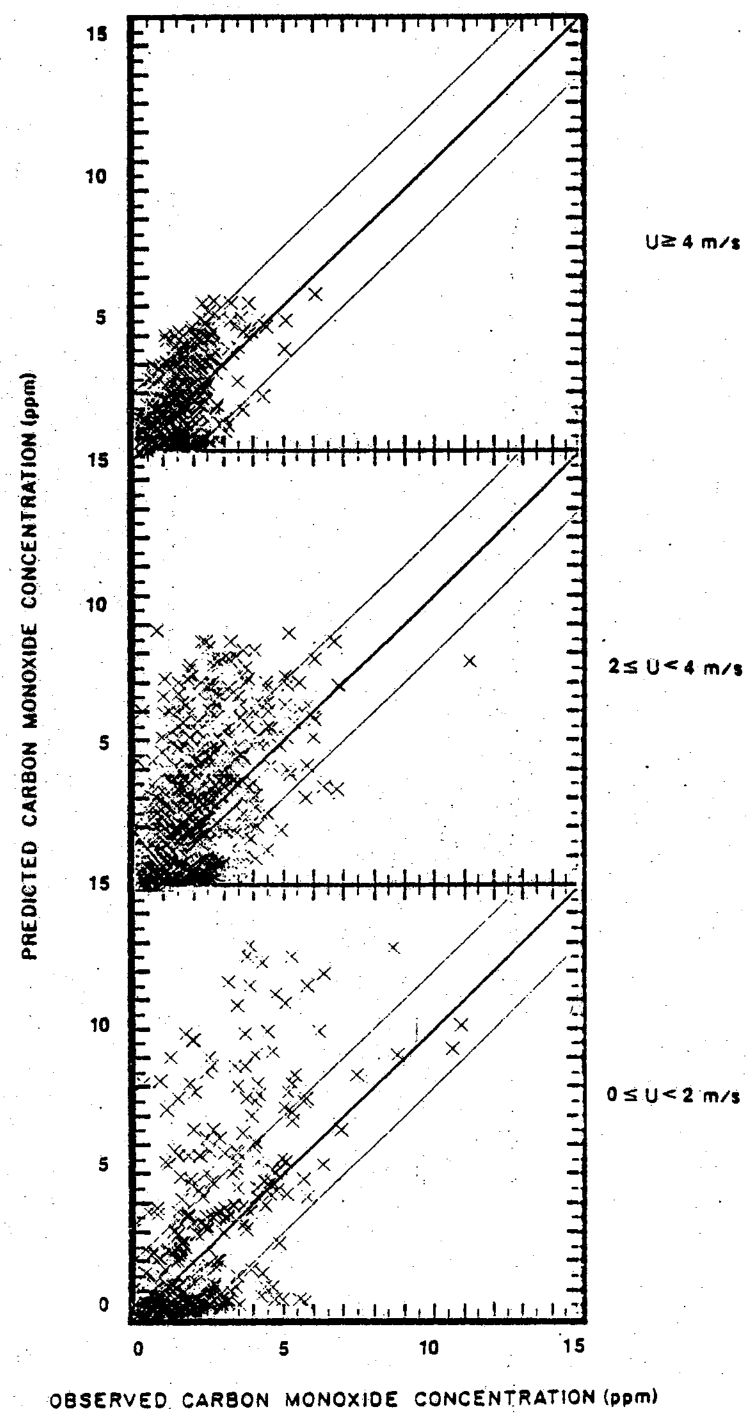


Figure 40. Scattergrams for near-forty-five degree wind cases from the TEXIN Model using the California data [29].

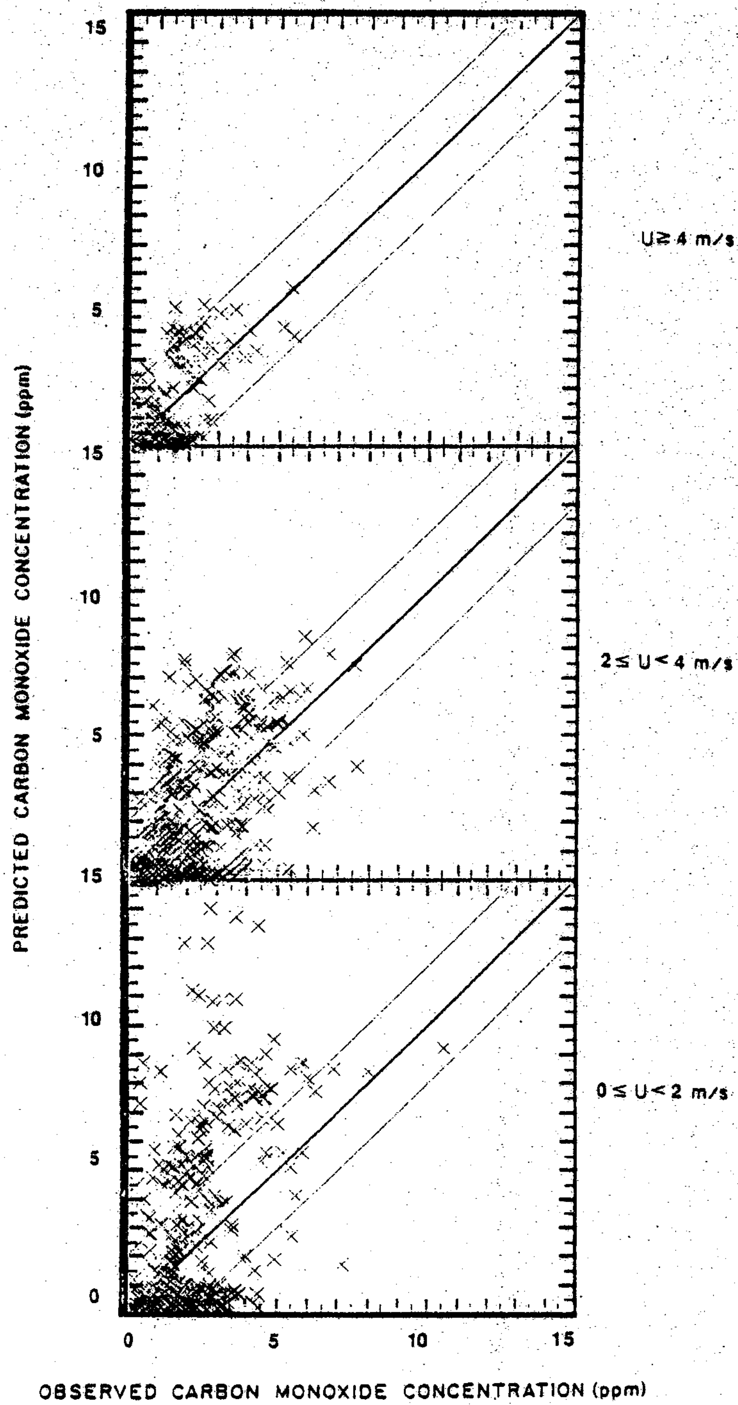


Figure 41. Scattergrams for near-perpendicular wind cases from the TEXIN Model using the California data [29].

applicability of the model to very low wind speeds. Again, it is possible that this correction might also be used to improve the IMM at very low wind speeds.

Figure 42 presents scattergrams for the California simulation at various receptor heights. The model predicts equally well for the 1, 2, 4 and even 10 metre (3.28, 6.56, 13.12, and 32.81 feet) receptors. The performance of the model for the 10 metre (32.81 foot) height is much better than for the 35 foot (10.67 m) College Station receptors (although there are not enough points at 10 metre (32.81 ft) receptors to make the results conclusive). There is also not enough data at the 15 metre (49.21 ft) level to warrant any conclusions for that case.

C. COMPARISON OF MODEL PREDICTIONS TO THE HOUSTON DATA

Late in the study, the Texas A&M - Houston data was made available for use. Only the TEXIN Model was used to simulate the Houston data for the same reasons presented previously for the California data. Although 5, 15, and 60-minute averages were available, only the 60-minute averages were utilized. Very little time was available for detailed study of the Houston data, and thus the conclusions regarding the Houston site should be regarded as preliminary in nature.

Input Parameter Discussion

The data acquisition equipment and techniques used at the Houston site were essentially identical to those at College Station. Thus, the conventions used in determining

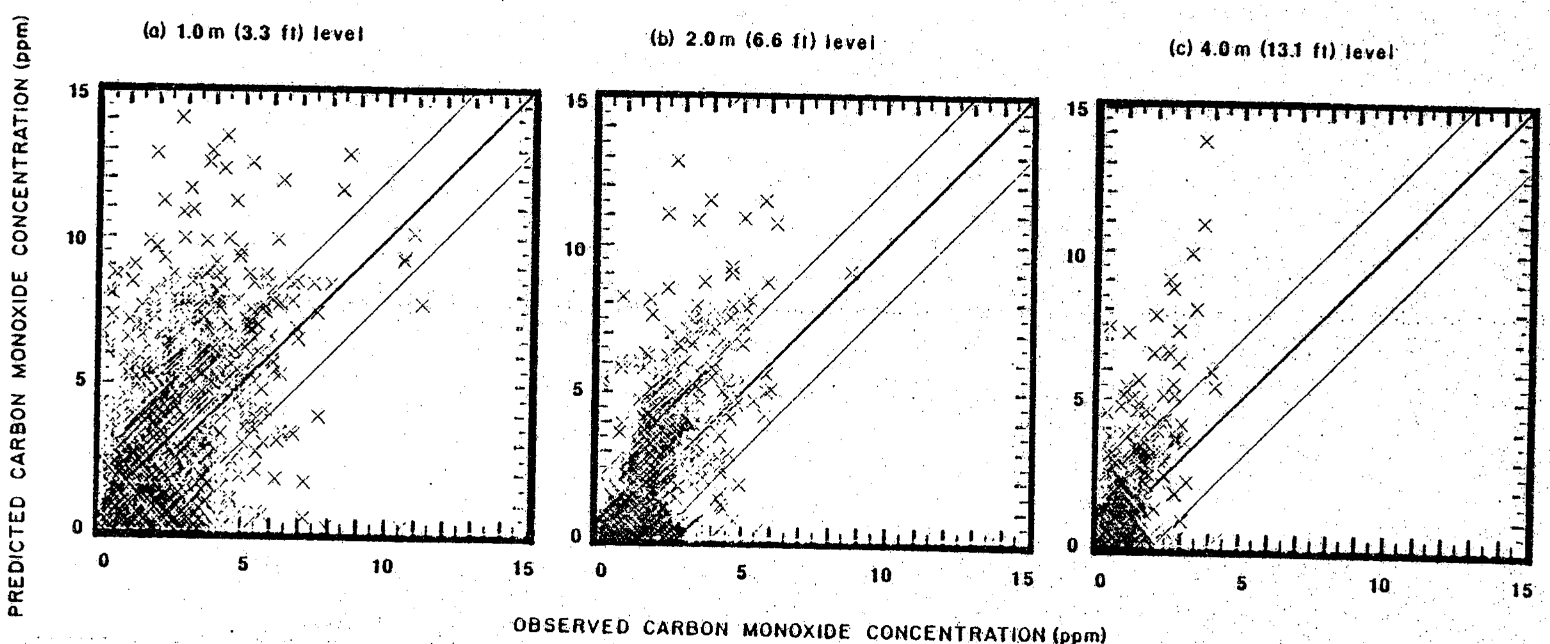


Figure 42. Scattergrams for receptors at the various levels from the TEXIN Model using the California data [29]. (a) 1.0m (3.3 ft) level, (b) 2.0m (6.6 ft) level, (c) 4.0m (13.1 ft) level.

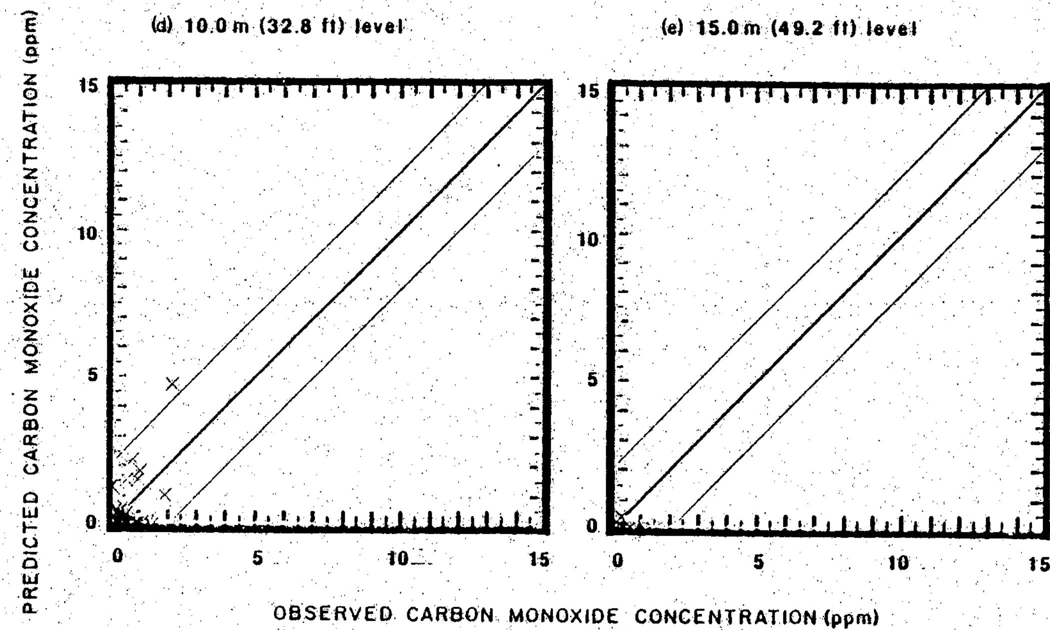


Figure 42. (d) 10.0m (32.8 ft) level, (e) 15.0m (49.2 ft) level.

the input parameters were similar to those for College Station.

The input values for wind speed, wind direction and temperature were taken as the arithmetic mean of the respective measurements. The stability class was determined through Pasquill's analysis (Figure 24). A value of 1000 meters (32.81 ft) was used as the mixing layer height, and the roughness height was determined using Myrup and Ranzieri's table of suggested surface roughness values [8]. Since the upwind region for the Houston site (the southeast and southwest quadrants) consisted of extremely tall buildings as described in Chapter II, a surface roughness height of 4.0 meters (13.12 ft) was chosen. Although the buildings upwind of the intersection were extremely tall, the location of the buildings with respect to the intersection was such that a narrow street canyon situation did not exist (i.e., a configuration where the buildings are sufficiently close to both sides of the roadway so that a vortex could form between the buildings). Actually, the site was half street canyon and half at-grade and thus was extremely difficult to categorize exactly.

The approach volumes, turning fractions and average vehicle speeds were obtained from the traffic loop counters. The input variables pertaining to the VMT mix and the operating mix (% cold starts, % hot starts, etc.) were county-wide values obtained from the Texas State Department of Highways and Public Transportation [39] and are given in Tables 16 and 17.

Table 16. VMT mix for Harris County [39].

Year	LDGV	LDGT1	LDGT2	HDGV	HDDV	MC
1981	0.635	0.185	0.091	0.043	0.039	0.007

Table 17. Percentage cold starts/hot starts (1981) for Harris County [39].

Time of Day	PCCN	PCHC	PCCC
00-02	22	7	27
03-05	25	7	26
06-08	22	10	24
09-11	10	18	18
12-14	9	18	18
15-17	13	14	19
18-20	8	17	20
21-23	12	11	25

Observed Concentration Convention.

The observed carbon monoxide concentration values were calculated as the measured downwind CO concentration minus the average measured upwind CO concentration. As at the College Station site, one tower (Tower 1) was set up as the primary upwind tower. Tower 1 was in the southeast quadrant; thus theoretically, only for those cases with a wind out of the southeast quadrant (winds blowing from any angle between the eastern leg of Woodway Boulevard and the southern leg of South Post Oak Lane, see Figure 10) could a true background concentration be properly determined. Since Tower 1 was relatively close to South Post Oak Lane, only those cases with a wind from the southeast quadrant were used in the analyses. Approximately two-thirds of the data had winds blowing from this quadrant.

Statistical Comparison

A scattergram of predicted versus observed CO concentrations (for the 60-minute average sampling periods) as simulated by the TEXIN Model is presented in Figure 43 and the statistical results of the regression analysis are given in Table 18. The regression line is also shown in Figure 44. The results from the Houston data differ little from those for the previous two data bases considered. This is readily apparent in the similarity of Figures 27, 37, and 43 as well as in the separate statistical analyses. The slopes, intercepts and regression coefficients are similar

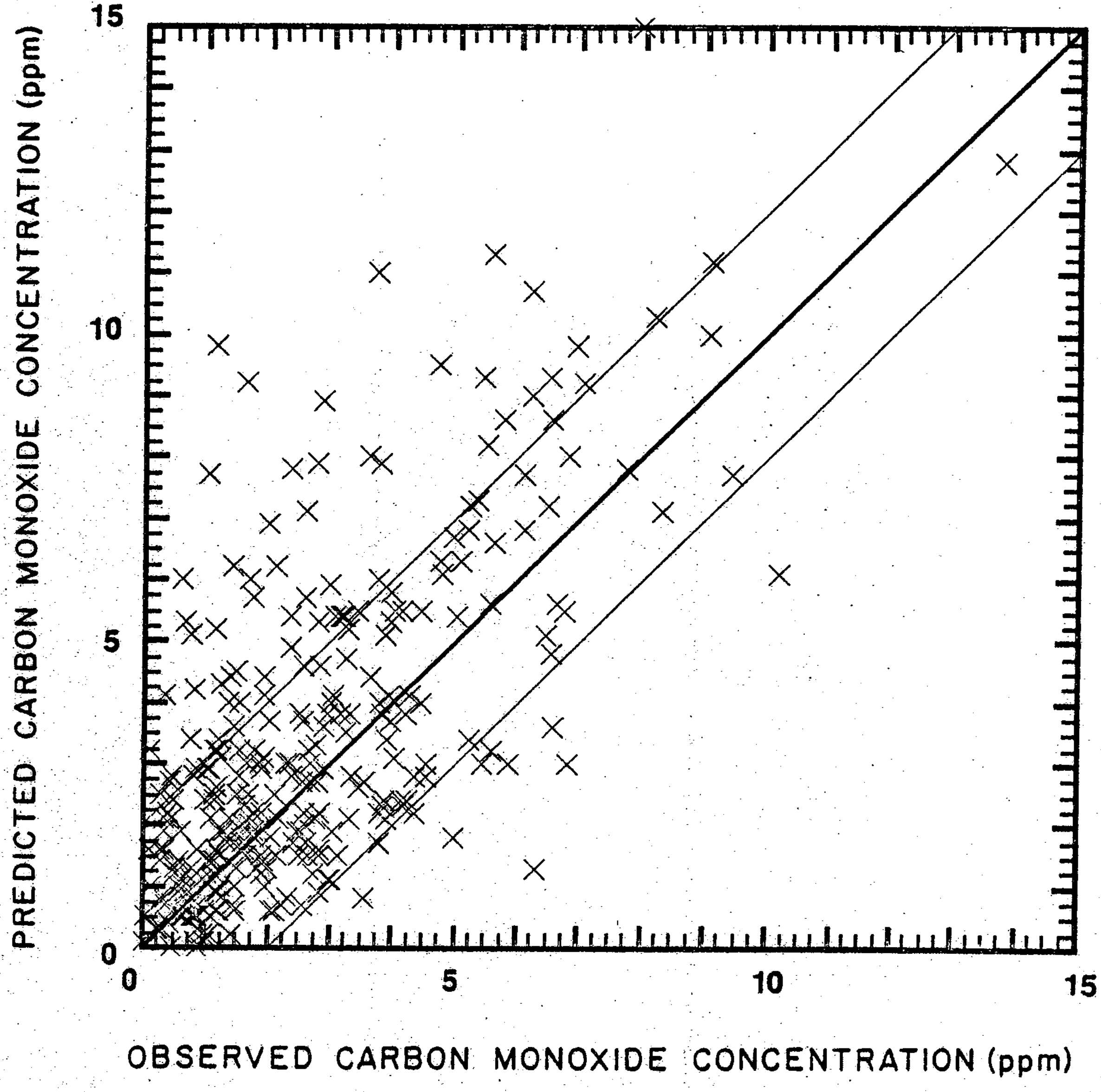


Figure 43. Scattergram of predicted versus observed CO concentrations for the TEXIN Model using the Texas A&M Houston data [28].

Table 18. Statistical comparison of the TEXIN Model predictions for the Texas A&M Houston data [28].

Statistic	TEXIN Model
Slope	0.89 ± 0.05
Intercept (ppm)	1.0 ± 0.2
r^2	0.470
Average Error (ppm)	0.73
Avg. Sq. Error (ppm^2)	4.43
Number of Points:	
Total	295
Within 2 ppm	220 (75%)
Within 1 ppm	139 (47%)

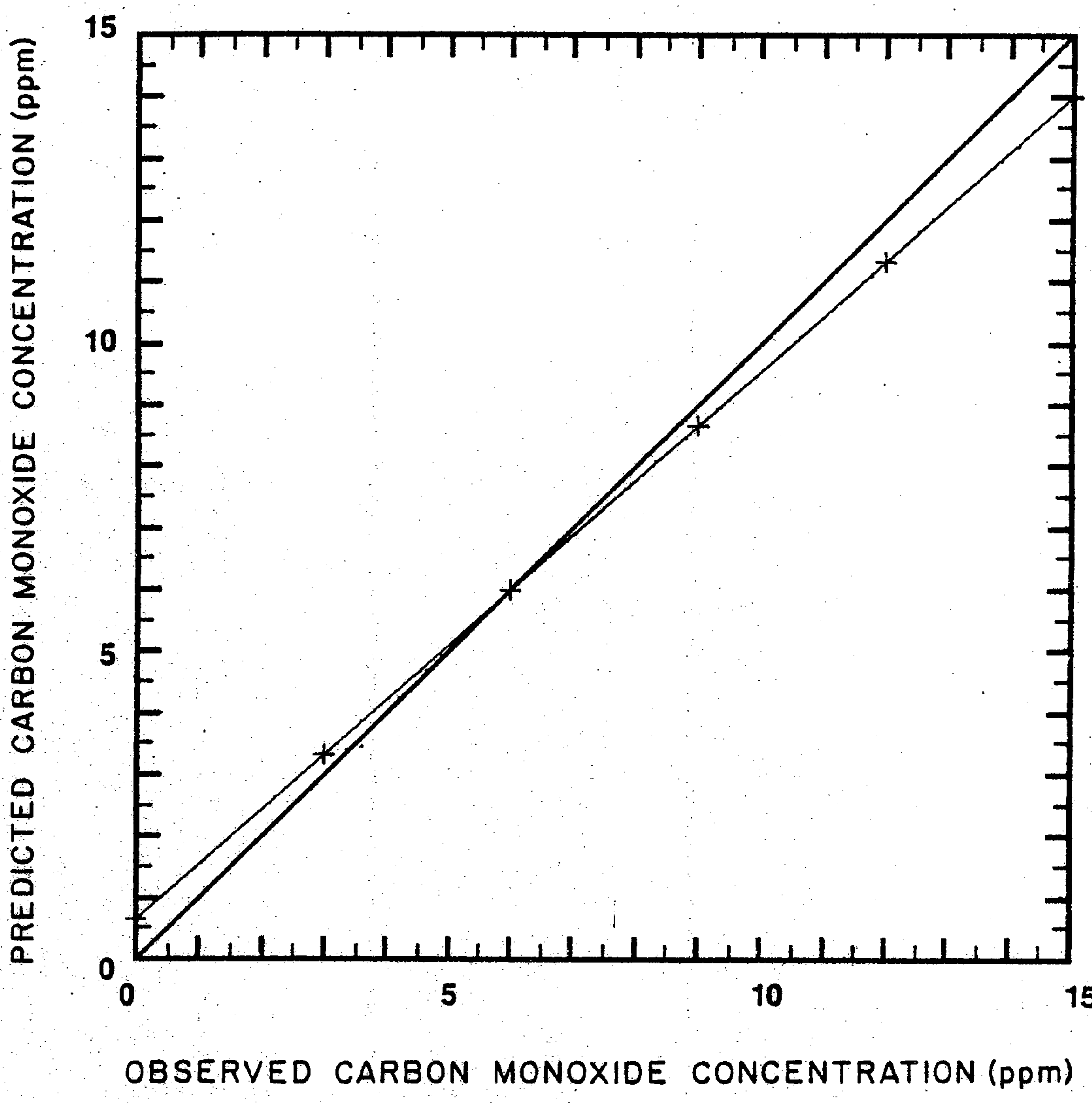


Figure 44. Regression lines for the TEXIN Model using the Texas A&M Houston data [28].

for all three analyses. The average error and the average squared error, however, are higher for the Houston results.

The data were separated into the nine wind speed/wind angle combinations as described previously, and the plots are presented in Figures 45-48. Once again there was no dependence on wind angle as far as accuracy was concerned, and the model still predicted best at high wind speeds. The wind speed classifications were low (0 to 2 m/s), medium (2 to 4 m/s) and high (above 4 m/s) for the College Station and California data. However, for the Houston site the following wind speed classifications were used: low (0 to 1 m/s), medium (1 to 2 m/s) and high (2 to 3 m/s). Despite this disparity between the wind speed classifications, the scattergrams for the various wind speed/wind angle categories for the Houston data are similar to those for the College Station and California data. For all three data bases, practically all of the points fall within the 2 ppm lines for the high wind speed cases, with fewer falling within the 2 ppm lines as the wind speed decreases to the medium and low classifications.

This phenomena is possibly the result of the vastly greater surface roughness at the Houston site. The extremely tall buildings at the Houston site most likely slowed the wind speed more than the relatively open College Station and California sites, while at the same time increasing the bulk flow of large masses of air at the Houston site. This increased vertical movement of air probably enhanced the dispersion to some degree. Clearly,

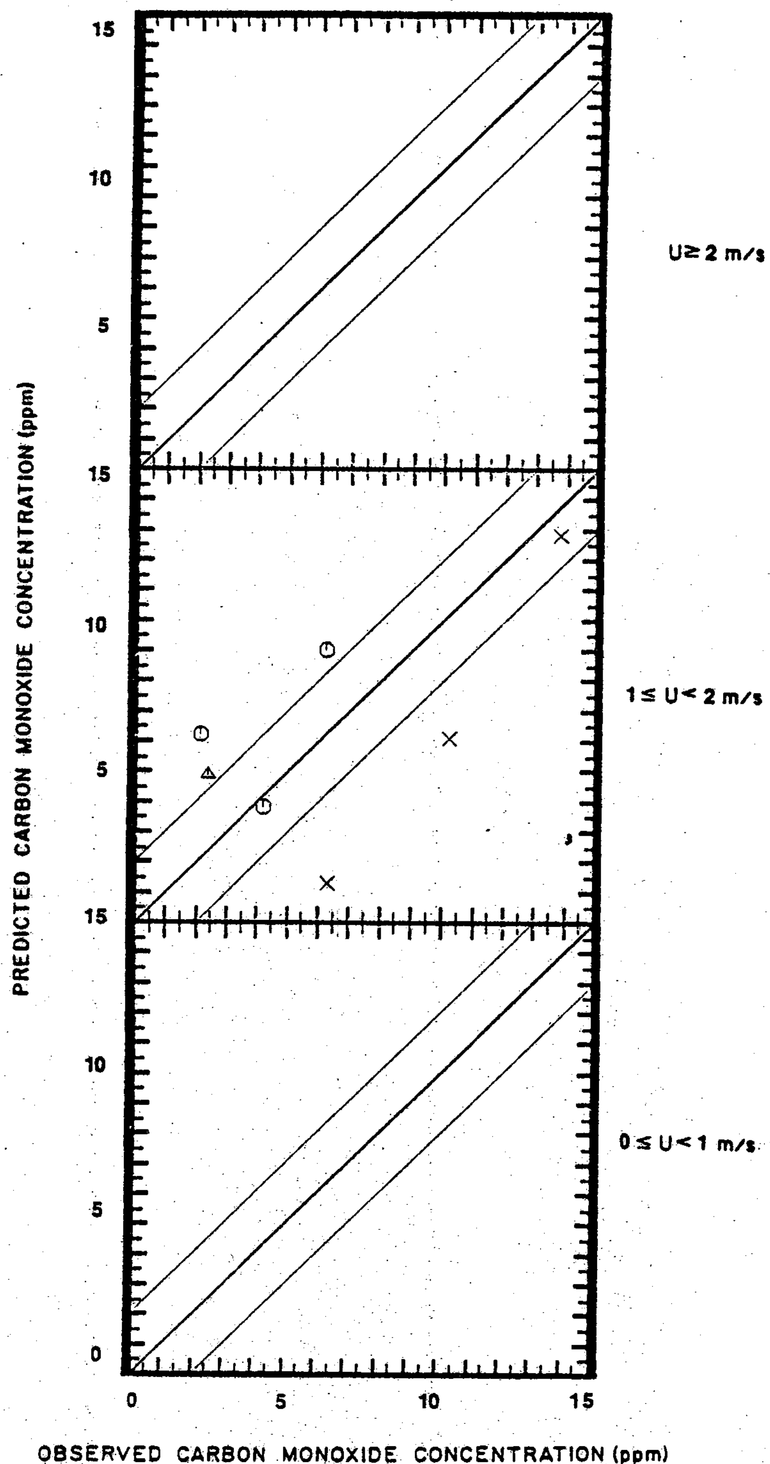


Figure 45. Scattergrams for near-parallel wind cases from the TEXIN Model using the Texas A&M Houston data (X-Tower 2, O-Tower 3, Δ-Tower 4) [28].

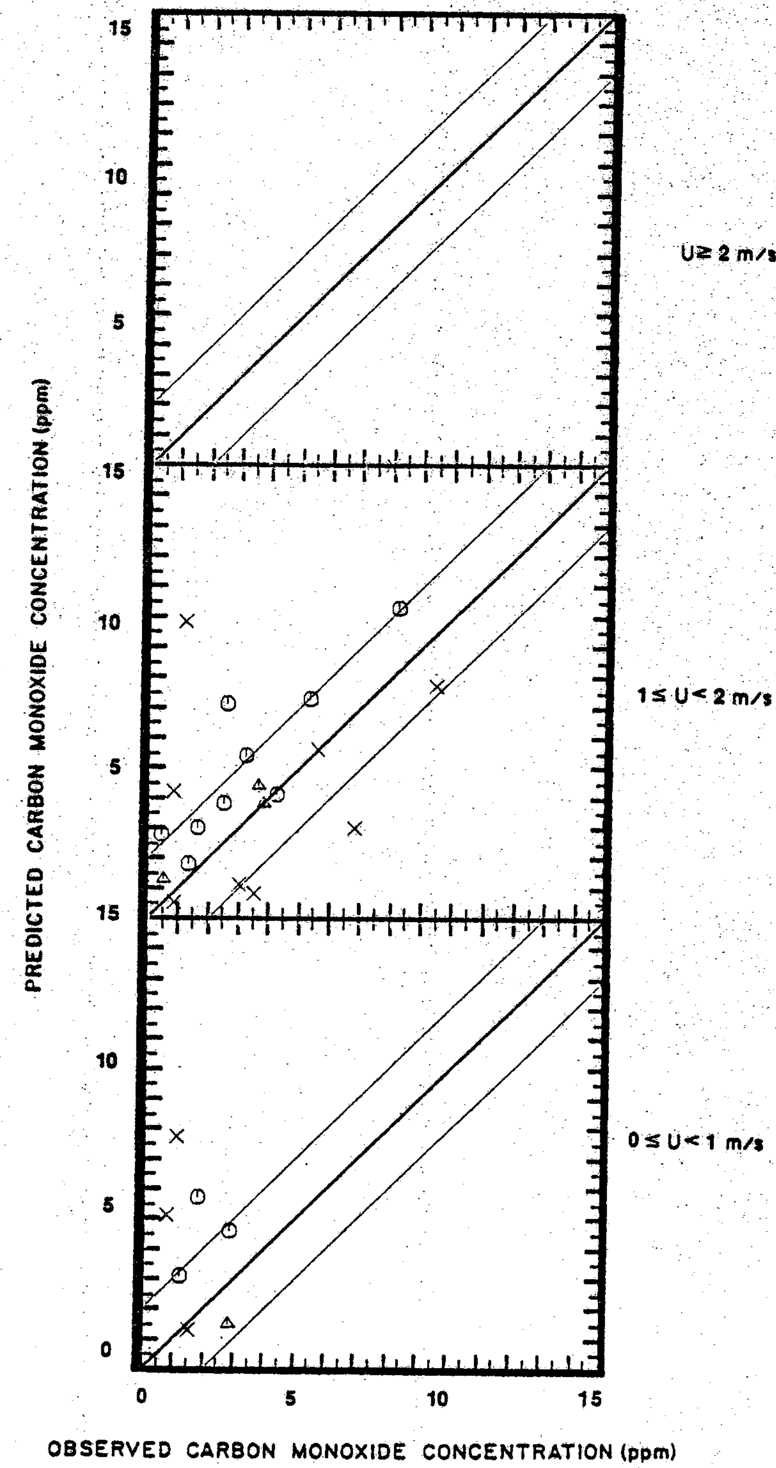


Figure 46. Scattergrams for near-forty-five degree wind cases from the TEXIN Model using the Texas A&M Houston data (X-Tower 2, O-Tower 3, Δ-Tower 4) [28].

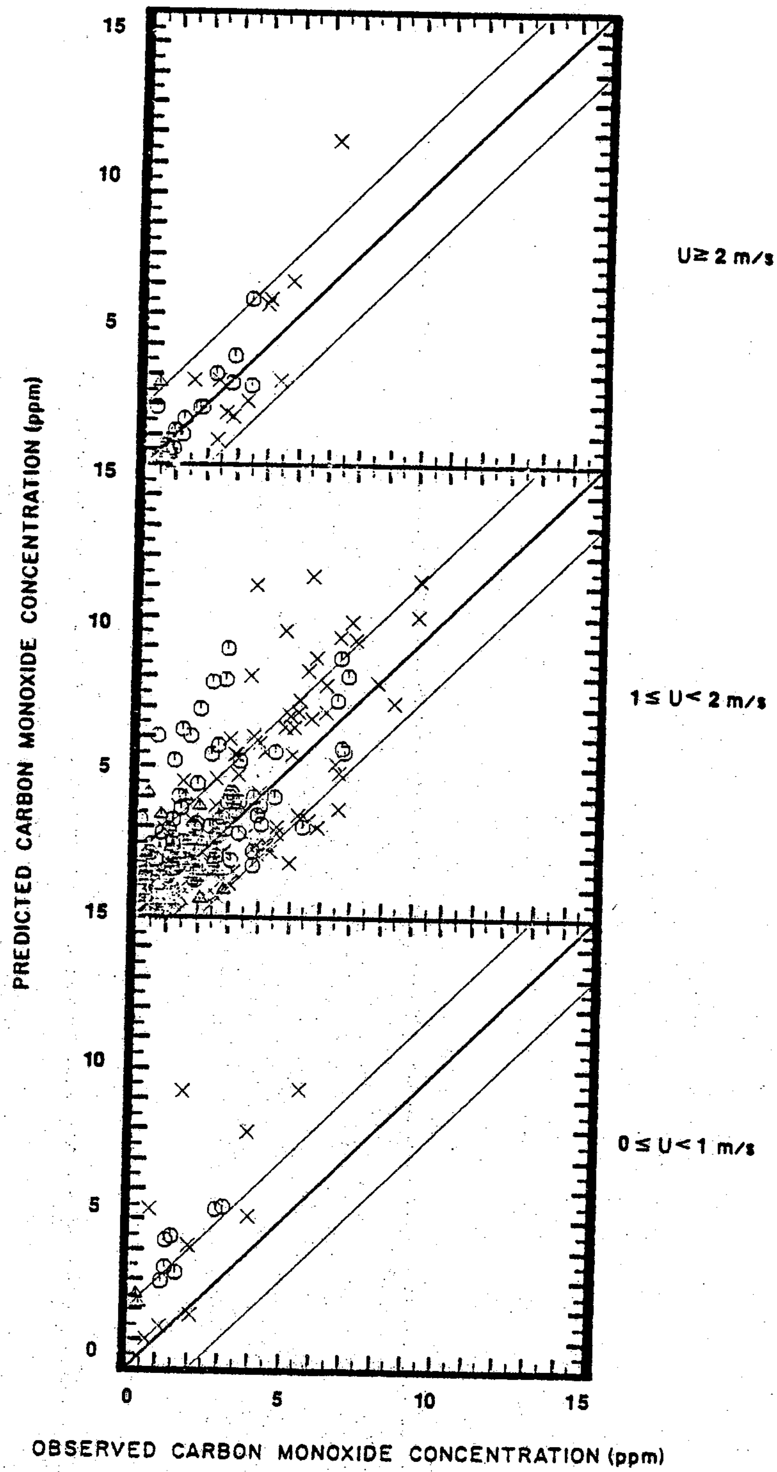


Figure 47. Scattergrams for near-perpendicular wind cases from the TEXIN Model using the Texas A&M Houston data (X-Tower 2, O-Tower 3, Δ- Tower 4) [28].

considerable further study of the Houston data and site geometry would be required before any more definitive conclusion can be made regarding this phenomenon.

Figure 48 presents scattergrams for the Houston simulation at various receptor heights. The model appears to predict equally well for the 5, 20, and even 35 foot (1.52, 6.10 and 10.67 m) receptors. The good performance at the 35 foot (10.67 m) level is contrary to the results obtained from the College Station data where the model performed poorly for the 35 foot receptors.

Once again, the TEXIN Model's accuracy does not depend on the location of the tower being modelled. From examination of Figures 45-48, it is evident that the TEXIN Model predicts CO concentration levels equally well for Towers 2, 3 and 4; and yet, the location of the three towers differ vastly with respect to the intersection as shown in Figure 10.

D. DISCUSSION OF MODEL APPLICATIONS

Due to the nature of current environmental legislation, the use of pollution models is often directed toward "worst case" analyses. Consequently, it is important to define not only what conditions constitute the "worst case," but also to clearly specify the proper receptor(s) and time periods involved.

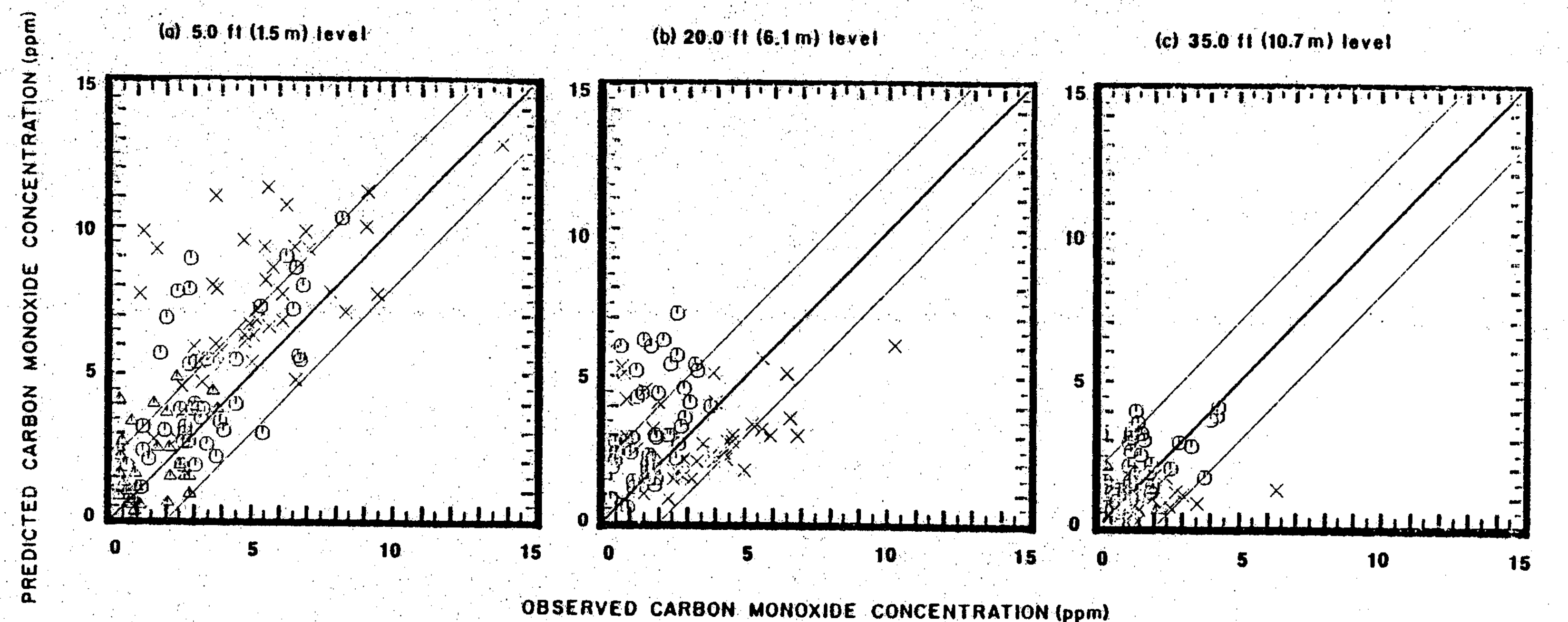


Figure 48. Scattergrams for receptors at the various levels from the TEXIN Model using the Texas A&M Houston data (X-Tower 2, 0-Tower 3, Δ-Tower 4) [28].

"Worst Case" Conditions

For one-hour periods the worst hourly carbon monoxide concentrations will normally coincide with the period of peak traffic volume. Traffic congestion, and thus delay, are greater under these conditions causing more pollutants to be emitted. Background concentrations will most likely be higher during these periods as well. As far as meteorological conditions are concerned, the TEXIN Model would be expected to predict higher concentrations as the wind speed decreases. This effect is due to the CALINE-3 dispersion model and would usually be observed experimentally. A value of one metre per second for the wind speed should probably be used for worst case analysis with moderately stable conditions (Pasquill type E). Again this lower limit is set by the CALINE-3 model and could perhaps be lowered by use of another dispersion model. A low ambient temperature should also be used as this increases CO emission rates, especially for cold-starting vehicles.

"Worst Case" Receptors

For a given intersection situation, one must exercise considerable judgement in locating realistic "worst case" receptors. The TEXIN Model and the IMM were found to predict equally well for various receptor locations. However, receptors near the intersection (rather than at midblock) will usually experience higher CO concentrations due to their proximity to the location of excess emissions.

One should thus be aware of these differences in choosing a receptor for worst case analysis.

A receptor height of about five feet (1.52 m) is recommended for worst case analysis since this is the normal pedestrian breathing height. A very high value for the receptor height should not be used since mixed results have been obtained for these cases.

Additionally, in a worst case analysis of an intersection, one should realize that the highest carbon monoxide concentrations will usually occur when the receptor is downwind of the entire intersection, rather than downwind of just one leg of the intersection. Exceptions to this rule will only occur when the emissions along one leg are substantially greater than those in the rest of the intersection.

Averaging Times

To analyze the worst-case carbon monoxide concentrations for an eight-hour period one should treat the eight-hour projection as the average of eight one-hourly analyses [8]. The principles presented above would be applied to the eight one-hour periods comprising the eight-hour period including maximum local CO emissions. The worst eight-hour CO concentrations can often be dominated by high background contributions, rather than local contributions. For these cases, procedures such as those developed by Holzworth [42] should be used.

Of interest in both the one-hour and eight-hour period analyses is the averaging time, defined as the time span over which observations are made. The number of turbulent fluctuations occurring at a point in a turbulent medium is related to the averaging time. Thus, for shorter averaging times a less variable family of turbulent fluctuations can be expected. The averaging time is a required input for CALINE-3; however, the model has only been verified for 30 and 60 minute averaging times.

The Texas A&M - College Station data base consists of 15 minute averaging times, and the California and Houston data bases of 60 minute averaging times as described in Chapter II. Although a more variable family of turbulent fluctuations (due to temporal variations of traffic, emissions, wind speed and wind direction) could be expected for the hourly averaging times of the California and Houston data bases, the TEXIN Model performed equally well for these hourly averaging times as for the College Station 15 minute averages. A more detailed examination of the time dependency of the recorded data at the College Station site is presented below.

Variability of Experimental Data

The raw data collected by Texas A&M at the Texas Avenue-Jersey Street intersection in College Station consisted of instantaneous data values which were compressed into 15 minute averages as described previously. However, the raw data provide insights that cannot be gleaned from the averages. To pursue these points, time periods of 135 minutes on several different days were chosen for examination. For these time periods, the carbon monoxide concentration, wind speed, wind angle, traffic, red delay, and signalization were plotted as functions of time.

To keep the traffic flow analysis tractable and the results meaningful, cases were chosen which had a wind direction such that the CO concentration at the sampling tower came primarily from one leg of the intersection. This leg was always the section of Texas Avenue nearest to Towers 1 and 2. Thus, the traffic flow examined was the traffic traversing Texas Avenue upwind of the receptor. The red delay recorded is the red delay incurred by this traffic and the signalization is that experienced by this traffic. Figures 49 and 50 are typical graphs of these instantaneous data values.

The traffic flow and wind direction data are shown in Figure 49, while wind speed and carbon monoxide concentration are given in Figure 50. Concerning the traffic flow, the dashes are the periods of time when the traffic was facing a red light and the gaps indicate a green light. The numbers following the dashes are the total amount of red delay experienced by the traffic during that red light period. The signalization and red delay are repeated on the CO concentration plot for reference. The carbon monoxide concentration is for the receptor at a height of five feet (1.52 m) on Tower 1.

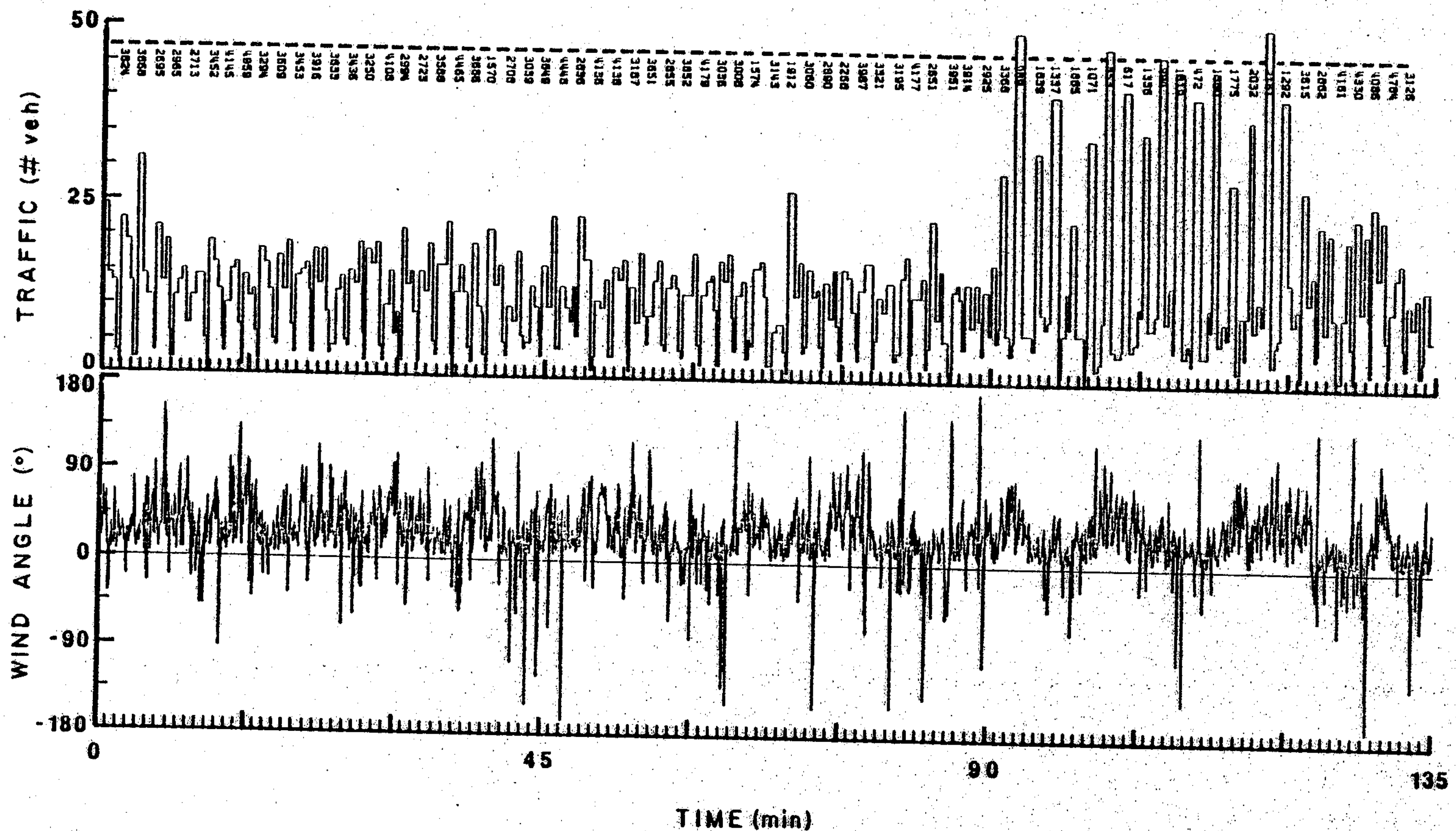


Figure 49. Variability of traffic volume, delay, signalization and wind direction with time.

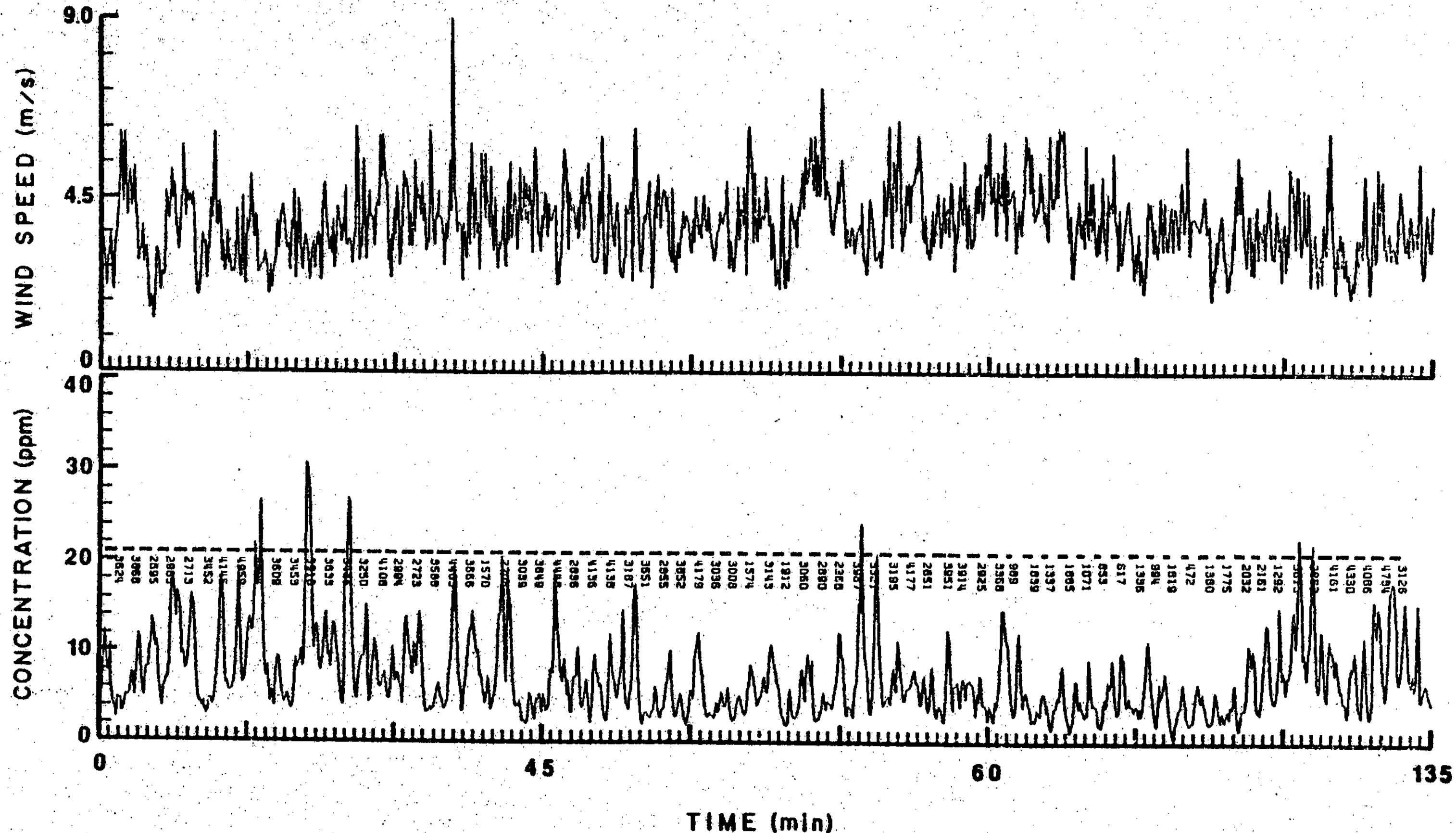


Figure 50. Variability of wind speed and carbon monoxide concentration with time.

Of interest is the carbon monoxide level between the time period 90-120 minutes after the start of the graph. During this time period, the volume of traffic traversing the section of roadway upwind of the receptor increases markedly. One would expect the CO level to do likewise, however, this is not the case. In fact, the CO level actually decreases. This decrease was due to a change in signalization during this period causing a decrease in the red delay levels.

Another aspect of interest in the graph of the CO concentrations is that for a given period of time (e.g., a fifteen minute period) the average concentration may be exceeded by a factor of up to five or six by excursions lasting as long as a minute. In addition, excursions are seen to be quite frequent.

These observations suggest several important conclusions. First of all, delay at an intersection appears to be a primary parameter in the estimation of intersection emissions. With increased delay, the idling emissions become more pronounced and undoubtedly contribute to this effect. Secondly, the variability of the data indicates that at a given time, the concentrations of carbon monoxide may be several times the average value. This occurs more often for low wind speeds and wind angles. Consequently, off-site meteorological or background concentration measurements are of dubious value. Also, for a given case, the method of data averaging could be significant. For example, a one sample "spot check" of an intersection could be several times above or below a realistic average value.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Comparisons of existing experimental data and corresponding intersection pollution model simulations have shown that the capabilities of these techniques are extremely limited even for a simple signalized intersection. The Intersection Midblock Model (IMM), as modified by Piracci, et al., was found to be the most reliable existing model. However, even for the IMM, simulations of the Texas A&M data were approximate at best, with regression coefficients (r^2) on the order of 0.4. Given the number and complexity of the inputs to the IMM, these approximate results suggested that a shorter, if not more accurate, model could be found.

A new model for the prediction of carbon monoxide pollution concentrations near intersections was developed. Designated the TEXIN (Texas Intersection) Model, this new model incorporates the MOBILE-2 and CALINE-3 programs with a set of established "short cut" traffic and excess emissions techniques. The result is an efficient program capable of estimating carbon monoxide levels near intersections (both signalized and unsignalized) given minimal geometrical, meteorological and traffic parameters.

A data base was assimilated from data collected by Texas A&M at a College Station, Texas, site and was used to test the performance of the TEXIN Model, the Intersection Midblock Model, the program MICRO and the Indirect Source Guidelines - Volume 9 (Revised) procedure. The TEXIN Model performed best in these comparisons with a regression coefficient (r^2) of 0.47. Moreover, the new model used less than one-tenth the computer time required by the Intersection Midblock Model. The TEXIN Model is much simpler to use than the IMM and requires considerably fewer inputs.

An extensive data base was also obtained from the California Department of Transportation. The TEXIN Model was used to simulate the California data and produced results similar to those for College Station. An additional data base was assimilated from data collected by Texas A&M at a "semi-street canyon" site in Houston, Texas. The TEXIN Model was used to simulate the data and produced results similar to those obtained from both the College Station and California data. More study of the Houston case is needed, however, and these results should be considered as preliminary in nature since the model has not been designed or verified for street canyon applications.

For the three data bases, the models were found to perform equally well for all wind angles. The models predicted best for high wind speeds with increased scatter at lower wind speeds.

The pollutant dispersion model incorporated into the TEXIN Model, CALINE-3, produced mixed results for receptors located near the roadway for heights above approximately 30 feet. At these receptors, the model performed poorly for the College Station data but performed well for the California and Houston data. The use of a more sophisticated dispersion model, such as a link version of TRAPS III (TXLINE), might correct this problem. The TEXIN Model performed equally well for receptors located near the intersection as for receptors near midblock. Consequently, the location of proper receptors for environmental impacts is not limited by the predictive model.

The instantaneous measurements of CO, traffic and meteorology for several days of the Texas A&M data were examined in detail. The effect of delay on the carbon monoxide concentrations was seen to be pronounced. As a result, minimization of delay should have a major impact on minimizing the overall pollution at intersections. The carbon monoxide concentrations were seen to fluctuate greatly with excursions as much as five to six times the average concentration for a given time period.

RECOMMENDATIONS FOR FUTURE WORK

Future research to extend this work include:

(1) Further attempts to determine and eliminate the cause of scatter in the results for low wind speeds should be pursued.

(2) By the use of nomographs along with the capabilities of the MOBILE-2 program, the TEXIN Model could easily be extended to handle hydrocarbons and nitrogen oxides. However, there are no data currently available for comparative purposes. Future experimental work could yield a data base. This added capability would, of course, increase the core space and execution time required by the model.

(3) The accuracy of the TEXIN Model might be improved by the use of a dispersion model superior to CALINE-3. A new model currently being developed by the principal investigators, TRAPS III (TXLINE), has shown substantial improvement over CALINE-3 for straight roadways. If TRAPS III is modified to include link capabilities, much better results may be possible. The accuracy of the model at high receptors would most likely be improved by the TRAPS III Model and the limitation of a 1 m/s lowest windspeed would also be removed.

(4) Improved techniques for modelling vehicle delay and modal emissions are equally important in improving intersection pollution models, and future work towards developing such techniques should be pursued.

(5) Further study and analysis of the data obtained by the Texas A&M and California groups are in order. The time variation of the important variables suggest that probabilistic approaches to the establishment of standards should be considered. The variability of the data indicate that the use of simple monitoring networks of pollution and meteorology for intersection analyses are not appropriate.

(6) The extension of this work to include street canyon situations would be extremely valuable to urban traffic engineers and planners. Detailed study of the Houston data would be a starting place for such an analysis and theoretical analyses such as those of the IMM may prove to be valuable. However, no extensive experimental data currently exist for street canyon situations and considerable experimental work will need to be done before any theoretical analyses can be verified.

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APPENDIX A

USER'S GUIDE FOR THE TEXIN MODEL

The TEXIN Model is a tool intended to provide improved perspective in the evaluation of pollution impacts from intersections considering temporal and spatial variations of traffic, emissions, meteorology, the nature of receptors, and their relation to local intersection air quality. This User's Guide briefly describes the TEXIN Model and its use. The input procedures are outlined in detail, the possible outputs are discussed, and several illustrative examples are presented.

Model Description

The TEXIN Model is a FORTRAN computer program which estimates carbon monoxide emissions and concentrations at

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The Texas Intersection (TEXIN) Model was developed by the Chemical Engineering Department and the Texas Transportation Institute at Texas A&M University. The work was sponsored by the U.S. Department of Transportation Federal Highway Administration through the Texas State Department of Highways and Public Transportation. A complete discussion of the development and validation of the TEXIN Model is presented in the Texas Transportation Institute final research report FHWA/TX-81/541, "Estimates of Air Pollution Near Simple Signalized Intersections" [A1]. Questions or comments regarding the model should be directed to Professor A.D. Messina or Professor J.A. Bullin, Chemical Engineering Department, Texas Transportation Institute, Texas A&M University, College Station, Texas, 77843, Phone (713) 845-3361 or to Mr. Roderick Moe, Texas State Department of Highways and Public Transportation, File D-8P, 11th & Brazos, Austin, Texas, 78701, Phone (512) 465-6170.

roadway intersections. The program performs three distinct tasks: (1) estimation of traffic parameters (stopped delay, time in queue, etc.);(2) estimation of vehicle emissions and their distribution; and (3) modelling of pollutant dispersion downwind of the intersection. The general flow diagram for the TEXIN Model is presented in Figure A1. The model requires a minimal set of four types of geometrical, meteorological, and traffic-related inputs, as shown in the figure.

The TEXIN Model is flexible enough to handle most intersection configurations which would realistically be encountered by highway engineers. The program can model the basic case of a simple intersection (signalized or unsignalized) with four straight legs; as well as more complex situations where the legs of the intersection may be curved. This is accomplished by approximating the curves as a series of connected straight links. In addition to modelling the major intersection, the program has the flexibility to concurrently model several minor intersections (controlled by stop or yield signs) arising from nearby side streets. The TEXIN Model is not applicable to street canyon configurations, however.

The first function performed by the program is that of traffic flow analysis. Initially, the traffic flow on the major intersection is evaluated, and afterwards any minor intersections are handled. The Level of Service, and thus the stopped delay per vehicle, of the major intersection is first determined. For a signalized intersection, this is accomplished through the use of Critical Movement Analysis, as presented in NCHRP Project 3-28, "Development of an Improved Highway Capacity Manual" [A2]. For an unsignalized intersection, a corresponding methodology presented in the same report is utilized. Several other traffic parameters of interest, including approach delay, time in queue, percent of vehicles stopping, and queue length are next calculated using the results from a study by Reilly, et al. [A3]. For minor side-street intersections, the methodologies for unsignalized intersections are utilized with certain simplifying assumptions made to keep the analyses tractable.

The second function performed by the program is the estimation of vehicle emissions. The emissions are modelled as the sum of two components: (1) the cruise emissions from free flowing traffic (assumed to be uniformly distributed along the entire length of the roadway); and (2) the excess emissions from vehicles incurring delay (assumed to be emitted only over the queue length). The MOBILE-2 [A4] program is incorporated into the TEXIN Model to estimate the cruise emissions of free flowing vehicles as well as the idle emission rate. The methodology for estimating excess

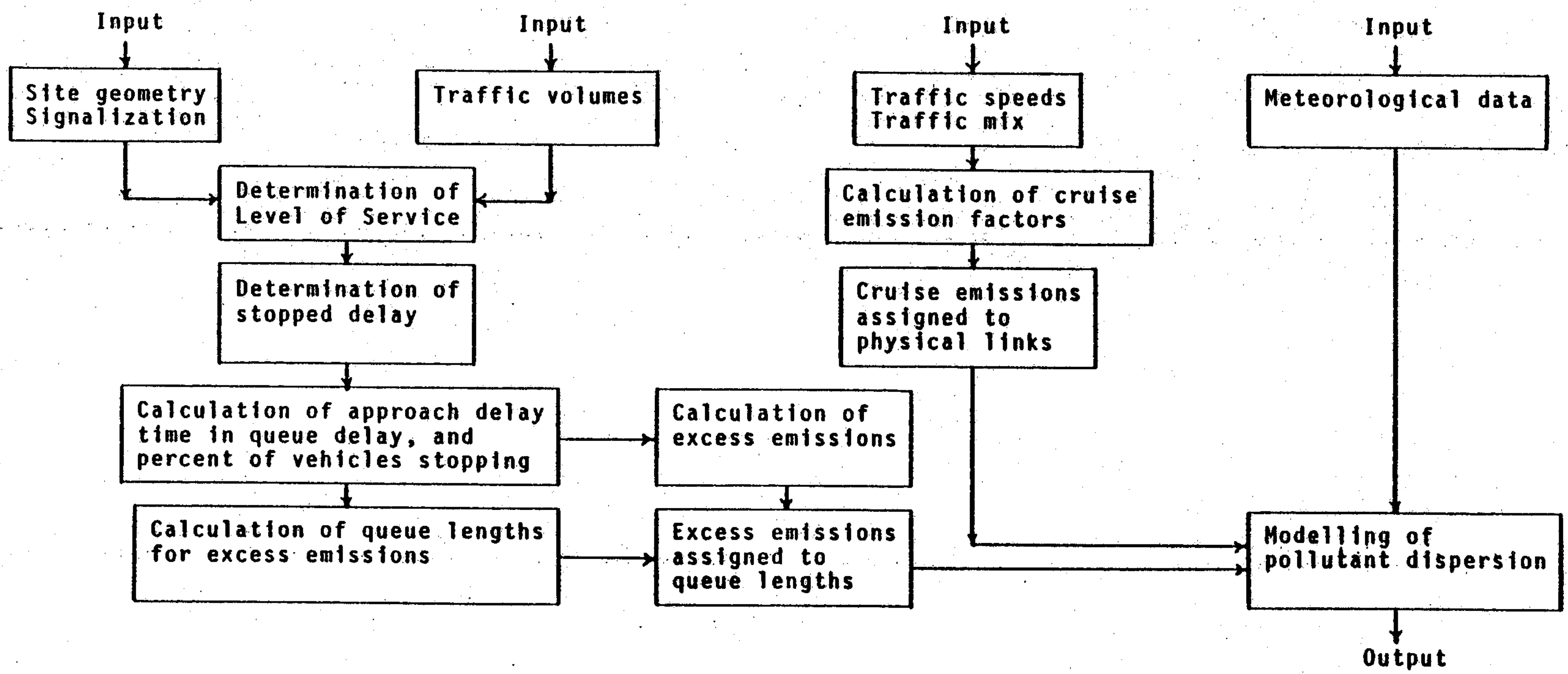

Figure A1. General flow diagram for the TEXIN Model.

emissions utilizes the traffic parameters calculated previously and nomographs relating excess emissions to speed changes, as suggested by Ismart [A5].

Once the estimation of vehicle emissions and distribution is accomplished, the final task of modelling the pollutant dispersion is performed. The Gaussian dispersion model, CALINE-3 [A6], is incorporated in the TEXIN program to calculate the dispersion of pollutants downwind of the intersection. Several minor modifications were made to the CALINE-3 program, mainly to the input/output routines, so that it could handle the constructed psuedolinks. Additionally, a modification raising the emission source height at very low wind speeds extended the applicability of the CALINE-3 to wind speeds below one metre per second [A1].

To conserve computer compilation and execution time, an effort was made to delete sizeable portions of the extremely large MOBILE-2 program which were not needed by the TEXIN Model. These deletions included the nitrogen oxides and hydrocarbon emission factors, optional correction factors for inspection/maintenance programs, air conditioning and extra-load towing, and most of the input/output processing. These modifications resulted in an approximate two-thirds decrease in storage space as well as a similar decrease in the compilation and execution time required to process the

MOBILE-2 program. The deletions in the MOBILE-2 program, and a general effort throughout the development of the TEXIN Model to minimize the amount of computer time required, have produced an efficient computer program. The TEXIN Model requires less than a tenth of the execution time required by the well known Intersection Midblock Model [A7], and yet achieves an accuracy surpassing the same [A1]. A further decrease in the execution time required can be achieved by performing numerous simulations in a single computer run. When more than ten simulations are performed, the execution time per simulation is approximately one-fourth of the execution time for a single simulation run.

Input Procedure

The TEXIN program requires five types of input cards. They are (in order):

(1) Heading and Flags card (one card)
(2) Link Description cards (one card per link)
(3) Receptor Location cards (one card per receptor)
(4) Meteorological Conditions card (one card)
(5) Vehicle Scenario card (one card).

The input sequence of the data is presented in Table A1 and described below. As shown in the table, all the input data are formatted according to standard FORTRAN conventions (it is especially important to note that all integer values are right-justified). These conventions are shown in Figure A2.

Table A1. Input data for the TEXIN Model.

Format	Variables	Units
Heading and Flags Card,	(1 card):	
10A4	HEAD	-
3I3	VMFLAG,PRTFLG,INTFLG,	-
4I3	NR,NNDL,NDL,NP	-
F4.0	CY	s
Link Description Cards,	(4+NNDL+NDL cards):	
I3	LA	-
4F6.0	XL1,YL1,XL2,YL2	m
A2	TYP	-
2F4.0	WL,HL	m
F6.0	VPHI	veh/hr
F4.0	VSP	mph
3I3	NLN,NLTL,NRTL	-
2F5.0,I3	FLT,FRT,LTFLG	-
Receptor Location Cards,	(NR cards):	
3F6.0	XR,YR,ZR	m
Meteorological Conditions Card, (1 card):		
F4.0	U	m/s
F4.0	BRG	deg
F4.0	TAMB	^oF
I1	CLAS	-
F5.0	MIXH	m
F5.0	AMB	ppm
F5.0	Z0	cm
F5.0	ATIM	min
Vehicle Scenario Card, (1 card):		
I1,I2	IREJN,ICY	-
3F5.0	PCCN,PCHC,PCCC	%
8F5.0	VMTMIX	-

DATA PROCESSING CENTER
TEXAS A & M UNIVERSITY

PROBLEM: INPUT DATA FOR TEXIN MODEL
PROGRAMMER: JPN
PAGE 1 OF 1
DATE 15/04/82

FORTRAN STATEMENT

HEADING AND FLAGS CARD:

HEAD / VMFLAG / PRTFLG / INTFLG / NR / NNDL / NDL / NP / CY

INPUT DATA CONVENTIONS 1 2 1 1 0 0 4 80. (1 card)

LINK DESCRIPTION CARDS:

LA / XL1 / YL1 / XL2 / YL2 / TYP / WL / HL / VPHI / VSP / NLN / NLTL / NRTL / FLT / FRT / LTFLG

1 0. 0. 0. 1000. AG 15.0 0. 950. 45. 2 1 0 0.25 0.15 1 (4+NNDL+NDL cards)

RECEPTOR LOCATION CARDS:

XR / YR / ZR

20. 20. 2. (NR cards)

METEOROLOGICAL CONDITIONS CARD:

U / BRG / TAMB / CLAS / MIXH / AMB / Z0 / ATIM

2.5 135. 68. 4 1000. 0.0 100. 60. (1 card)

VEHICLE SCENARIO CARD:

IREUN / ICY / PCCN / PCHC / PCCC / LDGV / LDGT1 / LDGT2 / HDGV / LDDV / LDDT / HDDV / MC

1 80 19.9 34.6 25.7 0.520 0.176 0.043 0.223 0.000 0.000 0.007 0.031 (1 card)

Figure A2. Input Data Conventions for the TEXIN Model.

Numerous runs may be simulated by repeating the sequence of input cards.

<u>Heading and Flags Card</u>. The first input card is the Heading and Flags card (See Table A1). The first 40 spaces are for the job title and may contain any combination of alphanumeric characters. The next 21 spaces are for the seven 3-digit integer variables: VMFLAG, PRTFLG, INTFLG, NR, NNDL, NDL, NP. The purposes of these variables are as follows:

VMFLAG - option flag for the VMT mix:
- 0 - MOBILE-2 supplied VMT mix,
- 1 - user-supplied VMT mix;

PRTFLG - output option flag (see the discussion of output for further clarification):
- 0 - abbreviated output,
- 1 - basic output,
- 2 - extended output;

INTFLG - option flag for the type of intersection:
- 0 - unsignalized intersection,
- 1 - signalized intersection;

NR - the number of receptors (maximum of twenty);

NNDL - the number of additional links (other than the four intersection links) on which the traffic incurs no delay (i.e., extensions of an intersection link to account for a curve in the road);

NDL - the number of additional links on which the traffic incurs delay (i.e., side streets controlled by stop or yield signs);

NP - the number of phases (zero for an unsignalized intersection).

The final variable on the card is the signal cycle length, CY, in seconds.

Link Description Cards. The second type of input card is the Link Description card. Unlike the Heading and Flags card (for which there is only one card per run), the number of Link Description cards depends upon the intersection configuration. CALINE-3 treats the entire roadway as a link, rather than each lane as an individual link, with uniform emissions within a mixing zone centered along the physical centerline of the link (roadway); thus, the TEXIN program does the same. To model various intersection configurations, the TEXIN program recognizes three different types of links: (1) intersection links representing the four legs of the major intersection (there must always be four of these cards, although for a "T" intersection one would contain zero values); (2) links on which the traffic incurs no delay, such as connecting links approximating curves in the roadway significantly distant from the intersection to be free of delay (there must be NNDL number of these); and (3) links on which the traffic incurs delay, such as side streets controlled by stop or yield signs (there must be NDL number of these). Table A1 gives the input data sequence (and format) for the Link Description cards as described below. Not all of these data are necessary for each type of link, and any unnecessary parameters may be omitted from the Link Description card. (see example two).

In determining geometrical inputs to the TEXIN program, a localized x-y coordinate system is assumed for the intersection locale with the origin of the coordinate system lying at the approximate physical center of the intersection. The positive y-axis is then taken as being aligned with due north (this is an arbitrary assignment, but must be adhered to for all geometric inputs).

The first four Link Description cards are for the four intersection links with the first card for the north leg, the second for the east leg, the third for the south leg, and the fourth for the west. <u>This sequence must be followed for proper traffic evaluation</u>. The Link Description cards contain the following data:

LA - the link association number (for the four intersection links, this is simply the link number where 1=North, 2=East, 3=South, 4=West; for NNDL and NDL links, this is the intersection link with which the link is associated);

XL1,YL1 - the endpoints of the intersection-end of the link (these should be at the approximate center of the intersection);

XL2,YL2 - the endpoints of the upstream-end of the link;

TYP - type of link:
- AG - at grade,
- FL - fill,
- DP - depressed,
- BR - bridge;

WL - the actual width of the roadway (do not include the width of the shoulders);

HL - the source emission height (zero for at-grade);

VPHI - the number of vehicles <u>approaching</u> the intersection on the link;

VSP - the average speed of non-delayed vehicles on the link;

NLN - the number of <u>approach</u> lanes on the link;

NLTL - the number of <u>exclusive</u> left-turn lanes on the link;

NRTL - the number of <u>exclusive</u> right-turn lanes on the link;

FLT - the fraction of vehicles turning left on the link;

FRT - the fraction of vehicles turning right on the link;

LTFLG - flag indicating left turn signalization for the link:
- 0 - no left turn phase,
- 1 - left turn phase.

For unsignalized intersections, the major roadway (that is, the roadway with the right-of-way) must align with the north-south direction (links 1 and 3), and the flag, LTFLG, indicates whether the minor street is controlled by a stop or yield sign (0 - yield sign, 1 - stop sign). The program is not capable of modelling an uncontrolled or four-way stop sign controlled intersection.

The program is capable of modelling a "T" intersection (three legs); however, four intersection Link Description cards must be inputted to preserve the input sequence. A "T" intersection is handled by simply setting the incoming traffic volume on the "missing" leg to zero. Additionally, the fraction of vehicles turning on the other three legs must be such that no traffic leaves the intersection on the "missing" leg.

If there are any links on which the traffic does not incur delay, Link Description cards for these are supplied next. The data on these cards begin with the link association number, LA, and ends with the source emission height, HL. The link association number simply indicates which of the four intersection links the particular link is associated with (1 - north, 2 - east, 3 - south, 4 - west), and the other variables are as described previously. There should be NNDL number of these cards and no particular sequencing of the cards is necessary (see Example Two).

Next, Link Description cards for any minor streets on which the traffic incurs delay are inputted. The cards must contain all the data from LA to LTFLG. The link association number, LA, indicates which of the intersection links the particular link intersects; the endpoints, XL1 and YL1, are the endpoints of the intersection-end of the minor link; the flag, LTFLG, is once again indicative of the type of control on the minor link (0 - yield, 1 - stop); and, the rest of the variables are as defined previously (see Example Three). Minor streets can only be modelled if they intersect one of the four intersection links; however, if they do not intersect one of these links, they are presumably at such a great distance from the intersection that they will contribute little to the air quality in the vicinity of the intersection.

Receptor Location Cards. The third type of input card is the Receptor Location card (See Table A1). One card is needed for each receptor, and thus, there must be NR number of these cards in any order. The Receptor Location card contains the coordinates, XR and YR (with respect to the localized x-y coordinate system), as well as the height, ZR, of the receptor.

Meteorological Condition Card. The next type of input card is the Meteorological Conditions card. Only one card is necessary per run, and Table A1 gives the input data sequence and format. This card contains the following data:

U - the wind speed;

BRG - the wind angle with respect to the positive y-axis (e.g., a wind from due east would be entered as 90 degrees);

TAMB - the ambient temperature;

CLAS - the Pasquill stability class (A=1 to F=6);

MIXH - the mixing height;

AMB - the ambient background concentration;

Z0 - the surface roughness;

ATIM - the averaging time.

Pasquill's analysis [A8] of atmospheric stability (Figure A3) and Myrup and Ranzieri's table [A6] of suggested surface roughness values (Table A2) are recommended for use in determining the stability class and surface roughness, respectively. A value of 100 metres is recommended for the mixing height.

Vehicle Scenario Card. The final type of input card required is the Vehicle Scenario card (See Table A1). Only one card is needed per run and contains the following data:

IREJN - the region being modelled:
- 1 - low altitude, non-California
- 2 - low altitude, California
- 3 - high altitude, non-California;

ICY - the last two digits of the calendar year being modelled;

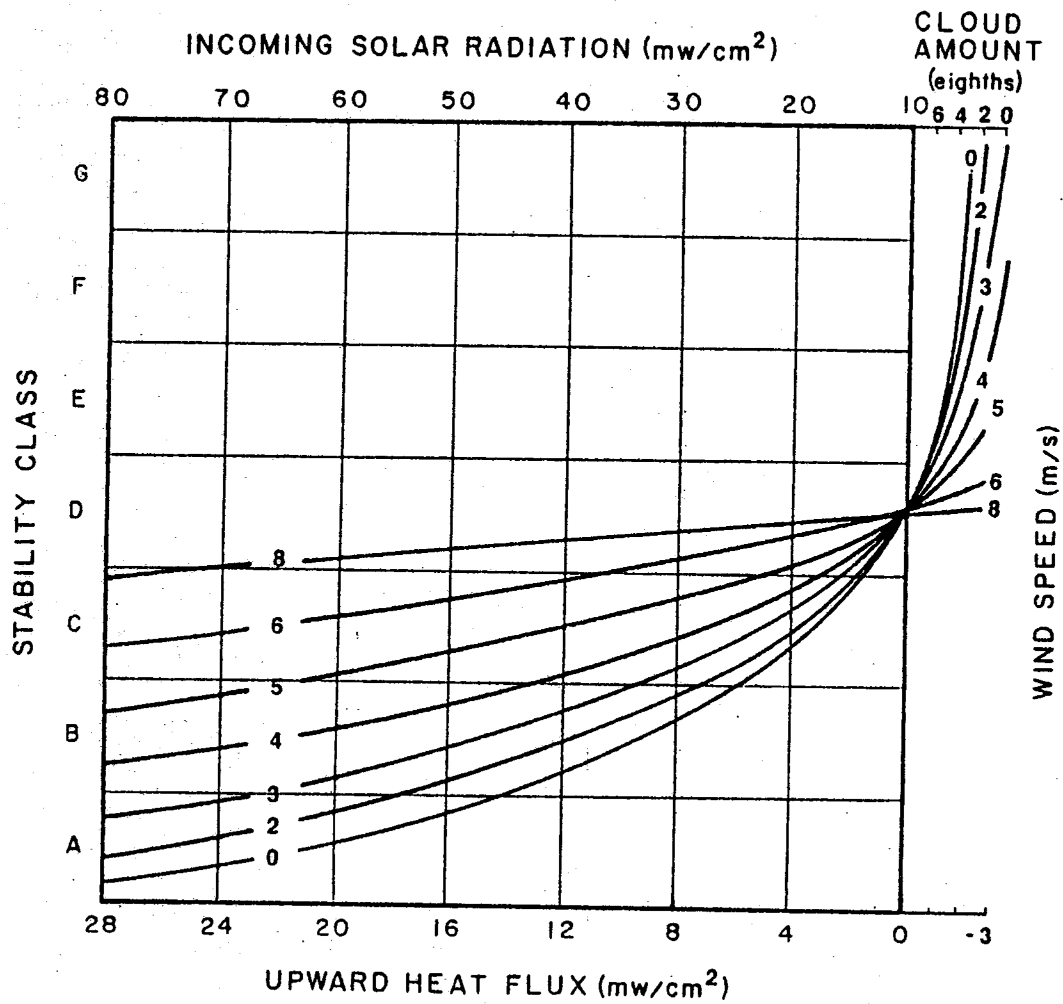

Figure A3. Pasquill stability, A-G, as related to wind speed and incoming solar radiation. [A8]

Table A2. Surface Roughness for Various Land Uses [A6].

TYPE OF SURFACE	Z0 (cm)
Smooth mud flats	0.001
Tarmac (pavement)	0.002
Dry lake bed	0.003
Smooth desert	0.03
Grass (5-6 cm)	0.75
(4 cm)	0.14
Alfalfa (15.2 cm)	2.72
Grass (60-70 cm)	11.4
Wheat (60 cm)	22
Corn (220 cm)	74
Citrus orchard	198
Fir forest	283
City land-use:	
Single-family residential	108
Apartment residential	370
Office	175
Central-business district	321
Park	127

PCCN - the percent non-catalyst equipped vehicles in cold start mode;

PCHC - the percent catalyst equipped vehicles in hot start mode;

PCCC - the percent catalyst equipped vehicles in the cold start mode;

VMTMIX - the VMT mix for the eight individual vehicle types (LDGV, LDGT1, LDGT2, HDGV, LDDV, LDDT, HDDV, and MC).

The VMT mix is only needed if a value of one (1) is inputted for VMFLAG on the Headings and Flags card; otherwise, the VMT mix is omitted and the MOBILE-2 supplied VMT mix will be utilized.

Discussion of Output

The output from the TEXIN Model is variable, depending on the value inputted on the Heading and Flags Card for the integer variable, PRTFLG. Three different output formats are available, and are: the abbreviated output, the basic output, and the extended output (corresponding to PRTFLG values of 0, 1, and 2, respectively).

The abbreviated output consists of a summary of the input meteorological conditions and a listing of the pollutant concentration at each receptor. In addition, the basic output also contains a section summarizing the intersection traffic flow analysis (including the volume to capacity ratio, stopped delay per vehicle, etc.) and a link description section (for both the physical links and the constructed psuedolinks). The extended output includes the MOBILE-2 emission factors and the contribution from each link to the pollutant concentration at each receptor.

<u>Examples</u>

Three examples have been prepared and are presented in order to facilitate the user's understanding of the capabilities and use of the TEXIN model.

<u>Example One</u>. The first example is the simple case of an intersection with four right angle corners. All four legs extend 1000 metres from the intersection and are geometrically identical (e.g., two approach lanes, one exclusive left turn lane, no right turn lanes, 15 metres in width, and at-grade). The x-y Cartesian coordinate system is mapped onto the intersection site, such that, the four legs lie along the x- and y-axes and the approximate center of the intersection is located at the origin of the coordinate system. This is shown in Figure A4.

The input cards for example one are presented in Figure A5. The first card is the Heading and Flags card. Note the flag values of zero for VMFLAG indicating that the MOBILE-2 supplied VMT mix is to be used, two for PRTFLG for the extended output format, and one for INTFLG indicating a signalized intersection. Two receptor locations are being

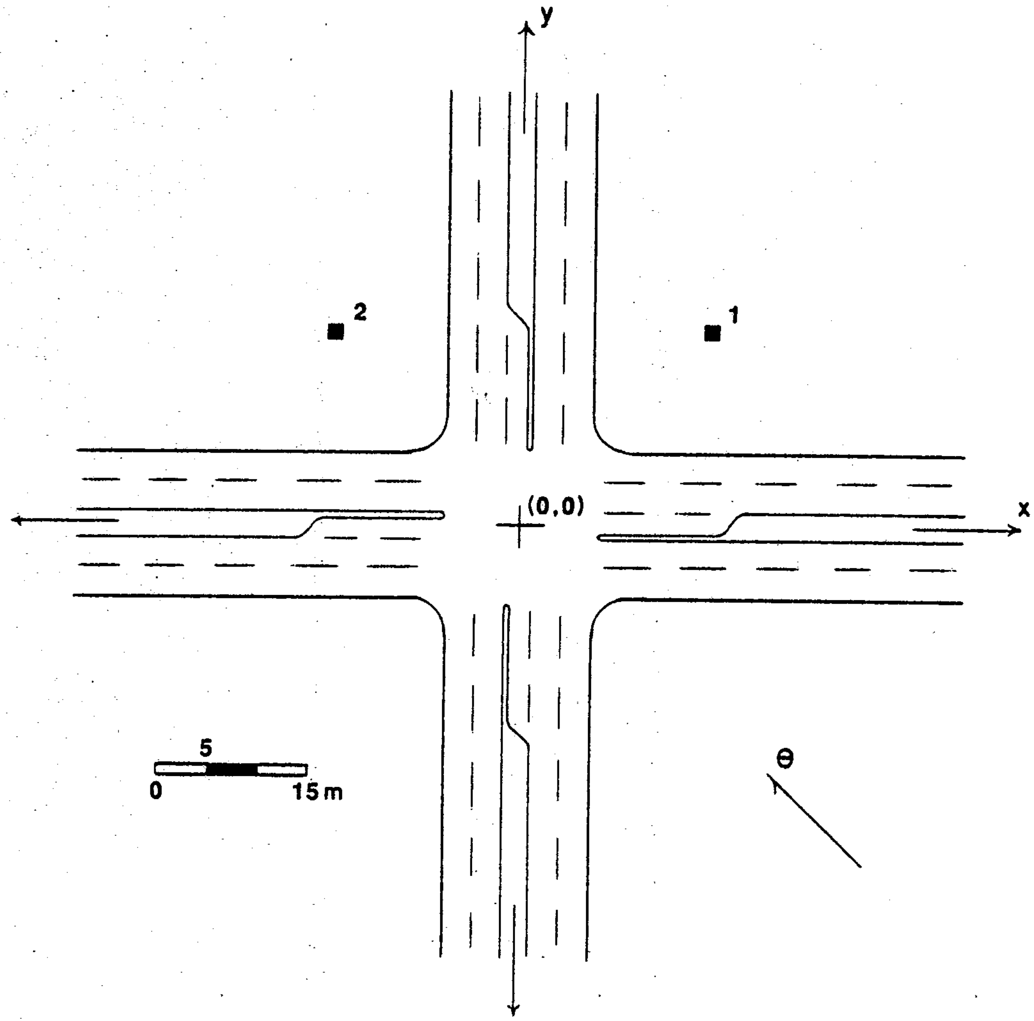

Figure A4. Intersection Geometry for example one.

modelled (NR = 2), and no additional links are needed for the simulation (NNDL = NDL = 0). The signalization is four phase (NP = 4) with an eighty second total cycle length (CY = 80.0) and these data are included on the first card as well.

The next four cards are Link Description cards which describe the four intersection legs. Note that XL1 and YL1 are the endpoints of the intersection-end of the link (e.g., (0.,0.) for all four links in this case), and that XL2 and YL2 are the upstream end of the link (1000 metres from the origin; e.g., (0., +1000.), (+1000., 0.), (0., -1000.), and (-1000., 0.) for links one through four, respectively). The links are all at-grade (TYP = AG), 15 metres in width (WL = 15.0), and the source emission height is taken as zero (HL = 0.0). All four links have two approach lanes (NLN = 2), one exclusive left turn lane (NLTL = 1), no exclusive right turn lanes (NRTL = 0), and a value of one is inputted on each card for the integer variable, LTFLG, indicating a left turn phase for all four approaches. The approach volumes, vehicle speeds, and fractions of left and right turning vehicles for the individual links are as shown on the Link Description cards (Figure A5); thus for link one: VPHI = 950.0, VSP = 45.0, FLT = 0.25, and FRT = 0.15.

Since there are no additional links to be modelled (NNDL = NDL = 0), the next input cards are the Receptor

```
 EXAMPLE ONE                                 Ø  2  1  2  Ø  Ø  4 8Ø.
  1     Ø.     Ø.     Ø. 1ØØØ.AG15.Ø  Ø.  95Ø. 45.  2  1  Ø  .25  .15  1
  2     Ø.     Ø. 1ØØØ.     Ø.AG15.Ø  Ø. 125Ø. 35.  2  1  Ø  .15  .1Ø  1
  3     Ø.     Ø.     Ø.-1ØØØ.AG15.Ø  Ø.  95Ø. 45.  2  1  Ø  .25  .15  1
  4     Ø.     Ø.-1ØØØ.     Ø.AG15.Ø  Ø. 125Ø. 35.  2  1  Ø  .15  .1Ø  1
   2Ø.   2Ø.     2.
  -2Ø.   2Ø.     2.
 3. 135. 68.41ØØØ.   Ø. 15Ø.  6Ø.
18Ø  2Ø.  35.  25.
```

Figure A5. Input file for example one.

Location cards giving the geometric coordinates of the receptors (one card per receptor) as shown in Figure A5. (These values are: XR = +20., YR = +20., and ZR = 2. for receptor one; and, XR = -20., YR = +20., and ZR = 2. for receptor two). Following these is the Meteorological Conditions card. The wind speed is three metres per second (U = 3.0). Note that wind direction is measured clockwise from the positive y-axis, thus a bearing of 135 degrees is inputted (BRG = 135.). The temperature is 68 degrees Fahrenheit (TAMB = 68.0), and the atmospheric stability is Pasquill type D (CLAS = 4). The mixing height is 1000 metres (MIXH = 1000.), the background concentration is zero (AMB = 0.0), the surface roughness is 150 cm (Z0 = 150.0), and the averaging time is 60 minutes (ATIM = 60.0), as shown on the Meteorological Condition card (Figure A5).

The final card is the Vehicular Scenario card. The region being modelled is low-altitude, non-California (IREJN = 1). Note that only the last two digits of the year being modelled (1980) are inputted (ICY = 80). The percentage of vehicles in the cold and hot start modes are as shown in Figure A4 (PCCN = 25.0, PCHC = 35.0, PCCC = 25.0), and since a value of zero is inputted for VMFLAG on the first card, no VMT mix data are supplied on this card.

Figure A6 gives the output from example one in the extended format. The first section gives the run title and

```
*******************************************  TAMU INTERSECTION MODEL --- TEXIN  *****************************
------------------------------------------------------------------------------------------------------------

TITLE:    EXAMPLE ONE

METEOROLOGICAL CONDITIONS:

WIND SPEED   =   3.Ø M/S              STABILITY CLASS        = 4              SURFACE ROUGHNESS= 15Ø. CM
WIND BEARING= 135. DEG                MIXING HEIGHT          = 1ØØØ. M        AVERAGING TIME   =  6Ø. MIN
TEMPERATURE = 68.Ø F                  AMBIENT CONCENTRATION=  Ø.Ø PPM
```

Figure A6. Output from example one.

MOBILE2 EMISSION FACTORS (GRAMS CO/VEHICLE MILE)

SCENARIO: REGION= 1
YEAR = 80
PCCN = 20.0
PCHC = 35.0
PCCC = 25.0

VEHICLE MIX: LDGV = 0.782
LDGT1= 0.082
LDGT2= 0.047
HDGV = 0.042
LDDV = 0.002
LDDT = 0.000
HDDV = 0.035
MC = 0.008

SPEED	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC	LDGT	ALL MODES
45.0	22.9	22.9	21.6	122.0	0.8	1.1	6.4	14.6	22.4	26.2
35.0	27.9	27.6	26.8	134.8	0.9	1.2	7.4	17.9	27.3	31.4

MOBILE2 IDLE EMISSION RATE (GRAMS CO/MIN)

	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC	LDGT	ALL MODES
	13.6	11.5	9.1	9.9	0.2	0.3	0.9	3.7	10.6	12.5

TRAFFIC FLOW ANALYSIS (MAJOR INTERSECTION - SIGNALIZED)

VOLUME/CAPACITY= 0.86
STOPPED DELAY= 32.3 SEC/VEH
APPROACH DELAY= 43.9 SEC/VEH
TIME IN QUEUE= 40.8 SEC/VEH
FRACTION STOPPING= 0.76

FRACTION OF EXCESS
EMISSIONS DUE TO:
VEHICLES SLOWING= 0.23
VEHICLES STOPPING= 0.44
VEHICLES IDLING= 0.33

Figure A6. (continued).

LINK DESCRIPTION

LINK	XL1	YL1	XL2	YL2	LENGTH	VEH/HR	SPEED	MGM CO/M-SEC
1	0.0	0.0	0.0	1000.0	1000.0	1832.	45.0	8.30
2	0.0	0.0	1000.0	0.0	1000.0	2567.	35.0	13.90
3	0.0	0.0	0.0	-1000.0	1000.0	1832.	45.0	8.30
4	0.0	0.0	-1000.0	0.0	1000.0	2567.	35.0	13.90
5	0.0	0.0	0.0	64.4	64.4	1832.	45.0	82.44
6	0.0	0.0	84.7	0.0	84.7	2567.	35.0	82.44
7	0.0	0.0	0.0	-64.4	64.4	1832.	45.0	82.44
8	0.0	0.0	-84.7	0.0	84.7	2567.	35.0	82.44

LINK POLLUTANT CONTRIBUTION

CONTRIBUTION FROM EACH LINK TO POLLUTANT CONCENTRATION AT RECEPTOR 1:

LINK NUMBER:	1	2	3	4	5	6	7	8
CONTRIBUTION(PPM):	0.0	0.8	0.0	0.0	0.0	4.6	0.0	0.0

CONTRIBUTION FROM EACH LINK TO POLLUTANT CONCENTRATION AT RECEPTOR 2:

LINK NUMBER:	1	2	3	4	5	6	7	8
CONTRIBUTION(PPM):	0.3	0.3	0.2	0.4	2.6	2.0	2.0	2.6

Figure A6. (continued).

------------------------RECEPTOR DESCRIPTION AND MODEL PREDICTIONS------------------------

RECEPTOR	XR	YR	ZR	CO (PPM)*
1	2Ø.Ø	2Ø.Ø	2.Ø	5.4
2	-2Ø.Ø	2Ø.Ø	2.Ø	1Ø.4

*INCLUDES BACKGROUND AMBIENT CONCENTRATION OF Ø.Ø PPM

****

Figure A6. (continued).

a summary of the meteorological conditions. Following this are the MOBILE-2 emission factors (differentiated according to vehicle speed and vehicle type, and the idling emission rates) as well as a summary of the vehicle scenario. The next section presents the intersection traffic flow analysis and gives values for the volume/capacity ratio, stopped delay, approach delay, time in queue, fraction stopping, and the fraction of excess emissions due to vehicles slowing, stopping, and idling.

A description of the links (both physical and psuedo) is presented in the following section. This description includes link endpoints, link length, link volume, vehicle speed, and the link emission factor for each link. The contributions from each link to the pollutant contribution at the individual receptors follow the link descriptions. The model's predicted concentrations at the receptors (including the background concentration) are presented in the final section of the output.

Example Two. The second example is an unsignalized intersection and illustrates the program's ability to model curved roadways (Figure A7 presents the site geometry). A value of one for VMFLAG (user-supplied VMT mix), zero for PRTFLG (abbreviated output), and zero for INTFLG (unsignalized) are inputted on the first card. A value of six is inputted for NNDL as that is the number of additional

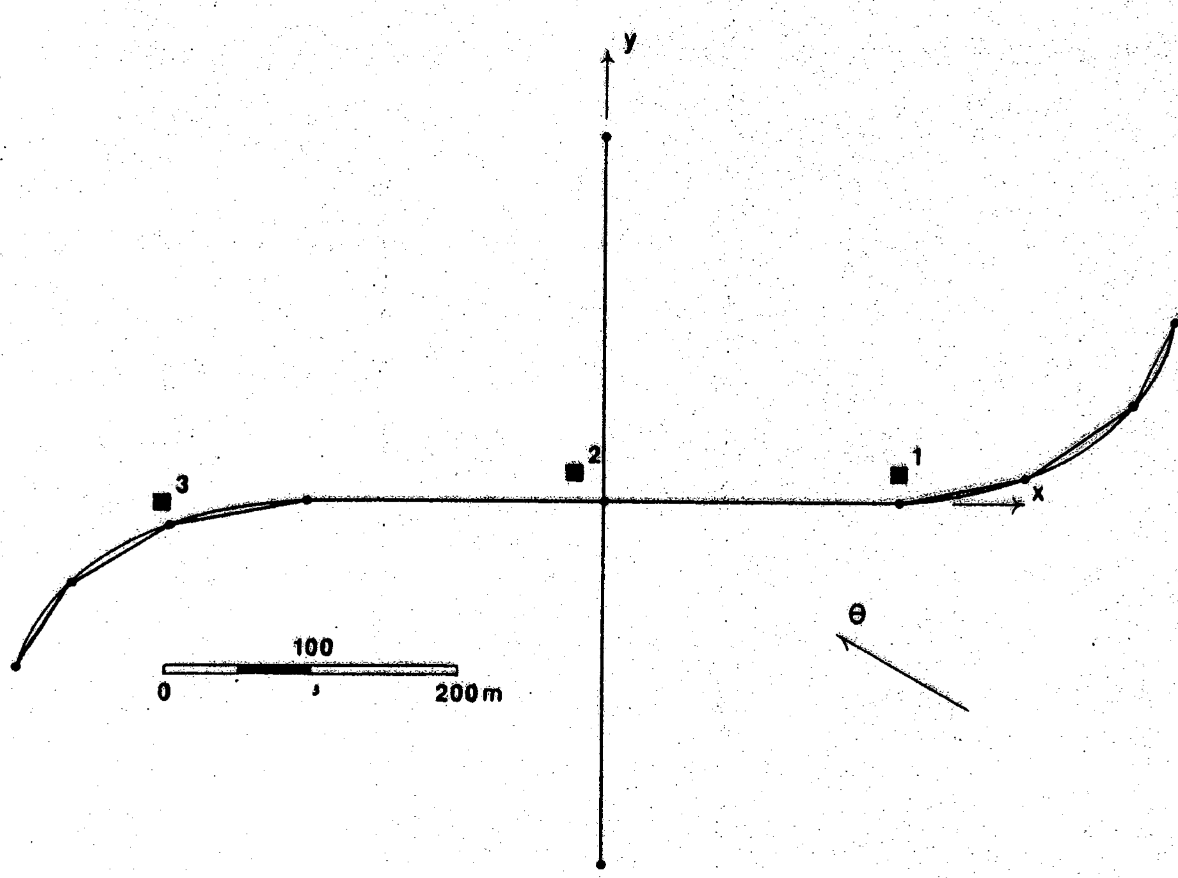

Figure A7. Intersection Geometry for example two.

links required to model the curved portions of roadway. Since the intersection is unsignalized, values for NP and CY need not be inputted. The input cards are shown in Figure A8.

The four Link Description cards for the intersection legs are inputted next. The coordinate system must be chosen such that the major road lies along the y-axis (and thus assigned to links one and three). Traffic on the major roadway is assumed to not incur delay (except for left turning vehicles). Values for LTFLG are not necessary for the major road (links 1 and 3), but are necessary for the minor road (links 2 and 4), and a value of one is inputted for both indicating stop sign controlled approaches. The next six cards are for the additional links required to fit the curves. The first variable on each of these cards is the link association number, LA, and indicates from which of the four intersection links the additional links extend. In this case, three of the links have an LA value of four (and three a value of two) since they are extensions of the minor road. The traffic on these links are assumed to incur no delay (as they are entered as NNDL links), and thus, must be sufficiently distant from the intersection to insure this. The variables VPHI through LTFLG are not needed for NNDL links and are omitted from the Link Description cards.

```
EXAMPLE TWO                                               1  Ø  Ø  3  6  Ø  Ø  Ø.
  1     Ø.     Ø.     Ø.   4ØØ.AG17.5   Ø.   45Ø. 35.  2  1  Ø  .1Ø  .1Ø  Ø
  2     Ø.     Ø.   2ØØ.     Ø.AG14.Ø   Ø.   1ØØ. 35.  2  Ø  Ø  .2Ø  .15  1
  3     Ø.     Ø.     Ø.  -4ØØ.AG17.5   Ø.   35Ø. 35.  2  1  Ø  .1Ø  .1Ø  Ø
  4     Ø.     Ø.  -2ØØ.     Ø.AG14.Ø   Ø.   125. 35.  2  Ø  Ø  .2Ø  .15  1
  2   2ØØ.     Ø.   285.    2Ø.AG14.Ø   Ø.
  2   285.    2Ø.   36Ø.    7Ø.AG14.Ø   Ø.
  2   36Ø.    7Ø.   39Ø.   12Ø.AG14.Ø   Ø.
  4  -2ØØ.     Ø.  -295.   -2Ø.AG14.Ø   Ø.
  4  -295.   -2Ø.  -36Ø.   -6Ø.AG14.Ø   Ø.
  4  -36Ø.   -6Ø.  -4ØØ.  -12Ø.AG14.Ø   Ø.
  2ØØ.    2Ø.     2.
  -2Ø.    2Ø.     2.
 -3ØØ.     Ø.     2.
 2. 12Ø. 75.31ØØØ.    Ø.   5Ø.   6Ø.
175 39.2 44.5 37.8 .52Ø .176 .Ø43 .223 .ØØØ .ØØØ .ØØ7 .Ø31
```

Figure A8. Input file for example two.

Following the Receptor Location and Meteorological Conditions cards is the Vehicular Scenario card. Since a value of one is inputted on the Heading and Flags card, the VMT mix data are supplied on this card as shown (LDGV = 0.520, LDGT1 = 0.176, LDGT2 = 0.043, HDGV = 0.223, LDDV = 0.000, LDDT = 0.000, HDDV = 0.007, MC = 0.031).

Figure A9 shows the output from example two in the abbreviated format. This output format includes a summary of the meteorological conditions and the model's predicted concentrations at the receptor sites.

Example Three. The third example illustrates TEXIN's ability to model several minor unsignalized intersections in conjunction with the major intersection. The intersection geometry is presented in Figure A10 (the major roadways in bold) and the input cards are shown in Figure A11. Three additional links are necessary to model the minor intersections. Traffic on these links will incur delay, and thus, they are inputted as NDL links (NDL = 3).

The Link Description cards for the three additional links follow the cards for the four intersection links. The first variable on all three cards is the link association number, LA, and indicates which leg of the intersection the minor road intersects. For the minor roadway which intersects (and terminates at) the positive x-axis, a value of two (corresponding to link 2) is inputted for the integer

** TAMU INTERSECTION MODEL --- TEXIN ****************************

TITLE: EXAMPLE TWO

METEOROLOGICAL CONDITIONS:

WIND SPEED = 2.0 M/S
WIND BEARING= 120. DEG
TEMPERATURE = 75.0 F

STABILITY CLASS = 3
MIXING HEIGHT = 1000. M
AMBIENT CONCENTRATION= 0.0 PPM

SURFACE ROUGHNESS= 50. CM
AVERAGING TIME = 60. MIN

------------------------------------RECEPTOR DESCRIPTION AND MODEL PREDICTIONS------------------------

RECEPTOR	XR	YR	ZR	CO (PPM)*
1	200.0	20.0	2.0	0.2
2	-20.0	20.0	2.0	4.7
3	-300.0	0.0	2.0	0.3

*INCLUDES BACKGROUND AMBIENT CONCENTRATION OF 0.0 PPM

****

Figure A9. Output from example two.

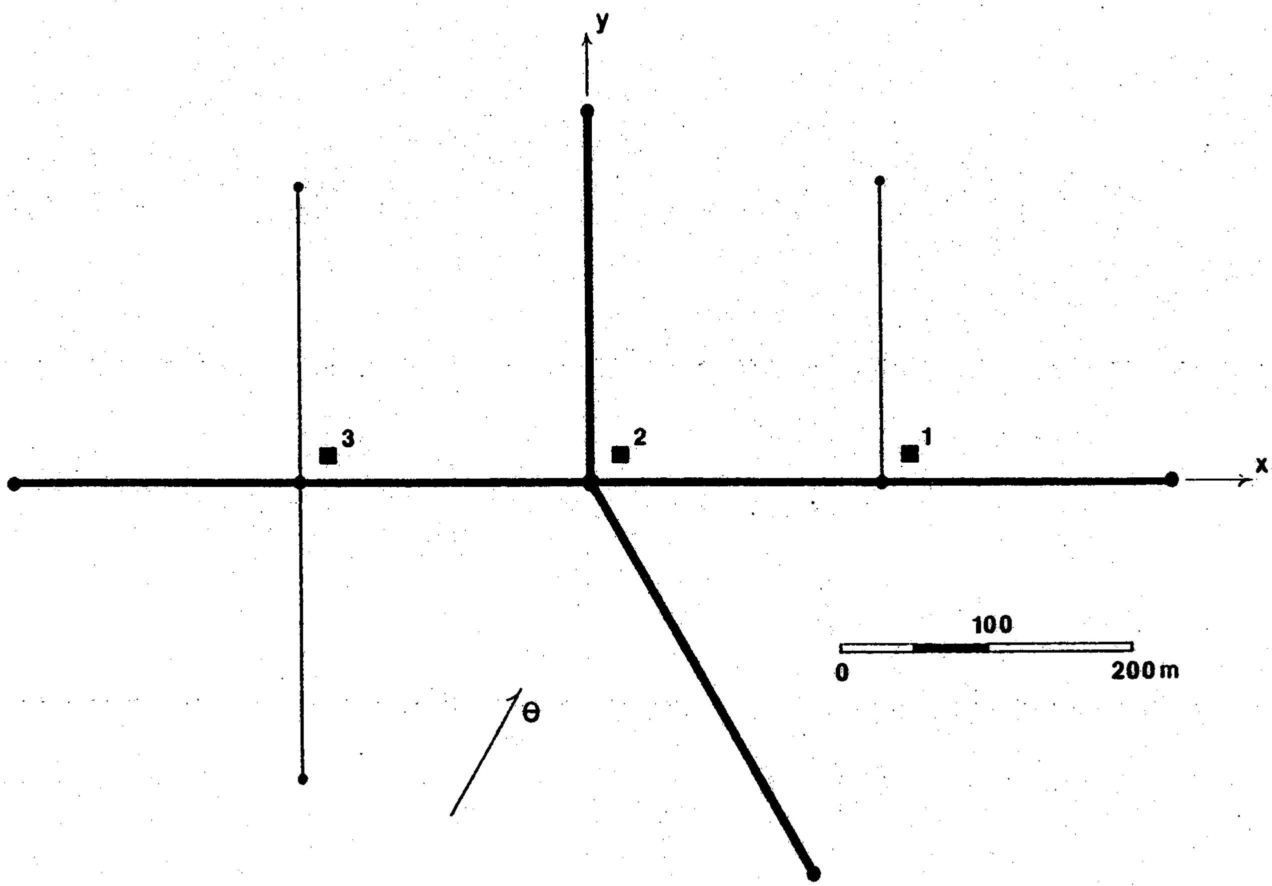

Figure A10. Intersection Geometry for example three.

```
EXAMPLE THREE                                     Ø  1  1  3  Ø  3  41ØØ.
 1     Ø.      Ø.      Ø. 1ØØØ.AG15.Ø  Ø. 125Ø. 45.  2  1  Ø  .2Ø  .Ø5  1
 2     Ø.      Ø. 1ØØØ.      Ø.AG17.Ø  Ø.  6ØØ. 45.  2  1  1  .15  .2Ø  1
 3     Ø.      Ø.  5ØØ. -866.AG15.Ø  Ø. 1Ø5Ø. 45.  2  1  Ø  .Ø5  .15  1
 4     Ø.      Ø.-1ØØØ.      Ø.AG17.Ø  Ø.  4ØØ. 45.  2  1  Ø  .3Ø  .1Ø  1
 4  -2ØØ.      Ø.  -2ØØ. 1ØØØ.AG14.Ø  Ø.    7Ø. 35.  2  Ø  Ø  .1Ø  .4Ø  1
 4  -2ØØ.      Ø.  -2ØØ.-1ØØØ.AG14.Ø  Ø.    8Ø. 35.  2  Ø  Ø  .Ø5  .45  1
 2   2ØØ.      Ø.   2ØØ. 1ØØØ.AG 8.Ø  Ø.    65. 35.  1  Ø  Ø  .35  .65  Ø
 22Ø.    2Ø.      2.
  2Ø.    2Ø.      2.
-18Ø.    2Ø.      2.
 2.521Ø. 68.31ØØØ.    Ø. 15Ø.   6Ø.
281 21.5 3Ø.6 29.4
```

Figure A11. Input file for example three.

variable, LA. For the minor roadway which intersects (and crosses) the negative x-axis, two links are necessary for the modelling and both have values of four inputted for LA. Note that like the four intersection links, the values, XL1 and YL1, for the three additional links correspond to the intersection-end of the link. The minor roadway intersecting the positive x-axis is controlled by a yield sign, and thus a value of zero is inputted for the integer variable, LTFLG. The other minor roadway is controlled by a stop sign, thus a value of one is inputted. Note that all the roadways actually extend further than shown in Figure A10.

Figure A12 illustrates the output from example three in the basic output format. For this example, there are two traffic flow analysis sections. The first is for the major intersection, and presents values for volume/capacity ratio, stopped delay, approach delay, time in queue, fraction stopping, and fraction of excess emissions due to vehicles slowing, stopping, and idling. The second is for the minor intersections and the same values are given, with the exception that the reserve capacity of the unsignalized intersections is given rather than the volume/capacity ratio. Note that for a stop sign controlled intersection the fraction of vehicles stopping is always one, while the same for a yield sign controlled intersection may be less

```
****************************************** TAMU INTERSECTION MODEL --- TEXIN ****************************
-----------------------------------------------------------------------------------------------------------

TITLE:    EXAMPLE THREE

METEOROLOGICAL CONDITIONS:

WIND SPEED  =  2.5 M/S          STABILITY CLASS      = 3             SURFACE ROUGHNESS= 15Ø. CM
WIND BEARING= 21Ø. DEG          MIXING HEIGHT        = 1ØØØ. M       AVERAGING TIME   =  6Ø. MIN
TEMPERATURE = 68.Ø F            AMBIENT CONCENTRATION=  Ø.Ø PPM

--------------------------------TRAFFIC FLOW ANALYSIS (MAJOR INTERSECTION - SIGNALIZED)-------------------

          VOLUME/CAPACITY= Ø.7Ø                          FRACTION OF EXCESS
          STOPPED DELAY= 21.9 SEC/VEH                    EMISSIONS DUE TO:
          APPROACH DELAY= 3Ø.1 SEC/VEH                   VEHICLES SLOWING= Ø.27
          TIME IN QUEUE= 27.4 SEC/VEH                    VEHICLES STOPPING= Ø.57
          FRACTION STOPPING= Ø.67                        VEHICLES IDLING= Ø.16
```

Figure A12. Output from example three.

----------------TRAFFIC FLOW ANALYSIS (MINOR INTERSECTION(S) - UNSIGNALIZED)----

FOR LINK 9:
RESERVE CAPACITY= 93. VEH
STOPPED DELAY= 34.4 SEC/VEH
APPROACH DELAY= 46.6 SEC/VEH
TIME IN QUEUE= 43.5 SEC/VEH
FRACTION STOPPING= 1.00

FRACTION OF EXCESS
EMISSIONS DUE TO:
VEHICLES SLOWING= 0.13
VEHICLES STOPPING= 0.60
VEHICLES IDLING= 0.27

FOR LINK 10:
RESERVE CAPACITY= 96. VEH
STOPPED DELAY= 34.2 SEC/VEH
APPROACH DELAY= 46.4 SEC/VEH
TIME IN QUEUE= 43.3 SEC/VEH
FRACTION STOPPING= 1.00

FRACTION OF EXCESS
EMISSIONS DUE TO:
VEHICLES SLOWING= 0.13
VEHICLES STOPPING= 0.60
VEHICLES IDLING= 0.27

FOR LINK 11:
RESERVE CAPACITY= 50. VEH
STOPPED DELAY= 37.0 SEC/VEH
APPROACH DELAY= 50.0 SEC/VEH
TIME IN QUEUE= 46.8 SEC/VEH
FRACTION STOPPING= 0.79

FRACTION OF EXCESS
EMISSIONS DUE TO:
VEHICLES SLOWING= 0.20
VEHICLES STOPPING= 0.49
VEHICLES IDLING= 0.30

Figure A12. (continued).

----------------------------------LINK DESCRIPTION--

LINK	XL1	YL1	XL2	YL2	LENGTH	VEH/HR	SPEED	MGM CO/M-SEC
1	0.0	0.0	0.0	1000.0	1000.0	2330.	45.0	7.96
2	0.0	0.0	1000.0	0.0	1000.0	1247.	45.0	4.26
3	0.0	0.0	500.0	-866.0	1000.0	2117.	45.0	7.24
4	0.0	0.0	-1000.0	0.0	1000.0	905.	45.0	3.09
5	0.0	0.0	0.0	93.4	93.4	2330.	45.0	49.45
6	0.0	0.0	44.8	0.0	44.8	1247.	45.0	49.45
7	0.0	0.0	39.2	-67.9	78.4	2117.	45.0	49.45
8	0.0	0.0	-29.9	0.0	29.9	905.	45.0	49.45
9	-200.0	0.0	-200.0	1000.0	1000.0	140.	35.0	0.57
10	-200.0	0.0	-200.0	-1000.0	1000.0	170.	35.0	0.69
11	200.0	0.0	200.0	1000.0	1000.0	130.	35.0	0.53
12	-200.0	0.0	-200.0	8.0	8.0	140.	35.0	30.01
13	-200.0	0.0	-200.0	-8.0	8.0	170.	35.0	36.39
14	200.0	0.0	200.0	10.4	10.4	130.	35.0	20.62

Figure A12. (continued).

--------------------------RECEPTOR DESCRIPTION AND MODEL PREDICTIONS--------------------------

RECEPTOR	XR	YR	ZR	CO (PPM)*
1	220.0	20.0	2.0	0.5
2	20.0	20.0	2.0	6.0
3	-180.0	20.0	2.0	0.8

*INCLUDES BACKGROUND AMBIENT CONCENTRATION OF 0.0 PPM

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Figure A12. (continued).

than one. The link descriptions and model predictions follow these sections.

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APPENDIX B

PLAN VIEW OF THE TEXAS A&M HOUSTON SITE