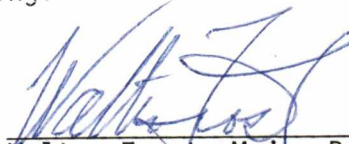


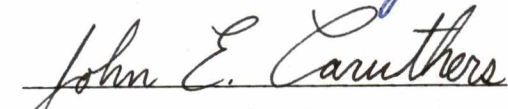
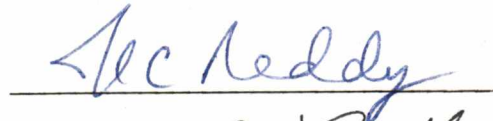
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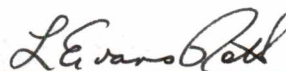


Walter Frost, Major Professor

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TRANSIENT ANALYSIS OF THE DISPERSION OF
VEHICLE POLLUTION WITHIN A HIGHWAY TUNNEL

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Kao-Huah Huang

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The last but far from the least, the author would like to thank Mrs. Pam Parsley for her efforts to translate the manuscript into presentable form.

ABSTRACT

A transient model is used to investigate the history of induced airflow as well as the dispersion of vehicle pollution within a highway tunnel. Simulation of traffic conditions including traffic start from undisturbed conditions, complete stall, slowdown, and/or normal speed resumption, pollutant concentration build-up, and propagation through the tunnel is computed, and parametric studies are reported.

The model assumes one-dimensional, incompressible airflow in the tunnel. The governing equation of transient induced airflow is derived from momentum balance and of pollution concentration distribution from a mass balance on the pollutant. A computer program is developed for calculating the transient longitudinal air velocities and pollution concentrations. The program, TN. DOT/UTSI TRANS, provides numerical solution for a wide range of traffic conditions and tunnel configurations.

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NOMENCLATURE

A_c	Acceleration rate of vehicle
A_t	Tunnel cross-sectional area
A_v	Average vehicle cross-sectional area
A_{vi}	i-th vehicle cross-sectional area
C_d	Average drag coefficient of vehicles
C_{di}	i-th vehicle drag coefficient
C_f	Tunnel coefficient of friction
CY	Calendar year
D	Hydraulic diameter of tunnel
D^*	Dimensionless hydraulic diameter of tunnel
D_c	Drag number defined as $D_c = \frac{C_d A_v L}{A_t S}$
D_k	Deceleration rate of K-th vehicle
D_s	Deceleration rate of the first stall vehicle
D_T	Traffic density
F_c	Friction number defined as $F_c = \frac{C_f L}{D}$
F_D	Drag force on the air by the vehicle (piston effect)
F_t	Friction force on the air by the tunnel wall
HDD	Heavy duty diesel
HDG	Heavy duty gas
K_s	Number of the first stall vehicle
L	Tunnel length
LDG	Light duty gas
LDV	Light duty vehicles
M	Mass

N	Number of vehicles
P_a	Atmospheric pressure outside of tunnel
Pe	Peclet number
P_e	Static pressure at exit plane of tunnel
P_i	Static pressure at inlet plane of tunnel
P_n	Initial position of the n-th vehicle from the entrance at time, $t = 0$
q_n	Emission rate of n-th vehicle
R	Rate of pollution generation due to chemical reaction
S	Spacing of uniform traffic stream
S_f	Final (minimum) spacing after traffic stall
S_v	Rate of pollution generation by vehicles
t	Time
$\bar{t}$	Nondimensional time scale $\bar{t} = V_o t/L$
t^*	Nondimensional time scale $t^* = V_{ref} t/L$
t_a	Traffic restart time
t_R	Reaction time between each vehicle when traffic stall
t_f	Time when the first stall vehicle reaches to final speed
t_k	Time when the K-th vehicle stalled to reach the final speed
t_s	Traffic stall time
t_w	Waiting time between each vehicle after traffic restart
U	Uniform traffic stream velocity
U^*	Nondimensional vehicle velocity
U_f	Final (minimum) speed of vehicle after stall
U_i	Velocity of i-th vehicle
U_n	Velocity of n-th vehicle
V	Induce airflow velocity

V^*	Nondimensional induced airflow velocity
V_0	Steady state induced airflow velocity
V_{ref}	Reference velocity
x	Distance from entrance of tunnel
$\bar{x}$	Nondimensional x
σ	Blockage ratio (BR) = A_v/A_t
$\gamma(x,t)$	Pollutant concentration at position x and time t
$\overline{\gamma(x,t)}^j$	Pollutant concentration at (x,t) after average j time
γ_i	Initial pollutant concentration
γ_n	Pollutant concentration contributed by n -th vehicle

CHAPTER I

INTRODUCTION

Most literature, to date, relating to tunnel ventilation research emphasizes steady state traffic flow. There is little information available for designers to evaluate how fast pollution builds up as traffic flow becomes congested, and how long it takes to relieve high concentrations once traffic again flows freely. This study analyzes pollution concentration transients in naturally ventilated highway tunnels.

Not only are highway tunnels used for bypassing natural obstacles such as rivers, harbors, and mountains, but they are being used increasingly in the urban environment. Reasons for this are both economical and environmental. A number of large highways passing through metropolitan areas reduce the utility of surface area, and also cause pollution in downtown regions. A set of interconnecting tunnels with proper ventilation of exhaust gases will alleviate the problem. Ventilation, however, requires special attention during the planning and design phases. The designer must consider sizing of ventilation shafts and power required for mechanical ventilation. One area important to design of ventilation systems where design criteria is not available is the buildup and decay of pollutants during traffic stall and restart.

In this report, the transient flow of pollutants in a tunnel is analyzed. The mathematical model was initially conceived by Caruthers [1]. The induced airflows in the tunnel interior of the induced air-

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

flows in the tunnel interior is analyzed first, see Chapter II. The method of evaluating velocity of the induced airflow is based on a momentum balance on the air. The assumption of one-dimensional, incompressible flow is made and an equation for the transient induced flow is derived. Both analytical and numerical solutions to the equation are presented. The numerical solution is applied to handle the more complicated traffic flow patterns. Several types of transient traffic flow patterns are analyzed such as traffic suddenly beginning to flow through a tunnel of initially undisturbed air, traffic stalling from steady traffic flow conditions, traffic slowing down during congested traffic situations, etc.

The equation governs the induced motion of air in a tunnel due to one or more cars passing through. Several factors affecting the induced air velocity such as the tunnel friction factor, the road vehicle drag coefficient, vehicle speed, spacing and blockage ratio, etc., are included in the discussion.

The concentration of pollutants throughout the tunnel is discussed in Chapter III. The governing equations are derived based on a mass balance of the pollutant in the tunnel and the induced airflow equations developed in Chapter II. It is assumed that the pollutant transport is predominately due to convection rather than diffusion. This is definitely true if only molecular diffusion occurs; however, the magnitude of turbulent diffusion which is not fully understood at this time can be significant. Thus, the diffusion term is dropped from the time dependent pollutant, mass transport equation. Later, however, approximate techniques to account for turbulent diffusion are incorporated which are functions of time as well as functions of longitudinal

position in the tunnel.

Vehicle exhaust rate depends on vehicle type, speed of the vehicle (i.e., age, maintenance, etc.) and other such factors. Estimates of the vehicle exhaust rates have been determined by Abdulraham and Frost [2]. These were calculated using the computer code BIGAP-42, provided by the Tennessee State Department of Transportation. These gases - carbon monoxide, oxides of nitrogen, and hydrocarbons - are analyzed separately for each set of traffic conditions discussed in this report.

A computer program called TN. DOT/UTSI TRANS was developed to obtain numerical solutions for the distribution of pollutant concentration along the tunnel with respect to time. The program is coded to include all of the following possible traffic flow patterns:

1. The case of a traffic stream suddenly beginning to pass through the undisturbed air in a given tunnel (i.e., start-up problem).
2. The case of a steady state traffic stream which slows or stalls to any prescribed final speed and spacing.
3. The case of a traffic stream restarting with any prescribed acceleration rate after stall or slow down.

In Chapter IV, computed pollutant distributions are presented for emission rates of 1975 and 1980 vehicles, respectively.

Application of the TN. DOT/UTSI TRANS computer program allows diagnoses of potentially hazardous pollution concentration build-up and the rate of decay which may occur during a traffic stall and re-start in a naturally ventilated tunnel.

CHAPTER II

INDUCED VELOCITY

Airflow is induced in a highway tunnel by the vehicles passing through it. Thus, induced airflow is a major factor in diluting pollution concentration and its transient behavior must be jointly analyzed with the convection of pollutants within the tunnel. Many factors influence the magnitude of this airflow making it difficult to predict precisely. The induced airflow is dependent on vehicle speed and spacing, the dimensions and shapes of the vehicles, the tunnel dimension, the roughness of vehicle surface and of the tunnel walls. It is also affected by mechanical ventilation if any. All these factors are discussed in this chapter.

I. GOVERNING EQUATION OF INDUCED VELOCITY

To analyze the aerodynamics of highway tunnels, the basic assumption that the air in the tunnel is an incompressible, constant density, fluid in one-dimensional flow is made. The static and dynamic properties of air in the highway tunnel are assumed to be near the prevailing atmospheric conditions outside the tunnel. According to the nature of the tunnel geometry and traffic flow, the turbulent cross-sectional mixing is sufficiently strong that the airflow properties can be assumed uniform. Thus, airflow in highway tunnels is essentially one-dimensional, axial flow. Based on the above assumptions, the transient governing equation of induced airflow is derived as follows.

Consider a force balance on the section of tunnel illustrated in Figure 2-1. According to Newton's law:

$$\Sigma F \text{ (external force)} = m \frac{dV}{dt}$$

The summation of forces, ΣF , include piston force, friction force and pressure loss forces. m is the mass of air in the tunnel. With the assumption of constant density, ρ , constant cross-sectional area, A_t , and uniform velocity, V , over the cross-section, the equation for a tunnel with one-directional traffic reduces to

$$F_D - F_t + (P_i - P_e)A_t = \rho A_t L \frac{dV}{dt} \quad (2-1)$$

where F_D is the drag force on the air by the vehicle, (often called the "piston effect") F_t is the friction force on the air by the tunnel walls, P_i and P_e are the pressure on the inlet and exit planes of the tunnel, respectively. The "piston effect", F_D , is the sum of the aerodynamic drag force on the air in the axial direction exerted by all vehicles in the tunnel. Hence, F_D is found by determining the axial aerodynamic drag force on all vehicles over the tunnel length.

$$F_D = \sum_{i=1}^n \frac{\rho}{2} C_{di} (U_i - V(t))^2 A_{vi} \quad (2-2)$$

where C_{di} , and U_i , and A_{vi} are the i -th vehicle drag coefficient, speed, and cross-section area, respectively. The "piston effect" forces act in the positive tunnel direction, thus tending to increase longitudinal flow velocity. According to the principle of dynamic equilibrium, the "piston effect" force must be balanced at any instant by forces oriented in the opposite direction. The most important

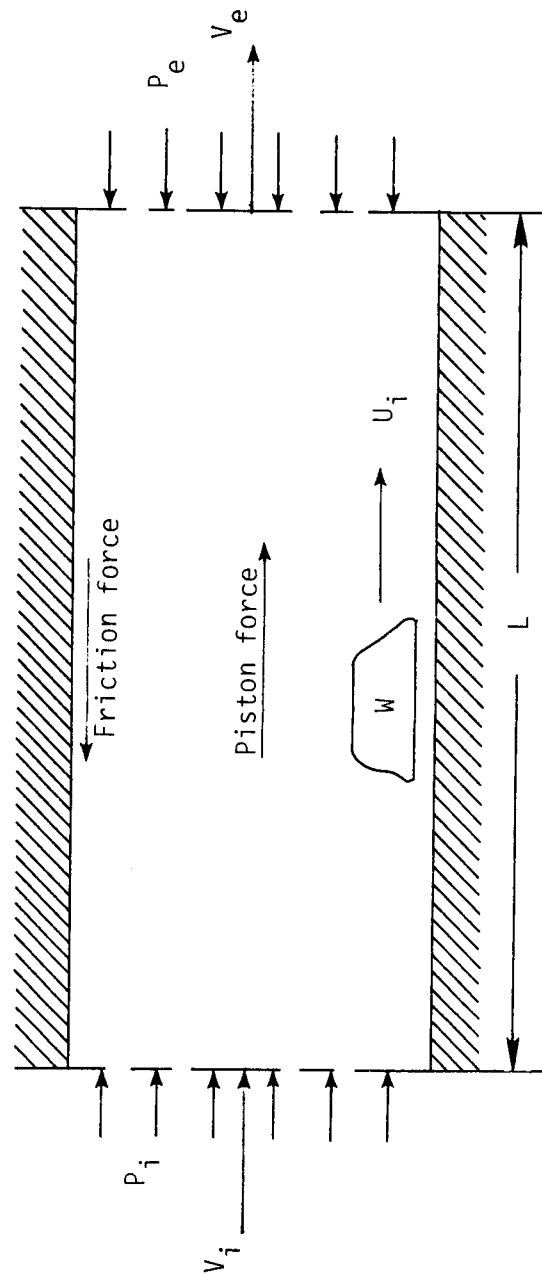


Figure 2-1. Momentum balance over a whole tunnel.

opposing force is the friction force imposed on the air by the tunnel walls, F_t .

$$F_t = \frac{\rho}{2} C_f V^2 \frac{L}{D} A_t \quad (2-3)$$

where C_f is the tunnel wall friction coefficient, D is the tunnel hydraulic diameter defined as $D = 4A_t/(\text{wetted perimeter})$, A_t is the tunnel cross-sectional area. Applying Bernoulli's equation from section just outside and one just inside the entrance, the pressure drop across the tunnel entrance is given by:

$$P_a - P_i = \frac{1}{2} \rho V^2 \quad (2-4)$$

where P_a is the external atmospheric pressure. At the tunnel exit, it is assumed that $P_e = P_a$. Substitute Equations 2-2, 2-3, and 2-4 into Equation 2-1 and divide by $\rho V A_t$ gives:

$$\frac{dV}{dt} = -\frac{C_f}{2D} V^2 + \sum_{i=1}^n \frac{A_{vi} C_{di}}{2A_t L} (U_i - V)^2 - \frac{V^2}{2L} \quad (2-5)$$

This is the transient equation governing the induced air velocity in the tunnel. To solve this equation, both an analytical and a numerical technique are employed as described in the following sections.

II. ANALYTICAL SOLUTION

The right-hand side of Equation 2-5 can be rearranged as a second order polynomial in V , i.e.,

$$\frac{dV}{dt} = \left[-\frac{C_f}{2D} - \frac{1}{2L} + \sum_{i=1}^n \frac{C_{di} A_{vi}}{2A_t L} \right] V^2 - \sum_{i=1}^n \frac{C_{di} A_{vi} U_i}{A_t L} V + \sum_{i=1}^n \frac{C_{di} A_{vi}}{2A_t L} U_i^2 \quad (2-6)$$

Equation 2-6 is well known as Riccati's equation [3]. If the traffic flow is uniform, the number of vehicles in the tunnel (S = spacing) is constant. Also, if all vehicles are assumed identical, then Equation 2-6 reduces to:

$$\frac{dV}{dt} = \left(-\frac{C_f}{2D} - \frac{1}{2L} + \frac{C_d A_v}{2A_t S} \right) V^2 - \frac{C_d A_v U}{A_t S} V + \frac{C_d A_v}{2A_t S} U^2 \quad (2-7)$$

To consolidate the large number of parameters influencing the induced velocity, two nondimensional parameters are constructed. This simplifies both the execution and interpretation of the parametric study. The tunnel length, L , is defined as a characteristic axial dimension, and an arbitrary reference velocity, V_{ref} , is introduced to normalize the velocity term. Thus, the time scale can be expressed as L/V_{ref} . The resulting dimensionless variables are then defined as:

$$V^* = \frac{V}{V_{ref}}, \quad D^* = \frac{D}{L}, \quad t^* = \frac{t}{L/V_{ref}}, \quad U^* = \frac{U}{V_{ref}} \quad (2-8)$$

Substituting the above dimensionless variable into Equation 2-7 gives:

$$\frac{dV^*}{dt^*} = \left(-\frac{C_f L}{2D} - \frac{1}{2} + \frac{C_d A_v L}{2A_t S} \right) V^{*2} - \frac{C_d A_v L U^*}{A_t S} V^* + \frac{C_d A_v L}{2A_t S} U^{*2} \quad (2-9)$$

Introducing two dimensionless numbers:

$$\text{Friction number, } F_c = \frac{C_f L}{D}, \text{ and Drag number, } D_c = \frac{C_d A_v L}{A_t S} \quad (2-10)$$

Equation 2-9 becomes:

$$\frac{dV^*}{dt^*} = \frac{1}{2}(-F_c - 1 + D_c)V^{*2} - D_c U^* V^* + \frac{1}{2} D_c U^{*2} \quad (2-11)$$

This demonstrates that the normalized induced airflow velocity is

$$V/V_{\text{ref}} = f(t^*, F_c, D_c) \quad (2-12)$$

for any given normalized traffic speed, $U^* = U/V_{\text{ref}}$. Let

$$A = \frac{1}{2}(-F_c - 1 + D_c), \quad B = -D_c U^*, \quad C = \frac{1}{2} D_c U^{*2}$$

then Equation 2-11 becomes:

$$\frac{dV^*}{dt} = AV^{*2} + BV^* + C \quad (2-13)$$

This is the Riccati equation with constant coefficients. There are three cases considered in analyzing the transient induced flow velocity with the analytical model. They are:

1. Induced airflow velocity buildup from an impulsive change in traffic speed.
2. Induced airflow velocity decay from steady state due to an impulsive traffic stall (cars remaining in tunnel).
3. Induced airflow velocity decay in tunnel after all cars have exited.

Case 1: In case 1, U is constant. Choosing V_{ref} equal to U , gives $U^* = 1$. Moreover, if the vehicle drag forces are spread out uniformly along the tunnel axis rather than being applied at the discrete vehicle locations, and if the vehicle remains constant after the impulsive change; the Equation 2-13 can be written as:

$$\int \frac{dV^*}{AV^{*2} + BV^* + C} = \int dt^* \quad (2-14)$$

Separating the integrant by partial fraction and carrying out the integration gives for Equation 2-14:

$$\int \left(\frac{1}{V^* - y_1} - \frac{1}{V^* - y_2} \right) dV^* = \sqrt{B^2 - 4AC} t^* + \text{constant} \quad (2-15)$$

where

$$y_{1,2} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad (2-16)$$

and the subscripts 1 and 2 denote the + and - of the radical, respectively. Integrating Equation 2-15 and determining the constant from the initial condition $V^* = 0$ at $t^* = 0$ gives:

$$V^*(t) = \frac{y_1 y_2 [1 - \exp[A(y_2 - y_1)t^*]]}{y_2 - y_1 \exp[A(y_2 - y_1)t^*]} \quad (2-17)$$

Since $A = \frac{1}{2}(-F_c - 1 + D_c)$, $B = -D_c$ and $C = \frac{1}{2} D_c$, Equation 2-16 becomes:

$$y_{1,2} = \frac{1}{1 \pm \sqrt{(F_c + 1)/D_c}} \quad (2-18)$$

Induced velocity computed from Equation 2-17, i.e., case 1, are shown in Figures 2-2 and 2-3. The range of parameters studied bracket values typical of those used in practical applications.

Figure 2-2 shows the effect of varying friction number from 0.25 to 3.0 with the drag number, D_c , constant and equal to 2. The non-dimensional induced velocity decreases as the friction number increases. In Figure 2-3 the friction number is held constant, and the drag number is varied from 0.25 to 2.0. The induced flow velocity increases as the drag number increases. This is due to the fact that

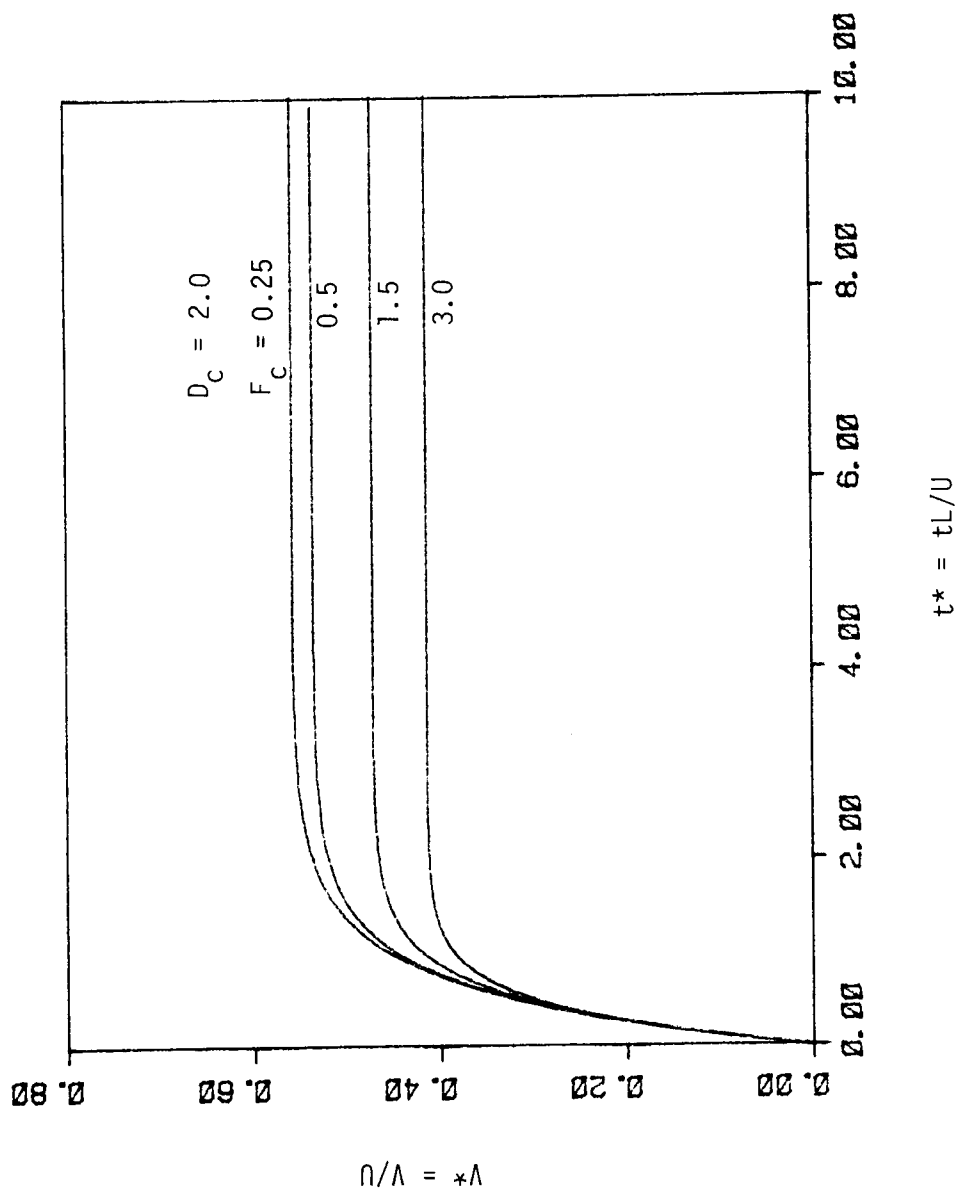


Figure 2-2. Analytic solution of transient induced air velocity for the case of an impulsive start through a tunnel with initially undisturbed air and constant drag number.

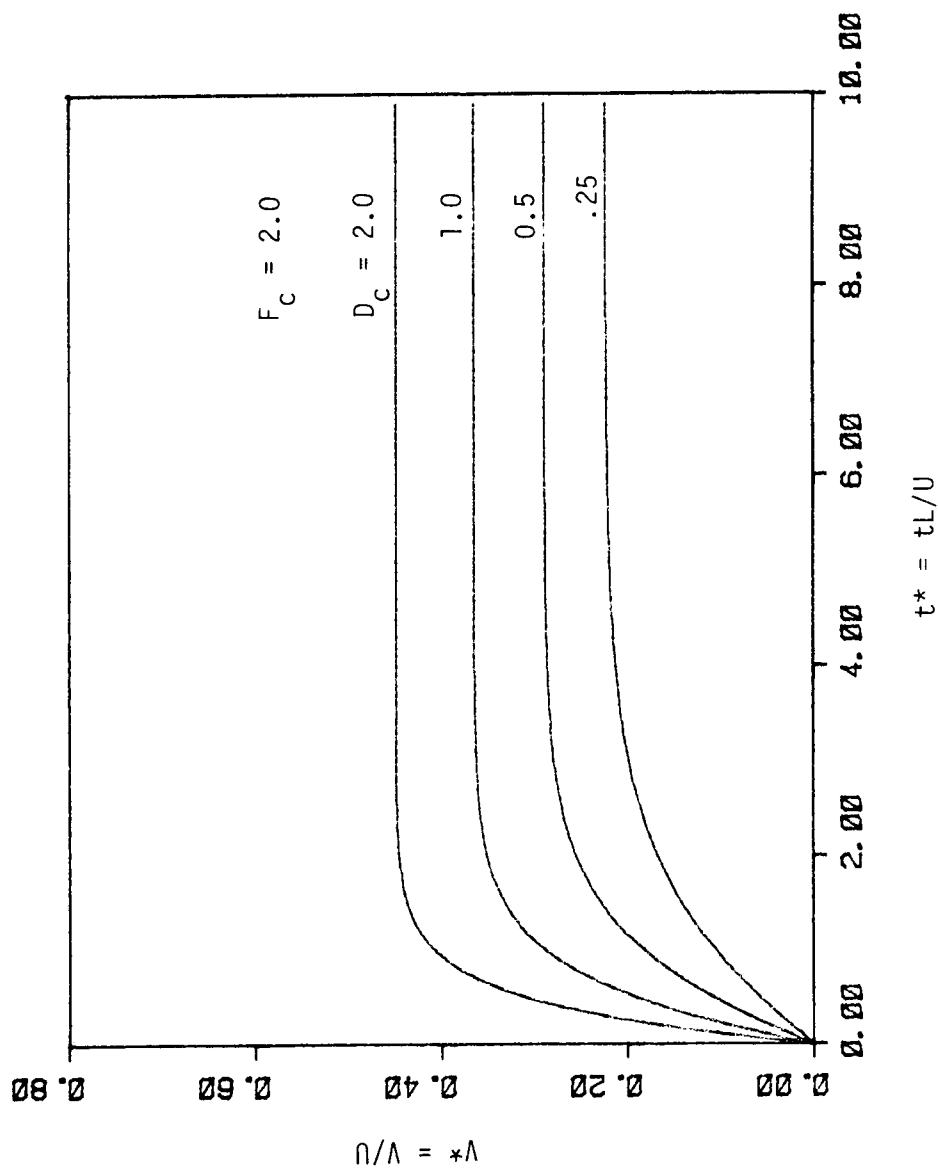


Figure 2-3. Analytic solution of transient induced air velocity for the case of an impulsive start through a tunnel with initially undisturbed air and constant friction number.

the drag number represents an increase in the piston effect. The variation of induced flow velocity due to changing drag numbers is more sensitive than changing the friction number, especially during the transient conditions. For non-zero U , Equation 2-17 approaches a limit with increasing time given by:

$$\frac{V}{U} = \frac{1}{1 + \sqrt{(F_C + 1)/D_C}} \quad (2-19)$$

Case 2: For case 2, the traffic flow is impulsively stopped at $t = 0$. Thus $U = 0$, $U^* = 0$. Also B and C of Equation 2-13 are equal to zero because $B = -D_C U^*$, $C = \frac{1}{2} D_C U^{*2}$. Then Equation 2-13 can be simply integrated to yield:

$$V^* = \frac{1}{1 + \frac{1}{2}(F_C + 1 + D_C)t^*} \quad (2-20)$$

Solutions of Equation 2-1 are shown in Figures 2-4 and 2-5. Figure 2-4 shows that induced velocity decreases faster for higher friction numbers. In case 2, all vehicles are impulsively stopped, and thus the piston effect immediately reverses direction. The induced velocity therefore decreases more rapidly than for case 3 to be described next.

Case 3: For case 3, the decay in induced velocity after all vehicles have left the tunnel is analyzed. In this case, D_C is equal to zero and Equation 2-19 simplifies to:

$$V = \frac{1}{1 + \frac{1}{2}(F_C + 1)t^*} \quad (2-21)$$

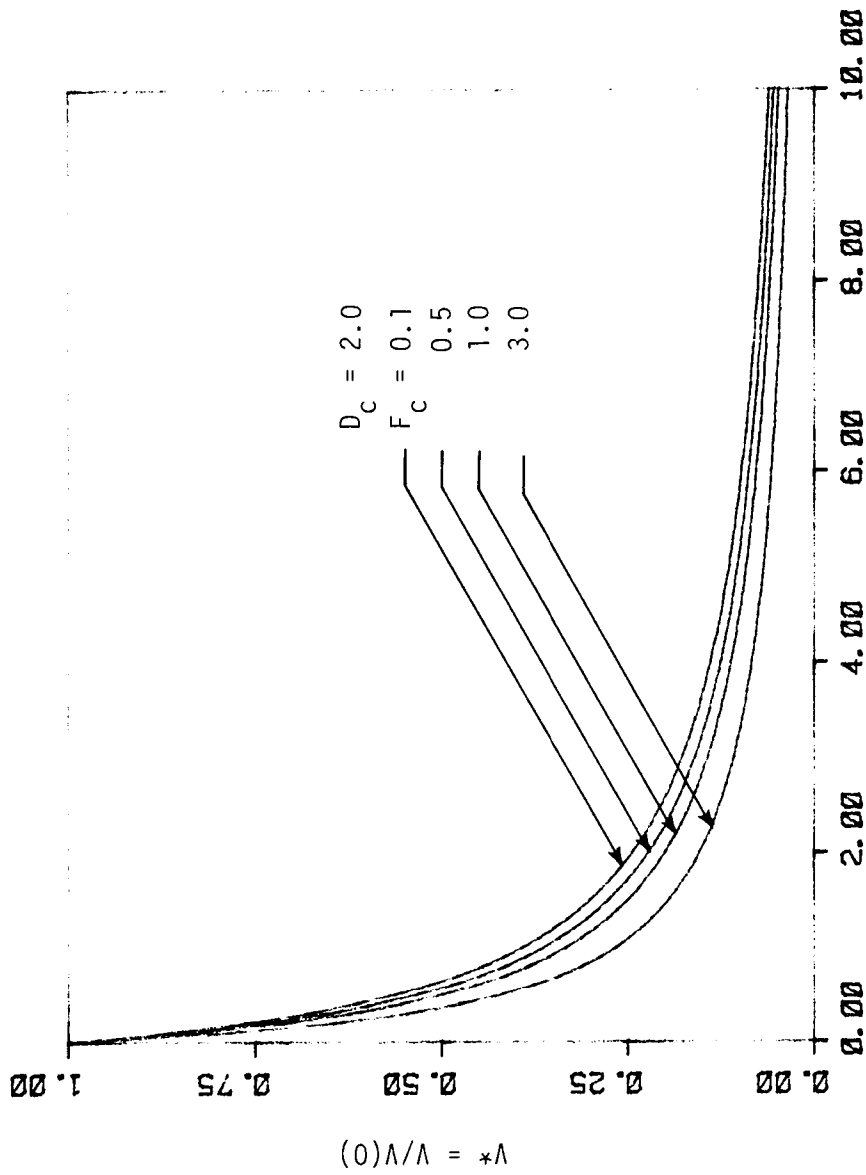


Figure 2-4. Analytic solution of induced velocity for impulsive traffic stall with respect to different friction number (case 2--cars remain in tunnel).

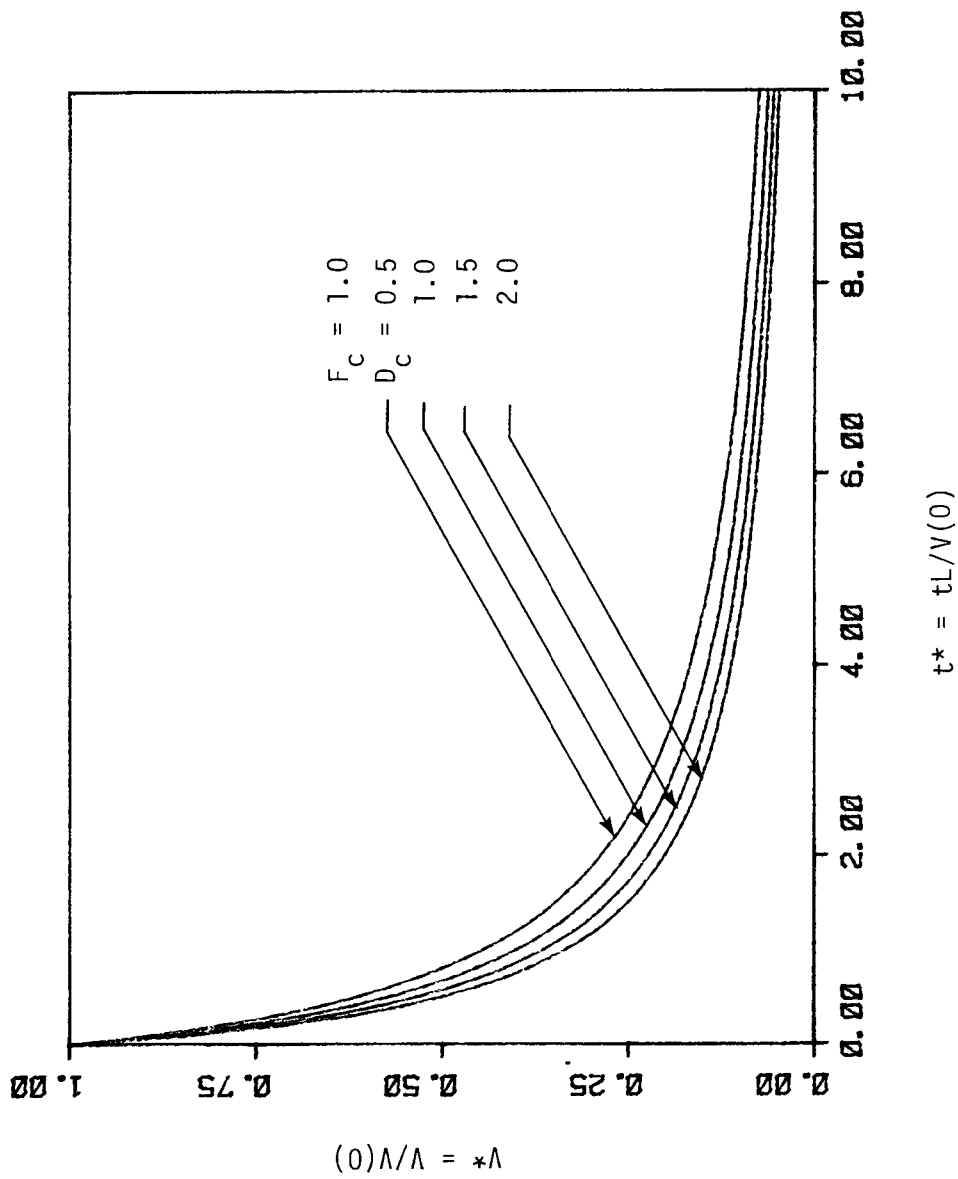


Figure 2-5. Analytic solution of induced velocity for impulsive traffic stall with respect to different drag number (case 2--cars remain in tunnel).

Solutions of Equation 2-21 are shown in Figure 2-6 for different friction numbers. As expected, the decay rate is considerably slower than for case 2 where the cars remain stalled within the tunnel.

III. NUMERICAL SOLUTION

Although the transient induced flow velocity equation (Equation 2-6) can be solved analytically for special cases, these cases do not simulate useful traffic patterns. Numerical methods are more flexible, and can simulate more complicated traffic patterns. Therefore, a numerical technique for solving the induced flow equations is developed in the following section.

Again directing attention to Equation 2-5, the right hand side of Equation 2-5, can be expressed as a function of V , i.e.,

$$\frac{dV}{dt} = f(V)$$

This relationship can be integrated numerically. The induced velocity at the $j + 1$ time step is calculated from the previous step with the velocity V^j , i.e.,

$$V^{j+1} = V^j + f(V^j)\Delta t \quad (2-22)$$

The initial condition used is $V^1 = 0$. The i -th vehicle, U_i , is a function of time and must be specified for each vehicle prior to carrying out the integration. In other words, the traffic patterns are specified. Three transient traffic patterns are studied:

1. A uniform traffic flow which suddenly ($t = 0$) enters a tunnel with initially undisturbed air.

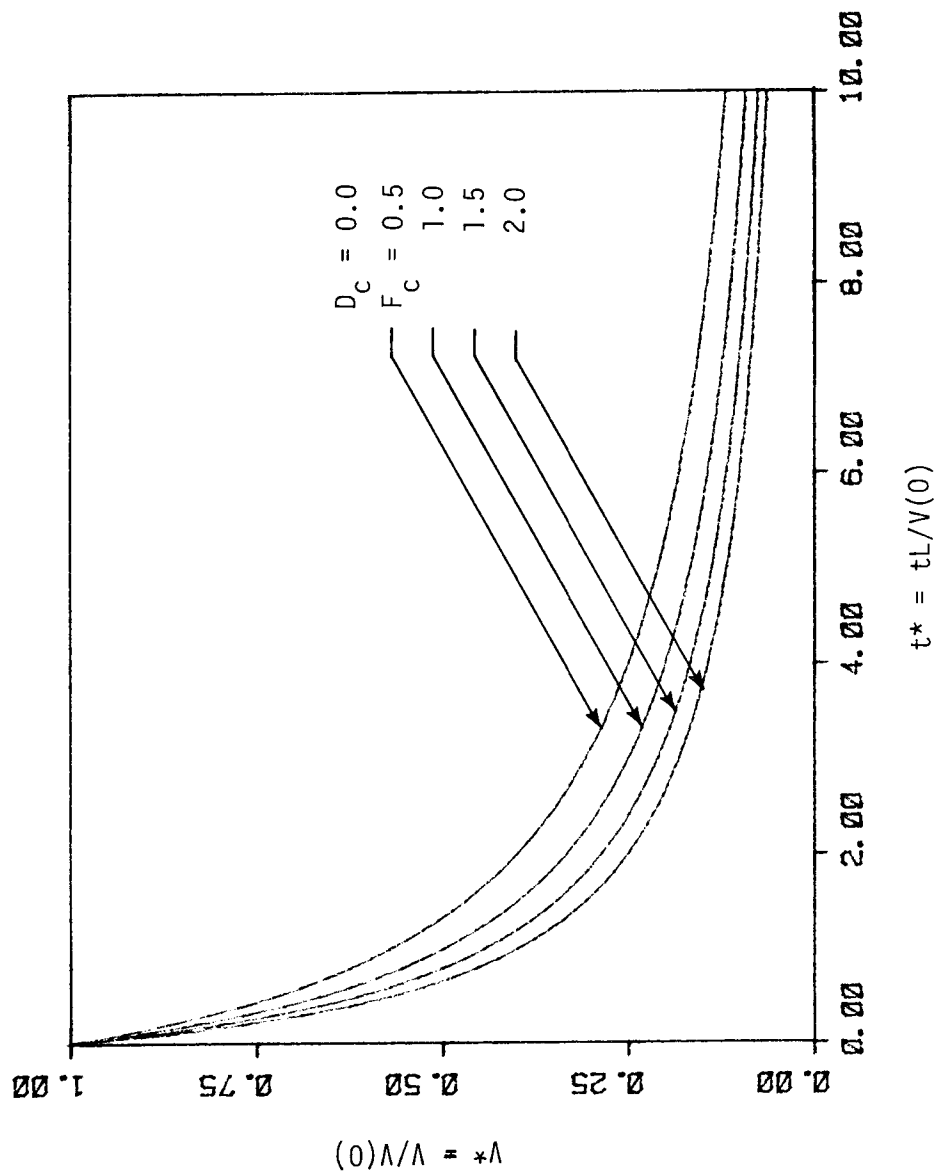


Figure 2-6. Analytic solution of induced velocity decay with respect to different friction number (case 3--no car in tunnel).

2. A uniform traffic flow passing through the tunnel stalls within the tunnel at a specified position and time. Each vehicle decelerates individually at a prescribed rate until all vehicles which would have entered the tunnel during the period of stalls have come to rest.
3. Traffic restarts after having been stalled for a given period of time. Each car begins to accelerate at a prescribed rate eventually the traffic again moves uniformly.

For case 1 of the numerical solution technique, the traffic flow velocity is uniform ($U_i = \text{constant}$). The difference between case 1 for the numerical model and that of the analytical model discussed previously is that the vehicles enter an unoccupied tunnel one at a time beginning at $t = 0$ until a steady periodic flow of vehicles occurs. In the analytical solution, a line of traffic impulsively occurs in the tunnel and a steady traffic flow instantaneously takes place.

In case 2 of the numerical model, the vehicles decelerate individually at a prescribed rate, stopping or slowing to a final spacing, S_f , which is also prescribed. (If the traffic decelerates to a bumper-to-bumper jam, S_f is set equal to the average vehicle length.) The derivation of the deceleration rate for a given stall condition is given in Appendix A. From this derivation it is shown that the deceleration rate of the K -th vehicle:

$$D_k = \frac{D_s}{1 + 2(K_s - D)D_s[(U - U_f)t_R + S_f - S]/(U - U_f)^2} \quad (2-23)$$

where D_s is the deceleration rate of the first vehicle to stall. The value of D_s is specified in accordance with the stall condition to be

simulated. K_s is the number of the first vehicle to stall, U is the speed of the uniform traffic stream before stall. Given the traffic stall time, t_s , and stall position, x_s , then K_s is calculated from

$$K_s = (Ut_s - x_s)/S + 1 \quad (2-24)$$

In Equation 2-23, U_f is the final speed reached by the traffic as a result of the stall or congestion (i.e., if the traffic stops completely, $U_f = 0$). t_R is the reaction time between each vehicle. In this study values of $D_s = 20$ ft/sec², $U_f = 0$, $S_f = 25$ ft, $t_R = 0.3$ sec were selected for analysis. The computer program, of course, allows for any input values desired. After the deceleration rate has been decided, the velocity of the K -th vehicle can be calculated as:

$$U_k = U - [t - (K - K_s)t_R]D_k \quad (2-25)$$

when

$$t \geq (K - K_s)t_R \quad \text{and} \quad t \leq t_s + (U - U_f)/D_s$$

Detail calculation is given in Appendix A.

For case 3, the traffic restart condition, the acceleration rate, A_c , is assumed equal for all vehicles which have stalled. The speed of the K -th vehicle is:

$$U_k = U_f + [t - t_a - (K - K_s)t_w]A_c \quad (2-26)$$

when

$$t \geq t_a + (K - K_s)t_w \quad \text{and} \quad t \leq t_a + (K - K_s)t_w + (U - U_f)/A_c$$

where t_w is the waiting time between the start of each vehicle, and t_a is restart time for traffic flow.

Calculating the velocity of each vehicle and employ these as inputs, Equation 2-22 can be numerically integrated. A time step of $\Delta t = 1$ sec is used. Numerical solution for the transient induced velocity over a wide range of parametric values is presented in Section V entitled, "Parametric Studies".

IV. COMPARISON OF THE ANALYTICAL AND NUMERICAL SOLUTIONS

The accuracy of the numerical solutions are first checked by comparing them with analytic solutions for identical traffic situations. Solutions of both cases 1 and 2 are discussed. The traffic conditions and tunnel characteristics are specified with the parameter values of $C_d = 0.6$, $C_f = 0.02$, $A_v = 27$ ft, $A_t = 300$ ft, $L = 1000$ ft, and $D = 20$ ft. Thus from Equation 2-10, $F_c = 1$ and $D_c = 0.54$. Comparison between the analytical solution given by Equation 2-17 and the numerical solutions given by the trapezoidal rule integration of Equation 2-22 for a range of traffic speeds is shown in Figure 2-7.

Comparison of the analytical and numerical solutions is also made for the analytical case 2 (traffic impulsively stopped) as shown in Figure 2-8. The agreement between the analytical solution and the numerical solution is very good.

V. PARAMETRIC STUDY

From the governing equation for the transient induced velocity (i.e., Equation 2-5), the induced flow velocity is found to be dependent on the friction coefficient of the tunnel, C_f , the hydraulic

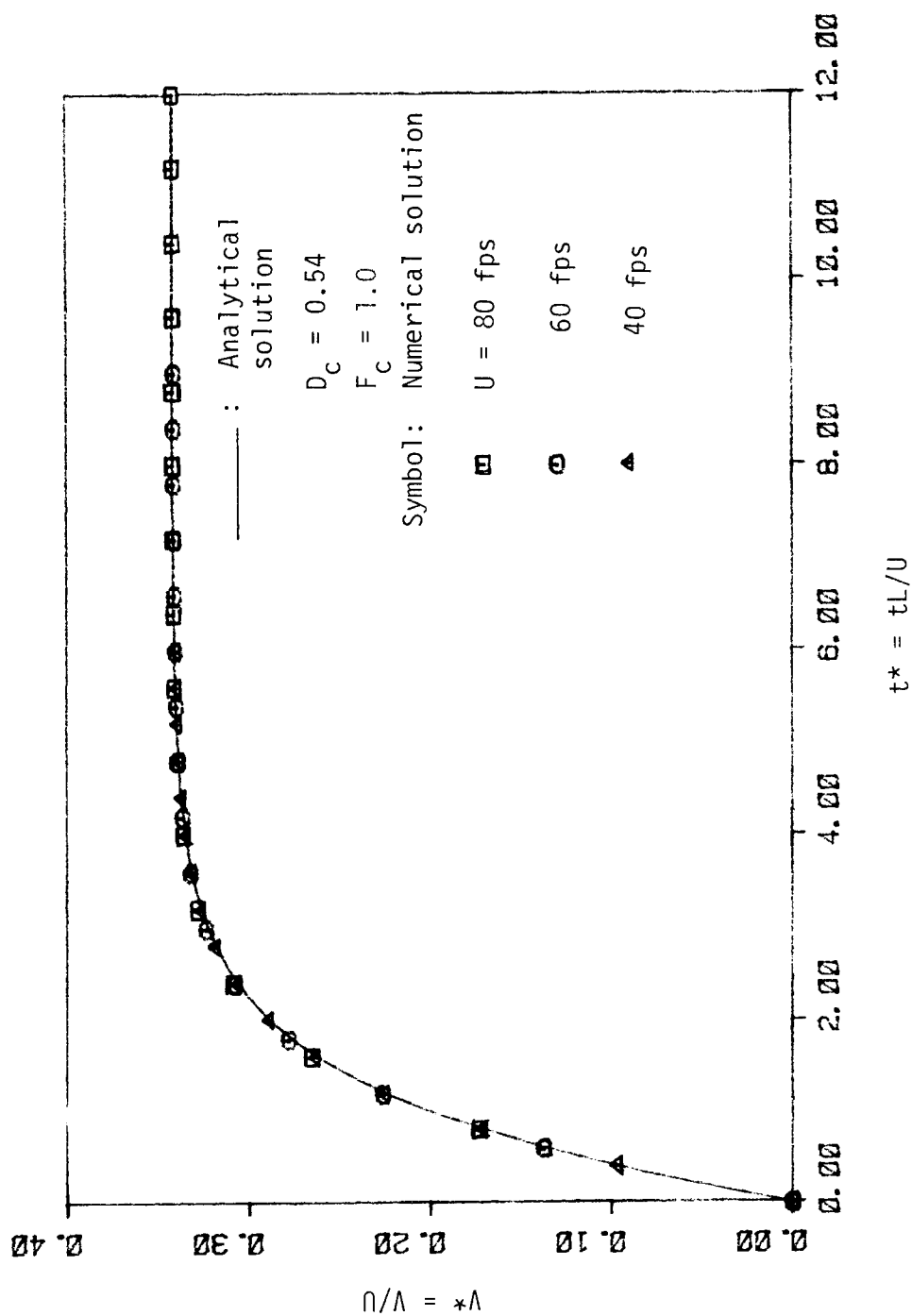


Figure 2-7. Comparison between the analytical and numerical solutions for the case of an impulsive traffic start.

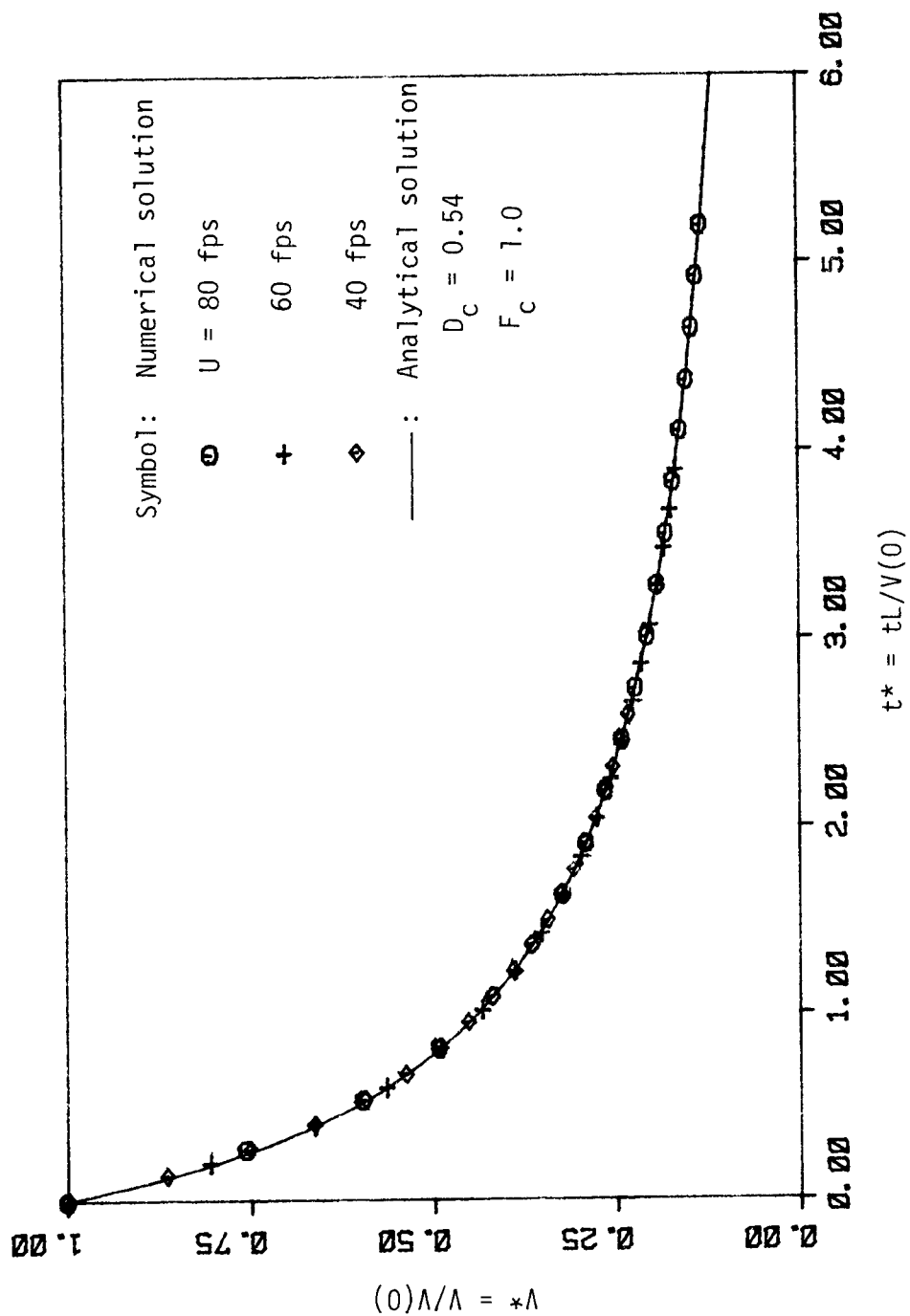


Figure 2-8. Comparison of the analytical and numerical solutions for the case of an impulsive traffic stall.

diameter of the tunnel, D , the blockage ratio, $\sigma = A_v/A_t$, the drag coefficient of the vehicle, C_d , the tunnel length, L , the spacing S , between vehicles, and the vehicle speed, U . All of these parameters are discussed in the following.

Figure 2-9 shows the growth of the induced velocity with time as traffic begins to flow through the undisturbed air within a tunnel. Higher traffic speeds clearly show a significant increase in the induced velocity. Under steady state conditions the induced air velocity is linearly related to the vehicle speed. Traffic density may be described in terms of flow rate and average speed.

$$D_T = \frac{N}{U} \quad (2-27)$$

where D_T = traffic density (vehicles/mile), N = flow rate (vehicles/hour), and U = average speed (miles/hour). In turn, the spacing is given by $S = 1/D_T$ (miles). The effects of spacing on the induced velocity are shown in Figure 2-10.

The aerodynamic drag force on a vehicle is composed of two major components. The principle component is form drag, that is, drag associated with the pressure difference between the nose and the rear of the vehicle. The second major component is friction drag. The British Motor Industries Research Association (MIRA) has published wind tunnel measured drag coefficients for some American and European Cars [4]. The measured values of the drag coefficient for a number of vehicles in current use is presented in Table 2-1. Values range from 0.23 to 0.48. Heavy-duty vehicles such as trucks and buses have larger drag coefficients than automobiles; these values are typically in the range of 0.6 to 1.0. An average value of the drag coefficient

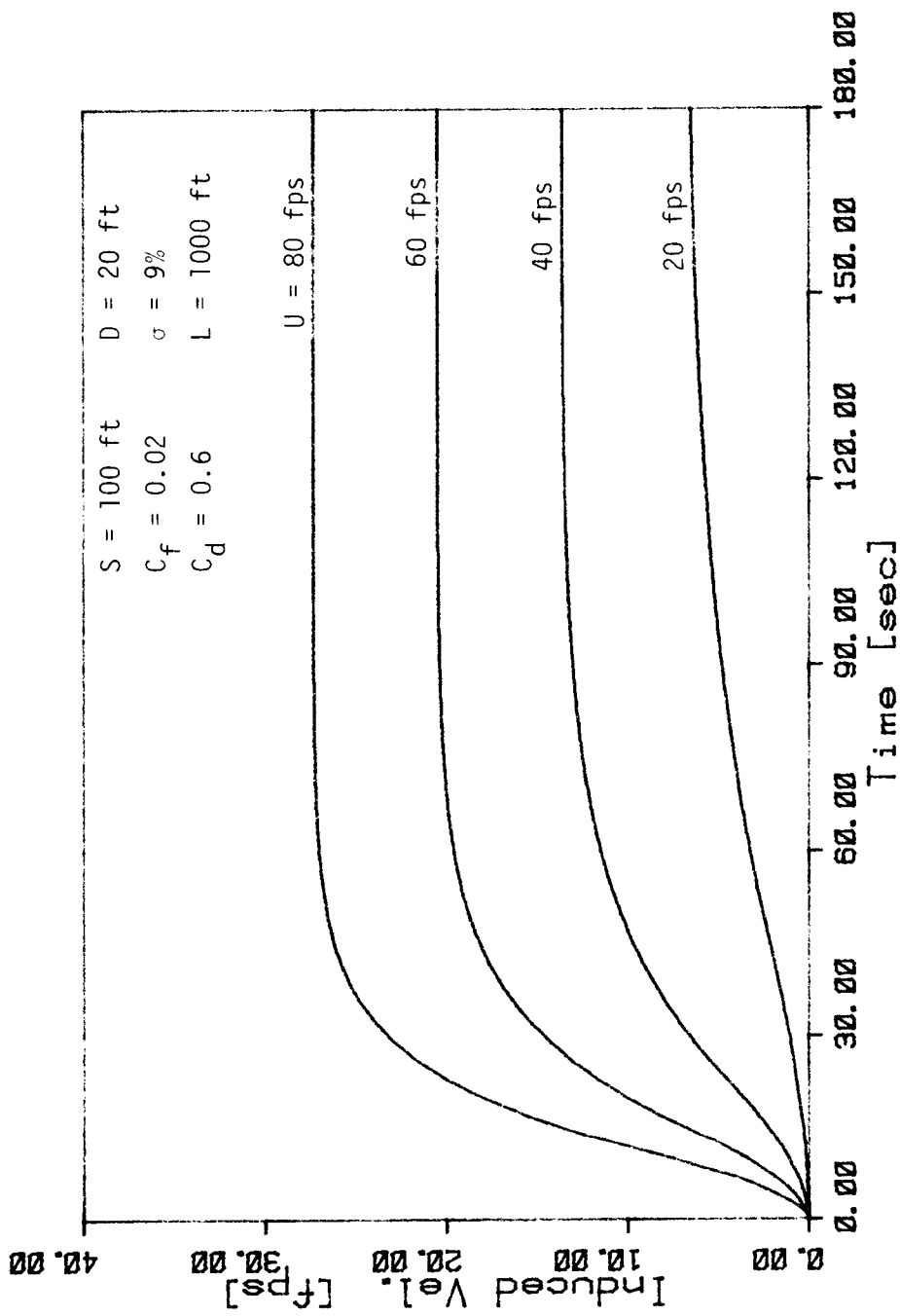


Figure 2-9. Effect of traffic flow velocity on induced air velocity.

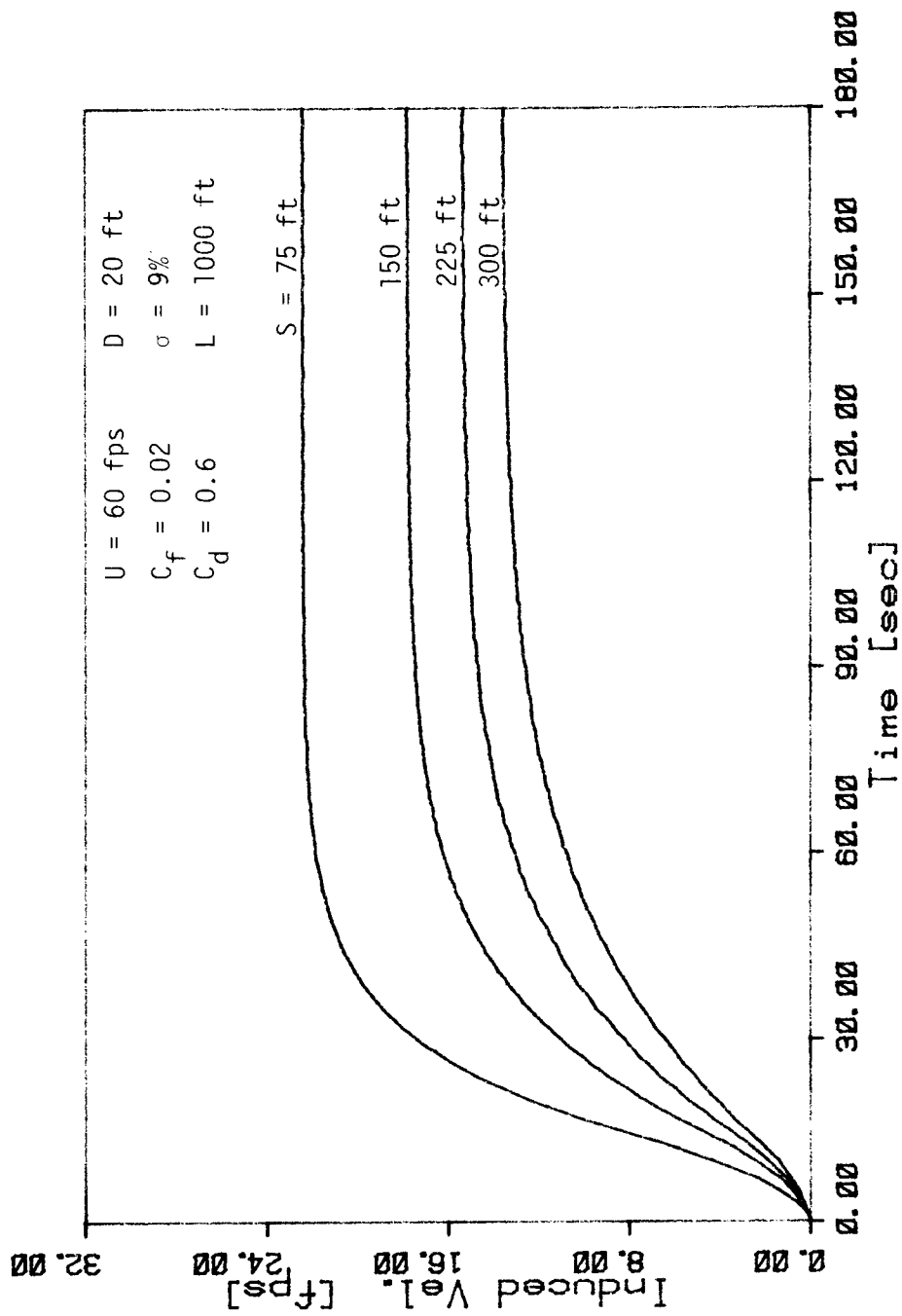


Figure 2-10. Effect of vehicle spacing on induced velocity.

TABLE 2-1

MIRA DRAG COEFFICIENTS FOR SELECTED VEHICLES IN CURRENT USE [4]

Vehicle	C_d	Vehicle	C_d
Fiat 128	0.48	Fiat 124	0.41
Ford Mustang	0.47	Mercury Capri	0.40
VW Beetle	0.46	Peugeot 504	0.39
Jaguar E type	0.44	Mercedes 220	0.38
BMW 1600	0.42	Alfa Romeo 1750 GT	0.38
VW Microbus	0.42	Porsche 911	0.34

for the traffic mix (80% light-duty and 20% heavy-duty) is taken as 0.6. Effects of the variation in the drag coefficient on induced velocity are shown in Figure 2-11. It is obvious that a larger drag coefficient produces a larger piston effect and hence, a larger induced flow velocity as clearly seen in the figure.

Piston effect (Equation 2-2) also depends upon the ratio of vehicle frontal area to tunnel cross-sectional area. Frontal area is essentially the maximum vehicle cross-sectional area parallel to the vehicle axis. Average geometric dimensions of automobiles currently in use in the United States are given in Table 2-2. Frontal areas for heavy-duty vehicles range from about 40 ft² and 80 ft² due to the wide range in size and configuration of the vehicles [5]. The average frontal area (maximum cross-section area) is about 27 ft² for a mixed traffic pattern. Blockage ratio, $\sigma = A_v/A_t$, were computed on the basis of these data and the effect on induced velocity is shown in Figure 2-12.

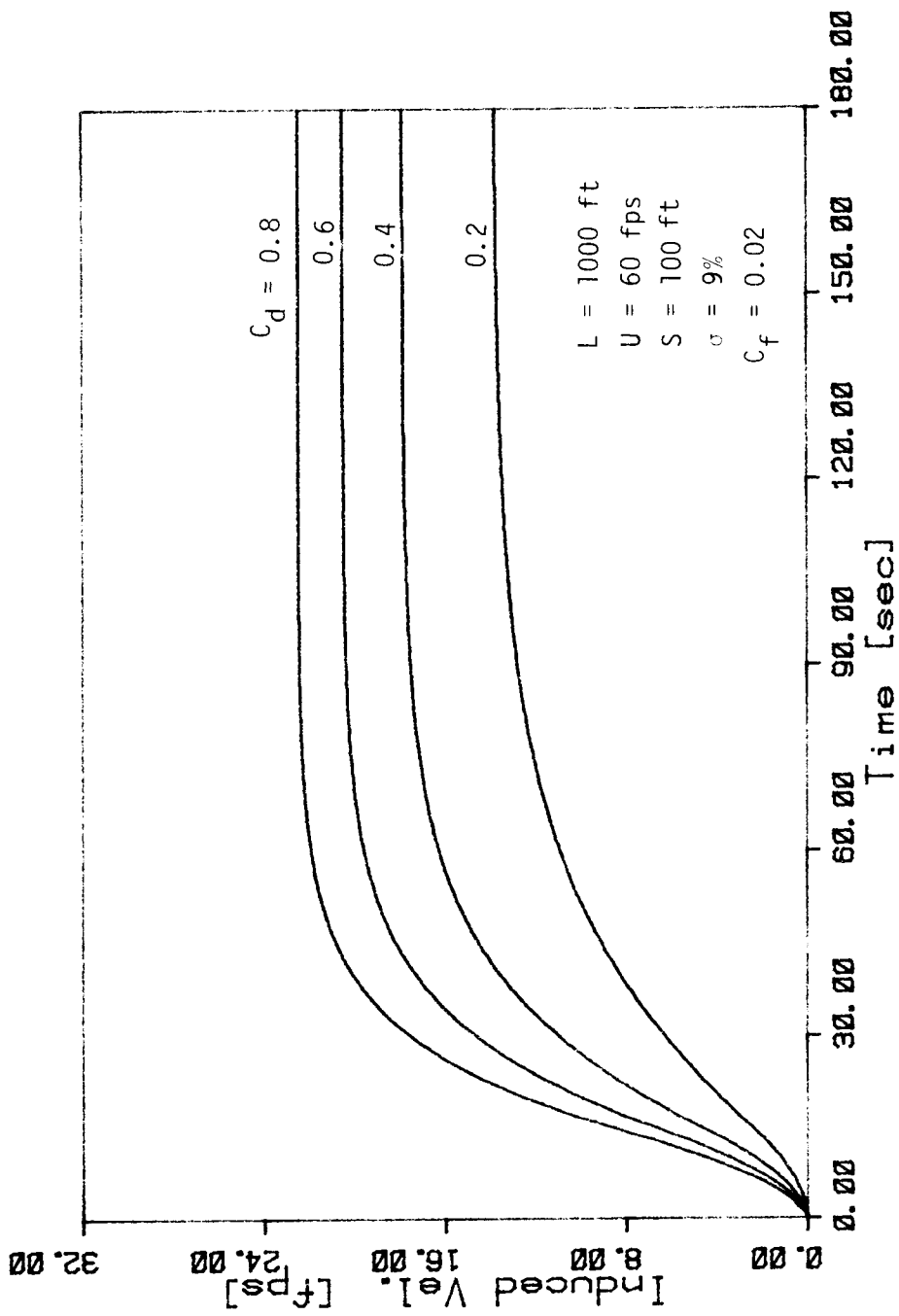


Figure 2-11. Effect of vehicle drag coefficient on induced velocity.

TABLE 2-2

AVERAGE DIMENSIONAL DATA FOR FOUR SIZE CLASSES OF AUTOMOBILES
CURRENTLY SOLD IN THE UNITED STATES [5]

Size Class	Wheelbase		Length		Frontal Area	
	(ft)	(m)	(ft)	(m)	(ft ²)	(m ²)
Subcompact	8.0	2.4	14.0	4.3	17.3	1.6
Compact	9.0	2.7	15.9	4.9	19.8	1.8
Mid-Size	9.7	3.0	18.0	5.5	21.9	2.0
Large	<u>10.0</u>	<u>3.1</u>	<u>18.5</u>	<u>5.6</u>	<u>22.4</u>	<u>2.1</u>
Average of Classes	9.2	2.8	16.6	5.06	20.3	1.89

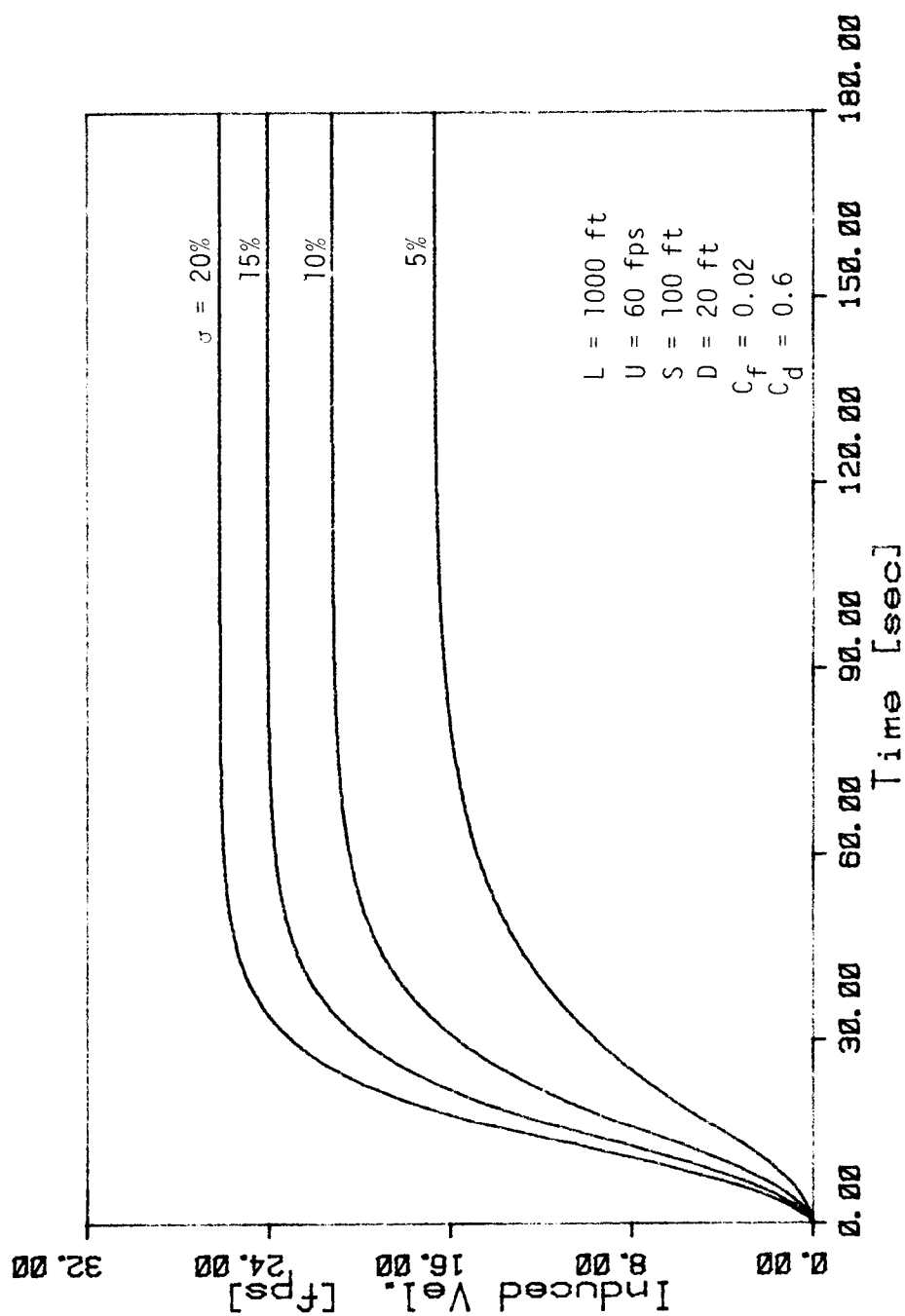


Figure 2-12. Effect of blockage ratio on induced velocity.

According to Equation 2-3, the friction force is dependent on the tunnel friction coefficient, C_f , and the hydraulic diameter, D . Effects of variation in the hydraulic diameter and the friction coefficient are investigated in Figures 2-13 and 2-14, respectively. The hydraulic diameter and the friction coefficient have only a small effect on the induced velocity and this effect becomes nonexistent at induced velocities less than 9 fps.

Figure 2-15 shows the effects of tunnel length on the induced velocity. The steady state value of induced velocity is proportional to tunnel length with higher induced velocity occurring for longer tunnels. This is due to the longer tunnels having more vehicles in them at any given time and hence a larger piston effect. However, it takes a longer time to reach steady state in the longer tunnel, i.e., the growth rate of the induced velocity is smaller. This is the result of competing forces. The friction force (Equation 2-3) is proportional to tunnel length and is initially stronger in the longer tunnel, but as the air mass gains momentum the piston forces take over.

The computer code for solving the induced flow velocity is flexible and can handle all traffic patterns discussed earlier. The previous computed results are only for case 1; however, to illustrate the computer program's capability for other traffic conditions, Figure 2-16 illustrates four traffic streams of different velocity starting through the undisturbed air in a tunnel, reaching steady conditions and then beginning to stall at $x_s = 500$ ft and $t = 150$ sec. From the time of stall the induced air flow velocity decreases exponentially. The computer code also has the capability to analyze the case when traffic slows (i.e., not a complete stall) to any prescribed final spacing, S_f ,

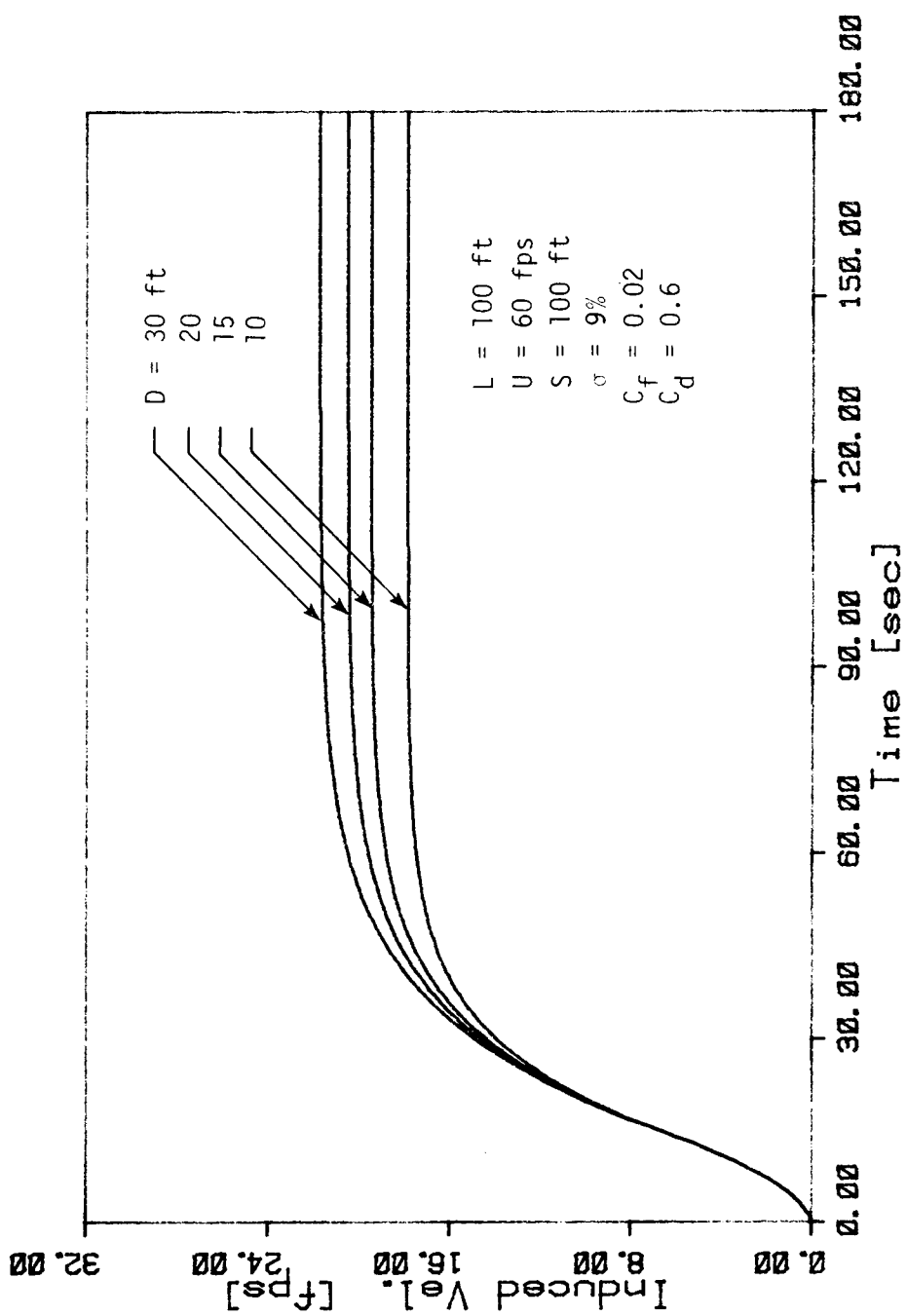


Figure 2-13. Effect of hydraulic diameter on induced velocity (with constant blockage ratio).

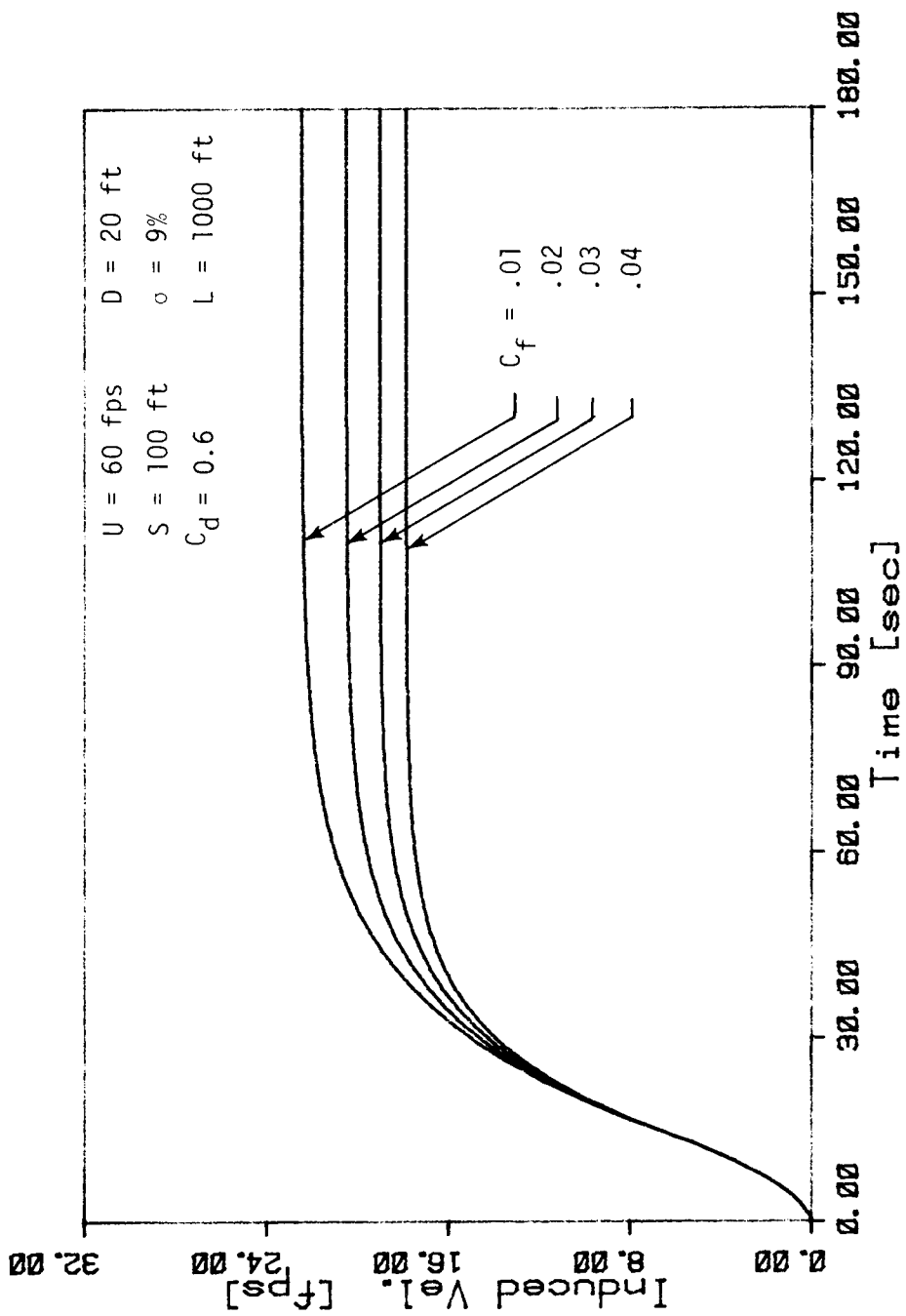


Figure 2-14. Effect of the tunnel friction coefficient on induced velocity.

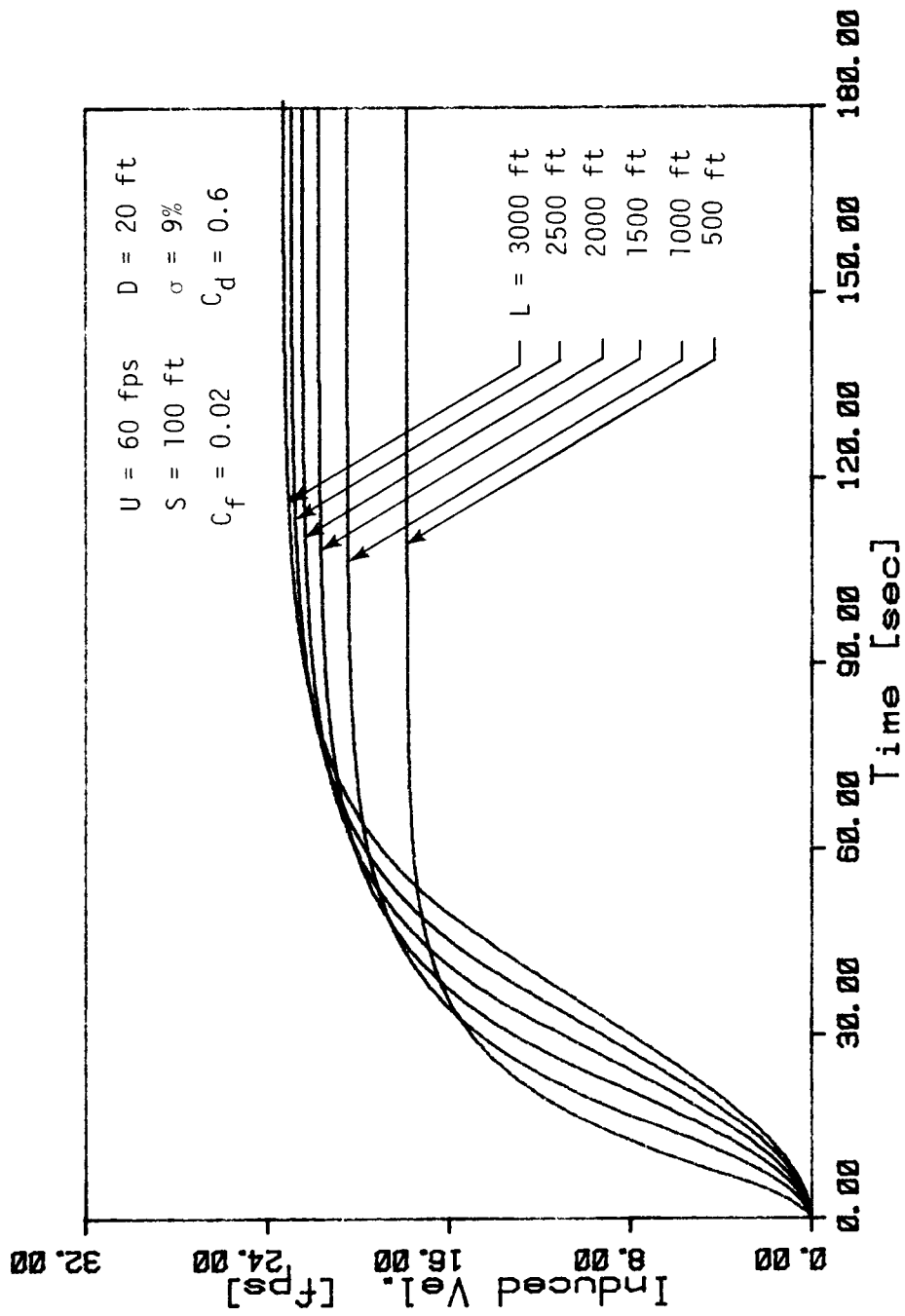


Figure 2-15. Induced velocity build-up with time for tunnels of different lengths.

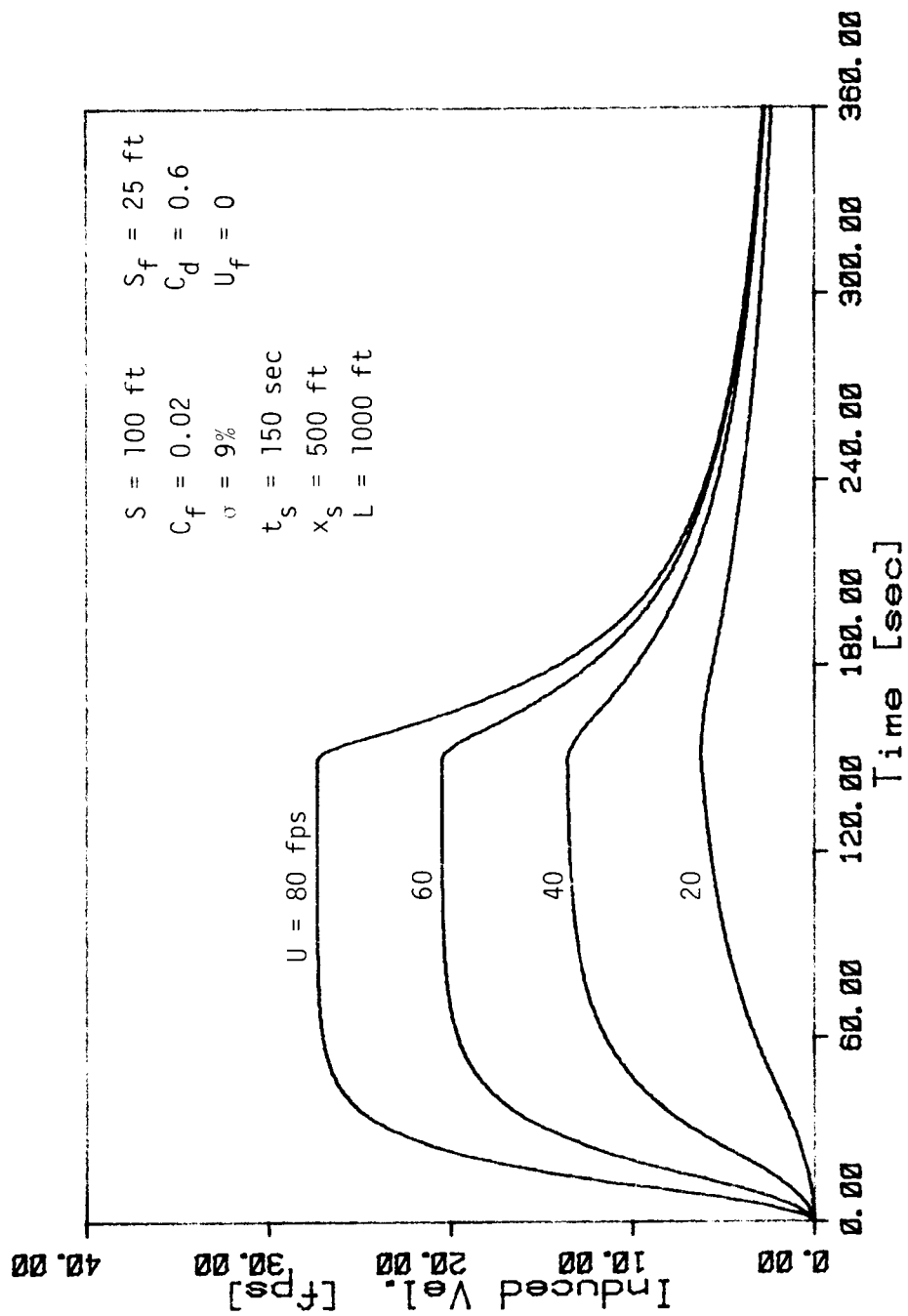


Figure 2-16. Induced velocity versus time for traffic streams of different velocities which stall at $x_s = 500 \text{ ft}$, $t_s = 150 \text{ sec}$.

and final speed, U_f . Figure 2-17 shows the effect on induced velocity of traffic slowing to different final conditions. Figure 2-18 combines all of the three cases described earlier. The traffic stream enters the tunnel at $t = 0$. Stalls occur at $t = 150$ seconds with restart taking place at $t = 200$ seconds, 250 seconds, or 300 seconds, respectively. The induced velocity reaches a new asymptotic value after traffic restart.

The induced velocity is observed to reach a new asymptotic value after traffic restart. The reason for this is that the traffic pattern is now different from the steady value before stall. The waiting time of each vehicle for restart is specified as $t_w = 2$ seconds. Because of this restriction, the spacing between two vehicles is changed and is therefore, different from the traffic pattern before stall.

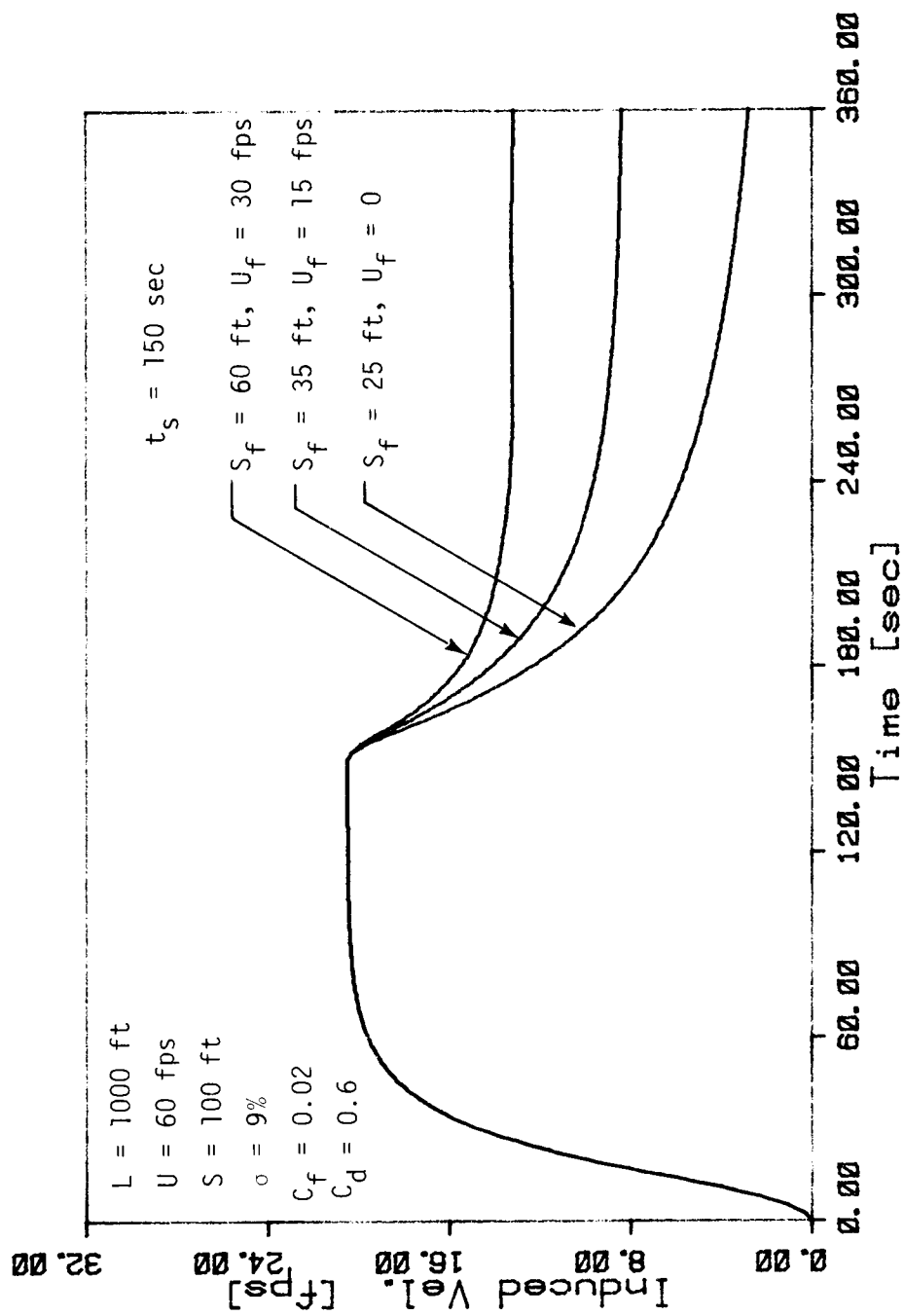


Figure 2-17. Induced velocity versus time for different conditions of incomplete stall.

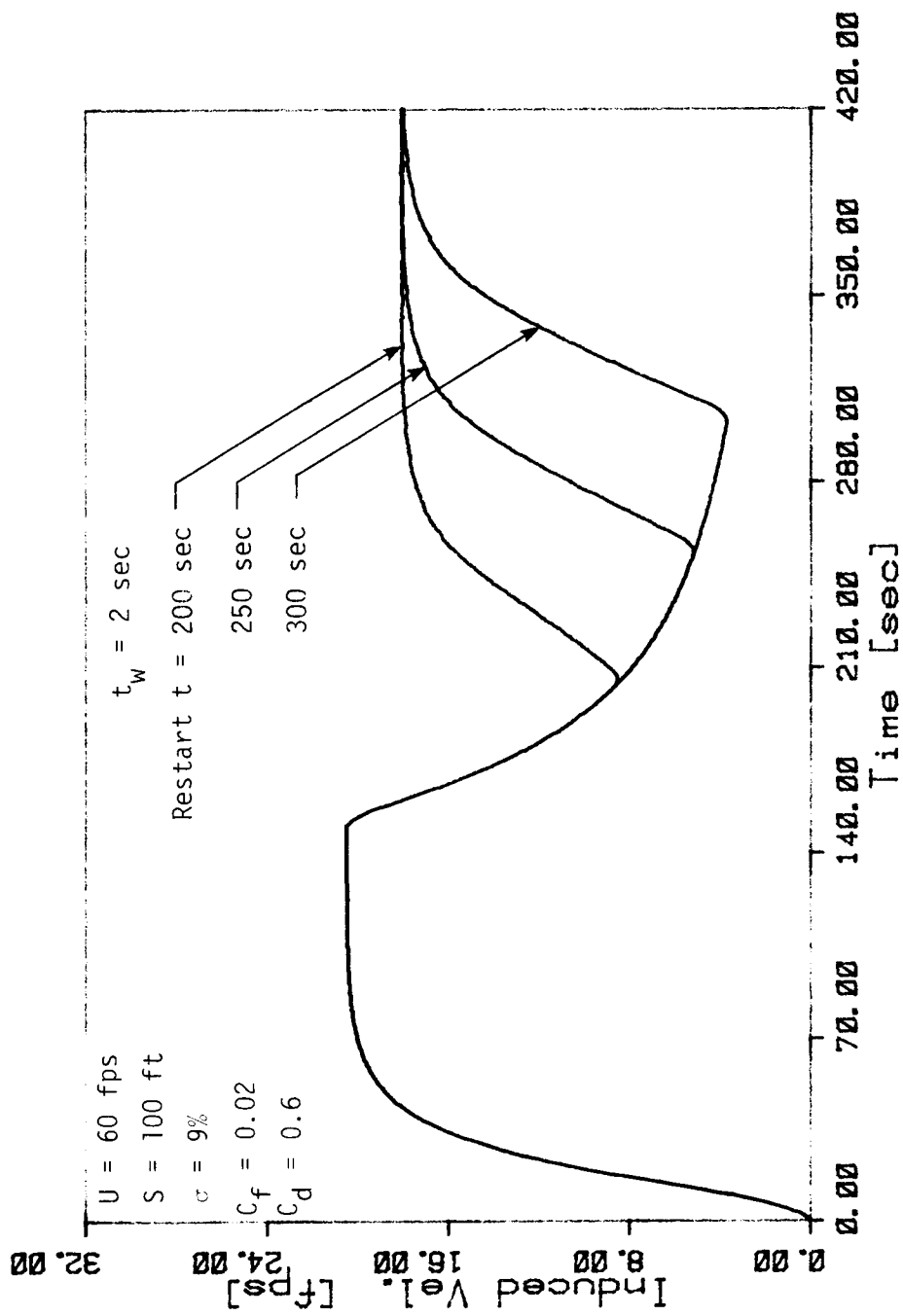


Figure 2-18. Induced velocity versus time for traffic stall at $t = 150 \text{ sec}$ and restart at different times.

CHAPTER III

DISTRIBUTION OF POLLUTANT CONCENTRATION

In Chapter II, the flow of air in a highway tunnel was discussed. Relations for computing the induced air flow velocity for a specified traffic flow pattern were derived. The influence of the air flow on the distribution of pollutants in a tunnel is described in this chapter. That is how pollutant constituents are transported in the tunnel environment.

I. BASIC ASSUMPTIONS

Consistent with Chapter II, the basic assumption of one-dimensional and incompressible mass transport of pollutants is made. The axial induced airflow in a tunnel is highly turbulent due to the cross-section size, induced airflow and traffic mixing effects. The typical magnitude of induced velocities in highway tunnels is on the order of 15 ft/sec. The axial flow Reynolds number is therefore on the order of 10^6 . Even in congested situations where the induced velocity may be as low as 1 ft/sec the flow is still fully turbulent. The combination of high Reynolds number turbulent flow and the fluid mixing effects of vehicles motion results in relatively uniform distribution of pollutant over any given cross-section of the tunnel. Uniform cross-section concentration in highway tunnels has been essentially verified from concentration measurements in five United States highway tunnels by Schlang and Carlin [4].

Another assumption required in order to simplify the governing

equation to a tractable form is to neglect axial diffusion of the pollutant. For a tunnel under normal operating conditions, the axial diffusion rate is generally believed to be small compared to the convective rate. The chemical reactions of pollutants which may have a small influence on the increase or decrease of a particular constituent of the pollutant are also neglected. Although chemical reaction may be important in the external environment, in a highway tunnel there is insufficient time for reactions to occur.

In summary, the basic assumptions inherent in the transient model for determination of air quality in highway tunnels are: one-dimensional (axial), incompressible airflow, negligible axial diffusion, uniform concentration distribution across the tunnel cross-section, and no chemical reactions.

II. GOVERNING EQUATION

The conservation of mass for a given pollutant element is illustrated in Figure 3-1. The mass balance equation can be written as:

$$\frac{\partial \gamma}{\partial t} + \frac{\partial}{\partial x} (\gamma V) = \nu \frac{\partial^2 \gamma}{\partial x^2} + S_v - R \quad (3-1)$$

where γ is the pollutant concentration, V is the induced velocity, ν is the total diffusivity, S_v is the rate of pollutant generation by vehicles in the tunnel, and R is the rate of pollutant generation due to chemical reaction. The term, R , is neglected in the present analysis. Also, the incompressible, induced air velocity, V , is not considered a function of x , but only a function of time. The assumption of incompressible flow implies that the instant a car enters the tunnel, the induced flow velocity, $V(t)$, is felt throughout. With

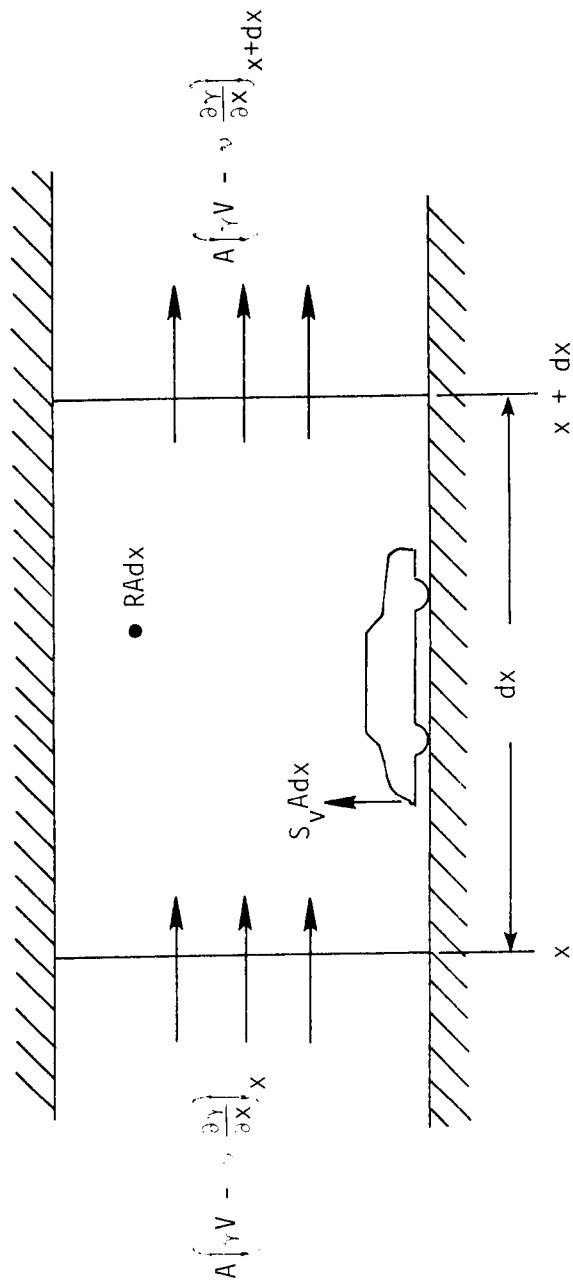


Figure 3-1. Mass balance for pollutant in an elemental control volume of the tunnel.

these assumptions, Equation 3-1 becomes:

$$\frac{\partial \gamma}{\partial t} + V \frac{\partial \gamma}{\partial x} = v \frac{\partial^2 \gamma}{\partial x^2} + S_v \quad (3-2)$$

Equation 3-2 is first converted to dimensionless form in order to analyze the relative importance of each term. The scaling parameters used are the tunnel length, L , as a characteristic axial dimension, and the time scale equal to L/V_0 where V_0 is steady state induced airflow velocity. V is a function of time in this study.

The resulting dimensionless variables are $\bar{t}$ and $\bar{x}$ as defined by:

$$\bar{t} \equiv \frac{V_0 t}{L} ; \bar{x} \equiv \frac{x}{L} ; \bar{v} \equiv \frac{v}{V_0} \quad (3-3)$$

In terms of these variables, Equation 3-2 becomes:

$$\frac{\partial \gamma}{\partial \bar{t}} + \bar{V} \frac{\partial \gamma}{\partial \bar{x}} = \frac{1}{Pe} \frac{\partial^2 \gamma}{\partial \bar{x}^2} + \frac{LS_v}{V_0} \quad (3-4)$$

where $Pe = V_0 L / v$ is the axial Peclet number. The Peclet number expresses the ratio of the convection rate to the diffusion rate. Large values of the Peclet number ($Pe \gg 1$) indicates dominance of convection effects, and therefore, the axial diffusion effects can be neglected. On the other hand, when $Pe \ll 1$, the diffusion effects override the convection effects. Generally, the turbulent diffusivity, v , within a highway tunnel is expected to be on the order of 1 to 10 ft²/sec [3]. The Peclet number is then on the order of $10^3 - 10^4$; for normal tunnel operations where $L = 1000 - 5000$ ft, and the induced air velocity, $V = 10 - 20$ ft/sec. Based on the above argument, the diffusion effects are not expected to be important even in congested traffic

situations as long as $V \geq 1$ ft/sec. The diffusion term of Equation 3-2 is thus neglected.

In the transient model, the pollutant concentration is a function of time and axial position. The pollutant production or source term, S_v , is a function of vehicle speed and therefore, can be expressed as a function of x and t . Equation 3-2, once again in dimensional terms becomes:

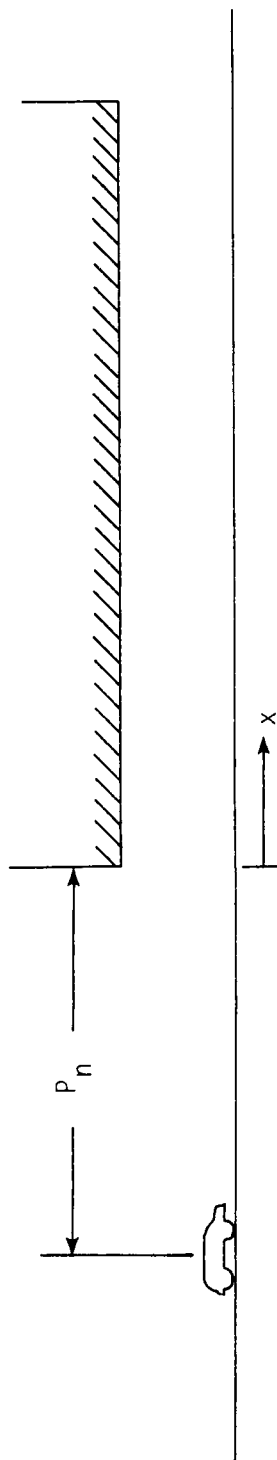
$$\frac{\partial \gamma(x,t)}{\partial t} = -V(t) \frac{\partial \gamma(x,t)}{\partial x} + S_v(x,t) \quad (3-4)$$

Physically, this equation expresses the pollutant concentrations in the highway tunnel as resulting from the pollution generated by vehicles in the tunnel, and from the propagation of pollutants by the induced airflow. The source term, S_v , represents the total rate of concentration generated by all vehicles in the tunnel at any instant of time. Each vehicle has an individual pollution exhaust rate which is a function of its type, its past history, and its operating condition. The magnitude of the vehicle exhaust rate is discussed later.

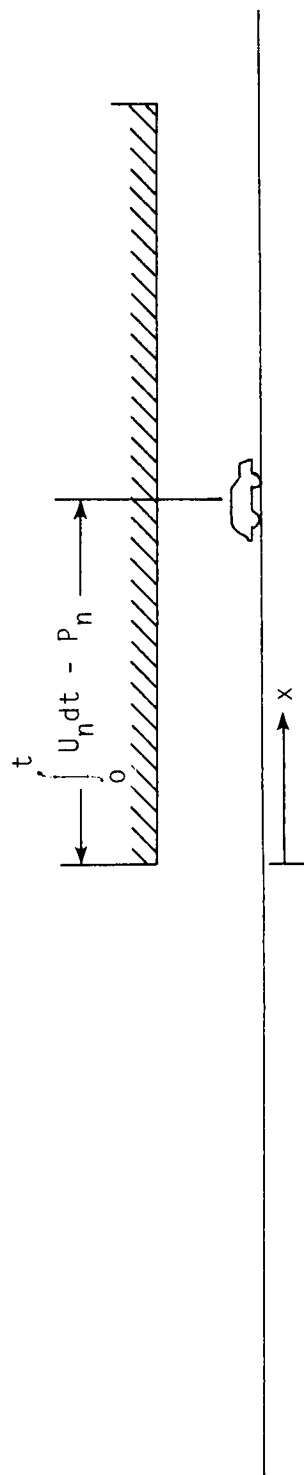
Let q_n represent the individual exhaust production rate for the n -th vehicle to enter the tunnel measured from some initial time $t = 0$. q_n is a function of velocity and therefore, can be expressed in terms of x and t . The total source term, S_v , can then be expressed as:

$$S_v(x,t) = \sum_{n=1}^{\infty} q_n H(t - t_n) \delta(x - (\int_0^t U_n(t) dt - P_n)) \quad (3-5)$$

P_n is the initial position of the n -th vehicle from the tunnel entrance at time, $t = 0$, see Figure 3-2. Also P_n can be expressed as:



(a) Position of nth vehicle at $t = 0$



(b) Position of nth vehicle at time t

Figure 3-2. The change of vehicle position with respect to time. (U_n is the speed of the nth vehicle.)

$$P_n = \int_0^{t_n} U_n(t) dt$$

where t_n is the time at which the n -th vehicle enters the tunnel. The velocity, $U_n(t)$ is the speed of the n -th vehicle which is a function of time. The problem is assumed to begin at time, $t = 0$, with the initial vehicle considered being at the tunnel entrance, i.e., $P_1 = 0$. The expression $H(t - t_n)$ is the Heaviside unit function defined as:

$$H(t - t_n) = \begin{cases} 1 & \text{when } t \geq t_n \\ 0 & \text{when } t < t_n \end{cases}$$

The delta function, $\delta(x)$, is defined as:

$$\delta(\zeta - x) = 0; \quad \zeta \leq x^- \quad \text{or} \quad \zeta \geq x^+$$

and

$$\int_{x^-}^{x^+} \delta(\zeta - x) dx = 1; \quad x^- < \zeta < x^+$$

Finally, x is an arbitrary position within the tunnel. The change of vehicles' position with respect to time is illustrated in Figure 3-2.

Equation 3-5 predicts the rate of pollution generation at position x at time t ; for example, when $t > t_n$ and $x = \zeta$ is the position of the n -th vehicle in the tunnel, then:

$$H(t - t_n) = 1, \quad \text{and} \quad \int_{x^-}^{x^+} q_n(U_n(t)) \delta(\zeta - x) dx = q_n(U_n(t))$$

hence,

$$\int_{x^-}^{x^+} S_v(x,t) dx = q_n(U_n(t))$$

If, on the other hand, no vehicle is at position x at time, $S_v = 0$.

Substituting Equation 3-5 into Equation 3-4, the pollutant mass balance equation becomes:

$$\frac{\partial \gamma(x,t)}{\partial t} = -V(t) \frac{\partial \gamma(x,t)}{\partial x} + \sum_{n=1}^{\infty} q_n(U_n(t)) H(t - t_n) \delta(x - (\int_0^t U_n dt - P_n)) \quad (3-6)$$

To solve this equation, the coordinates are transformed from the (x,t) system to the (ξ,τ) system by:

$$\tau = t, \quad \text{and} \quad \xi = x - \int_0^t V(t) dt \quad (3-7)$$

This means that the new coordinate (ξ,τ) is transported with the air in the tunnel at its induced velocity, $V(t)$. The position of the origin of the new coordinate system (ξ,τ) and time t is thus downstream at the location:

$$x = \int_0^t V(t) dt$$

Introducing the transformation of coordinates into Equation 3-6 gives:

$$\begin{aligned} \frac{\partial \gamma(\xi,\tau)}{\partial \tau} = & -V(t) \frac{\partial \gamma(\xi,\tau)}{\partial \xi} \frac{\partial \xi}{\partial x} + \sum_{n=1}^{\infty} q_n(\xi,\tau) H(\tau - \tau_n) \delta(\int_0^{\tau} (U_n - V) d\tau' \\ & - (\xi + P_n)) \end{aligned} \quad (3-8)$$

where $U_n(t)$ is a function of ξ and τ through the relationship:

$$x_n = \int_{t_n}^t U_n(t') dt'$$

In the moving coordinate system which is moving at the speed of the induced flow velocity, $V(t) = 0$. Therefore, Equation 3-8 becomes simply:

$$\frac{\partial \gamma(\xi, \tau)}{\partial \tau} = \sum_{n=1}^{\infty} q_n(\xi, \tau) H(\tau - \tau_n) \delta \left(\int_0^{\tau} (U_n - V) d\tau' - (\xi + P_n) \right) \quad (3-9)$$

Integrating both sides of Equation 3-9 with respect to τ gives:

$$\begin{aligned} \gamma(\xi, \tau) - \gamma(\xi, 0) = & \sum_{n=1}^{\infty} \int_0^{\tau} q_n(\xi, \tau') H(\tau' - t_n) \left(\int_0^{\tau'} (U_n - V) dt' \right. \\ & \left. - (\xi + P_n) \right) d\tau' \end{aligned} \quad (3-10)$$

Upon transforming back to the fixed coordinate system, as shown in detail in the Appendix B, the solution for the concentration $\gamma(x, t)$ is given by:

$$\begin{aligned} \gamma(x, t) = & \sum_{n=1}^{\infty} q_n(\beta + P_n) F_n(\beta + P_n) \left[H \left(\int_0^t U_n dt - x - P_n \right) \right. \\ & \left. - H \left(\int_{t_n}^t V dt - x \right) \right] + \gamma_i(\beta) \end{aligned} \quad (3-11)$$

where

$$\beta = x - \int_0^t V dt$$

$$F_n(\beta + P_n) = \frac{1}{U_n(\tau) - V(\tau)}$$

$$\tau = \tau(x + P_n - \int_0^t V dt)$$

Also, time τ has the following relation with x , V , and U_n :

$$\int_{\tau}^t V dt = x - \int_{t_n}^{\tau} U_n dt \quad (3-13)$$

The distance, ℓ , the n -th vehicle's pollutant has been carried down the tunnel in the time period t_n due to the induced airflow as given by:

$$\ell = \int_{t_n}^t V(t) dt$$

Thus, $\gamma_i(\beta)$ is a function of β . Normally, $\gamma_i(\beta)$ is a constant, however; if there is an initial concentration distribution in the tunnel, $\gamma_i(\beta)$ will be carried downstream by the induced velocity. New values of $\gamma_i(\beta)$ are drawn into the tunnel and are equivalent to the external distribution or background concentration.

Equation 3-11 is schematically illustrated in Figure 3-3. The concentration a (x is measured down the tunnel from the entrance)

and at time t , i.e., (x,t) , that is contributed by the n -th vehicle is equal to the pollutant production rate of that vehicle q_n times the known function F_n as long as x is in the shaded area of Figure 3-3. Each term appearing in the sum of Equation 3-11 represents the pollution plume of a single car so that the total effect consists of the sum of the plumes of all the cars (see Figure 3-4). Although the sum is expressed as an infinite sum, it can be truncated for any combination of finite x and t yielding contribution from only those vehicles which have reached or passed through the tunnel.

III. CORRECTION FOR TURBULENT AXIAL DIFFUSION

The diffusion term was neglected in the governing equation (Equation 3-4). Actually, the passage of a vehicle through the tunnel produces a turbulent wake which mixes the flow over a distance which can be subjectively argued as being approximately equal to a tunnel diameter. Further axial spreading of pollutants will depend on the intensity of turbulence [5].

This mixing effect can be simulated without resorting to a complex turbulent diffusion model by applying a successive averaging process to the terms and sums appearing in Equation 3-11. The value of $\gamma(x,t)$ is the sum of all values of γ contributed by each vehicle which has recently passed through the tunnel, see Figure 3-3. It γ_n represents the pollutant concentration of the plume of the n -th vehicle and N the number of vehicles which have reached or passed position x by time t , but less than time t_ℓ , t_ℓ is in the relation of:

$$x = \int_{t_n}^{t_\ell} V(t)dt$$

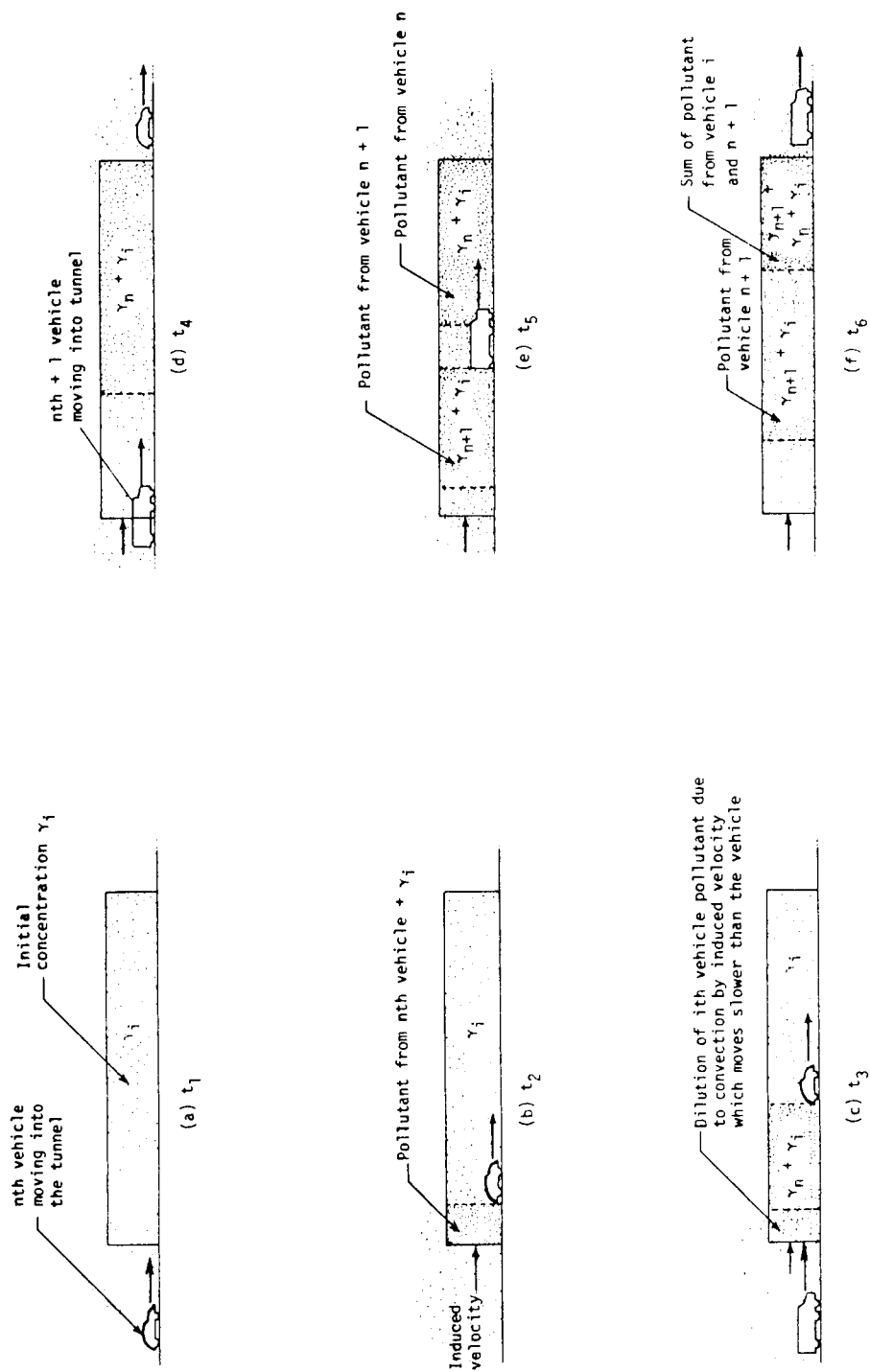


Figure 3.4 Illustration superpositioning of pollutant plume.

Equation 3-11 becomes:

$$\gamma(x,t) = \sum_{n=M+1}^{N+M} \gamma_{n-M} + \gamma_i \quad (3-13)$$

where M is total number of vehicles having passed through the tunnel for a time longer than t_ℓ . The solution given by the above equation is modified to account for successive mixing by the following approximate procedure. Defining an averaged function $\overline{\gamma(x,t)}$ by:

$$\overline{\gamma(x,t)} = \frac{1}{D} \int_{x-\frac{D}{2}}^{x+\frac{D}{2}} \gamma(x,t) \quad (3-14)$$

where D is the tunnel diameter. The concentration at a given position x is taken as the average of the neighboring values included in the region $|x| \leq D/2$ for that vehicle, i.e.,

$$\overline{\gamma(x,t)}^1 = \frac{\gamma^0(x,t) + \sum_{i=1}^{N_0} [\gamma^0(x + i\Delta x, t) + \gamma^0(x - i\Delta x, t)]}{2N_0 + 1} \quad (3-15)$$

where $N_0 = D/2\Delta x$, γ^0 is pollution concentration distribution before mixing. Then for each time a vehicle passes through the position x the averaging process given in Equation 3-15 is repeated using the last averaged values of $\overline{\gamma(x,t)}$. For example, for the second vehicle to pass the point x:

$$\overline{\gamma(x,t)}^2 = \frac{\overline{\gamma(x,t)}^1 + \sum_{i=1}^{N_0} [\overline{\gamma(x + i\Delta x, t)}^1 + \overline{\gamma(x - i\Delta x, t)}^1]}{2N_0 + 1}$$

Hence, the general expression becomes:

$$\gamma(x,t)^j = \frac{\gamma(x,t)^{j-1} + \sum_{i=1}^{N_0} [\gamma(x + i\Delta x, t)^1 + \gamma(x - i\Delta x, t)^1]}{2N_0 + 1} \quad (3-16)$$

This process is believed to yield a more accurate distribution of tunnel pollution concentration, especially when the traffic stream stalls.

The significance of the contribution of this mixing process is shown in more detail later. For the present, reconsider Equation 3-11. The concentration distribution is a function of vehicle emission rate, q_n and a known function F_n . The effects of these variables are discussed next.

IV. VEHICLE EXHAUST RATES

The pollutant concentrations found by solving Equation 3-11 depends of the initial tunnel concentration distribution γ_i , and the emissions from the vehicles inside the tunnel. Each individual vehicle as an emission rate that is a function of:

1. Vehicle type, such as gasoline or diesel, automobile, truck or bus, etc.
2. Vehicle past history (age, mileage and maintenance record)
3. The conditions under which the vehicle is operated in the tunnel, i.e., speed, altitude, and grade.

In addition, other factors such as whether the vehicle is cold start or hot start (cold start and hot start are defined as vehicle running times of less than 505 seconds and greater than 505 seconds, respectively), the ambient temperature and humidity are also important.

Estimates of road vehicles' exhaust rates are required for pollution ventilation studies. According to Abdulrahman and Frost [2], the exhaust rate for carbon monoxide, oxides of nitrogen, and hydrocarbons of vehicles can be evaluated by the computer code BIGAP-42 [7]. The computer program accepts as input date of vehicle manufactured between 1970 and 1990, ambient temperatures between 20 °F and 80 °F, and vehicle speeds between 1 and 45 mph. The mix of vehicles can be varied. For the calculations reported in the study a peak traffic mix consisting of 80% light-duty vehicles (LDV), 12% light-duty gas vehicles (LDG), 4% heavy-duty gas vehicles (HDG), and 4% heavy diesel vehicles was assumed. Emission factors used in this study were for vehicles manufactured in 1980 and 1975 with 20% cold start and 27% hot start. Results were for an environment of 45 °F. Figures 3-5, 3-6, and 3-7 show the rate of pollutant mass exhausted for different traffic speeds. The vehicle emission rates shown in these figures are averaged values. Ideally, for the case of concern to this study (i.e., transient model), the individual emission rate for each vehicle should be considered. This option is available in the computer program developed, but for simplification, it is assumed throughout that the emission rates for all vehicles are the same for a given speed. Also for slow moving (less than 1 mph) or stalled vehicles, it is assumed that the emission rates are constant from zero to 1 mph. In the governing equation, Equation 3-11, the emission rate q_n is in dimension of g/sec/veh. The mass of exhausted pollutant per vehicle per mile is converted to emission rate (mass per vehicle per second) by multiplying by the traffic speed.

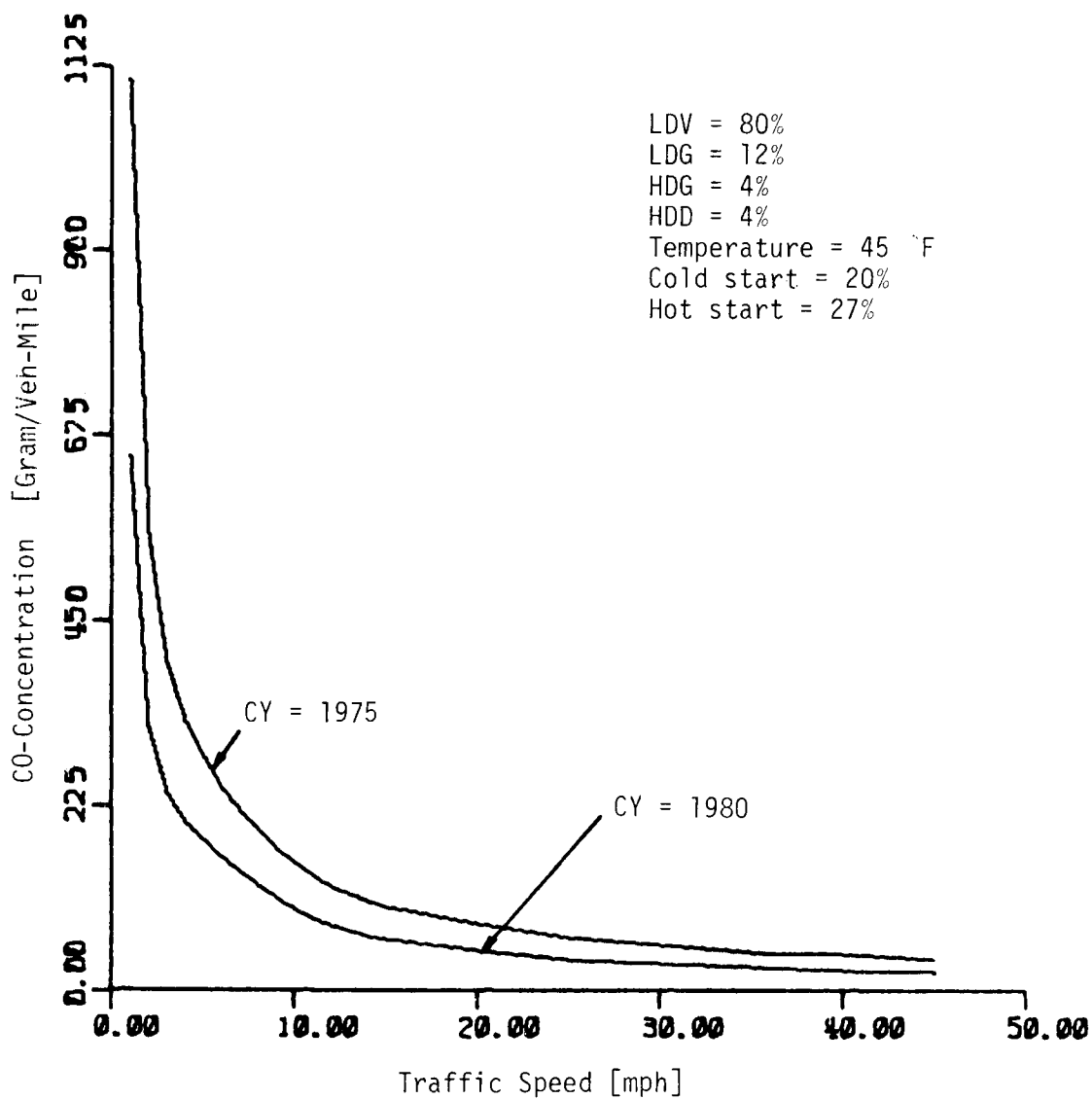


Figure 3-5. Carbon monoxide exhaust rate versus traffic speed for the peak traffic mix shown in the insert.

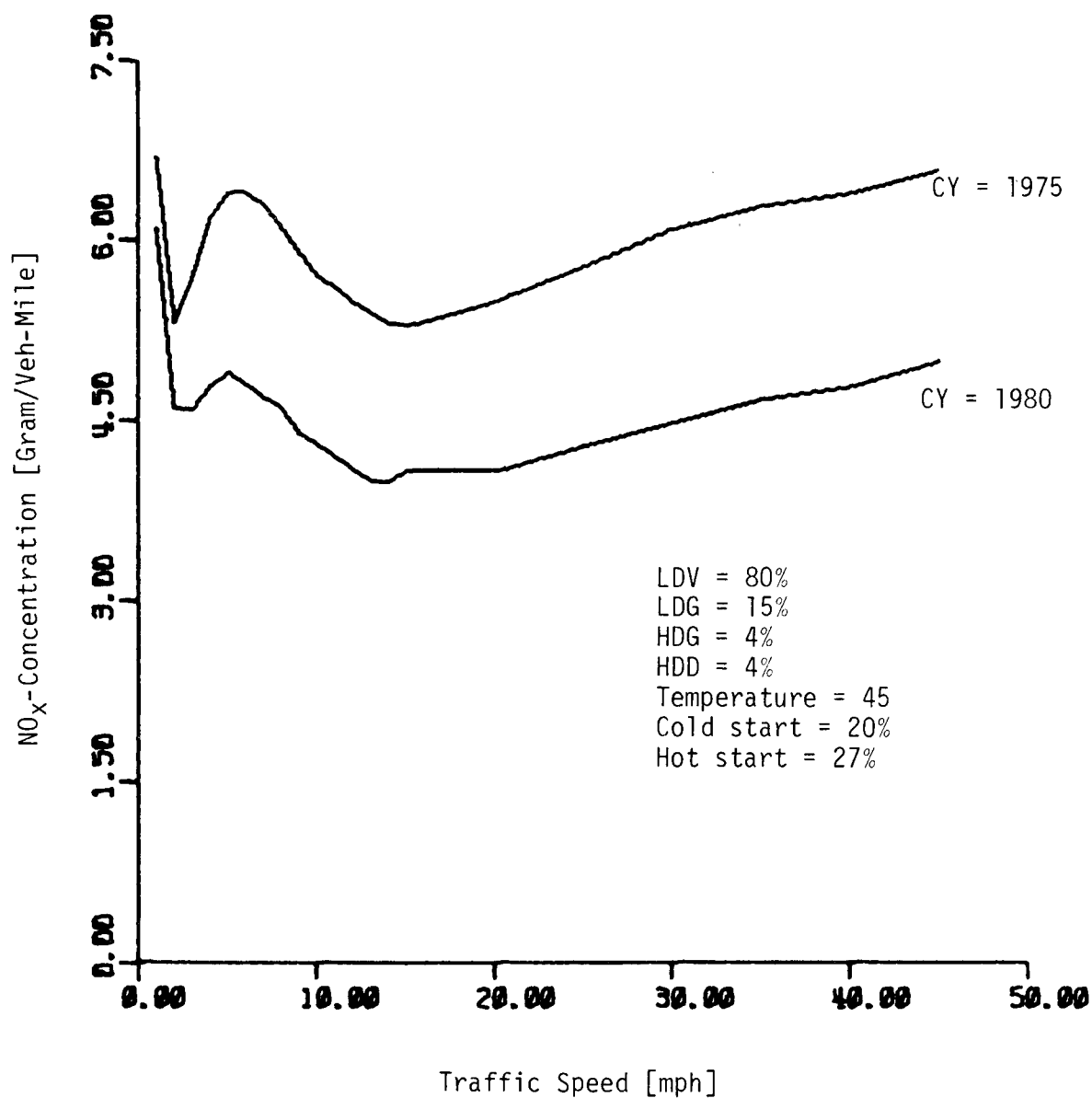


Figure 3-6. Oxides of nitrogen exhaust rate versus traffic speed for the peak traffic mix shown in insert.

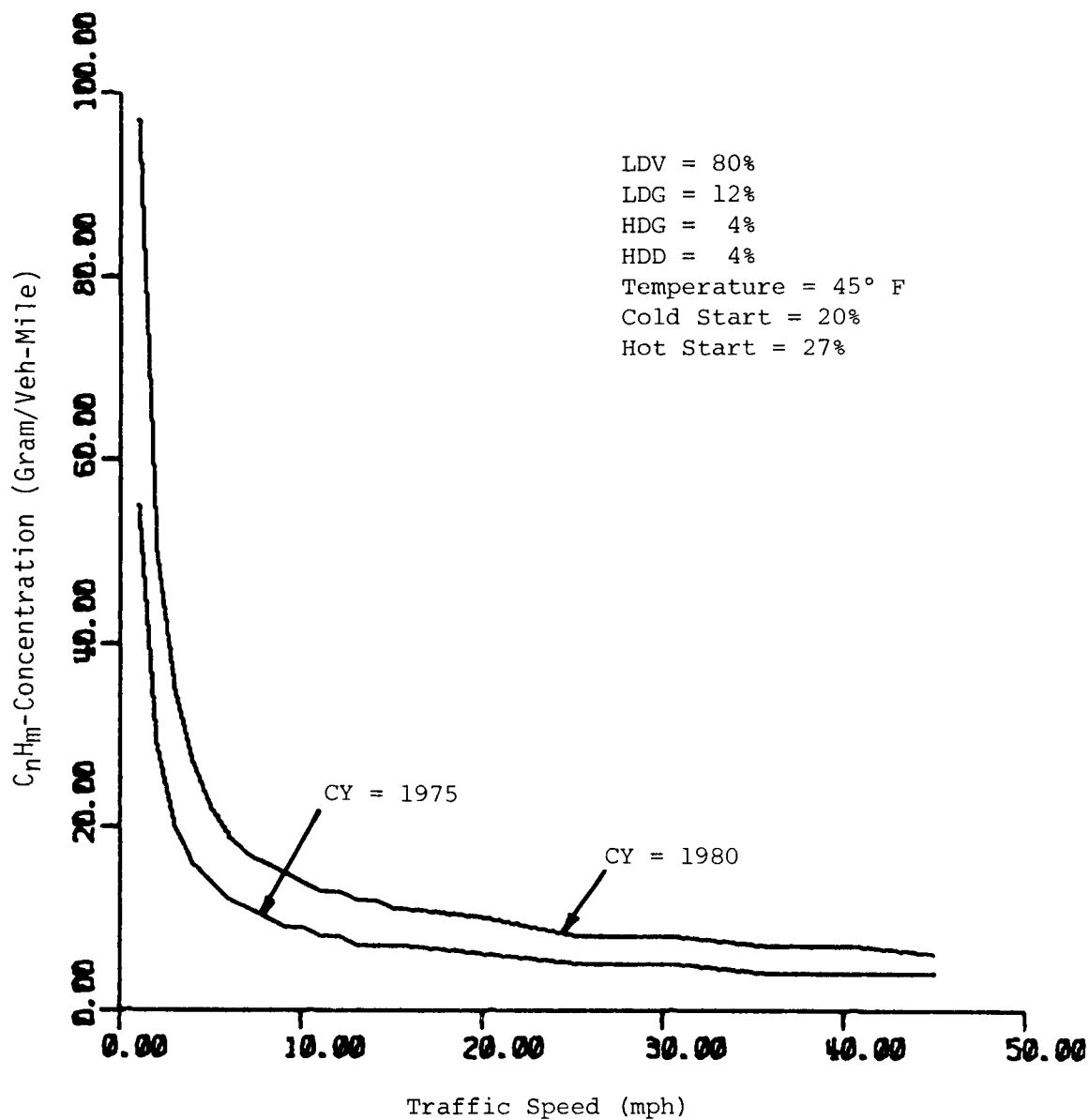


Figure 3.7 Hydrocarbons exhaust rate versus traffic speed for the peak traffic mix shown in the insert.

V. COMPUTATIONAL PROCEDURE

The basic organization of the TN. DOT/UTSI TRANS program is shown in Figure 3-8. The input data include:

1. The physical characteristics of the tunnel, such as tunnel length, cross-section area, hydraulic diameter, etc.
2. Traffic condition, such as speed of vehicle, front area of vehicle, drag coefficient, traffic stall time and stall position, etc.

A complete list of the input data, users' instructions, and a source listing of the entire program is given in Appendix C.

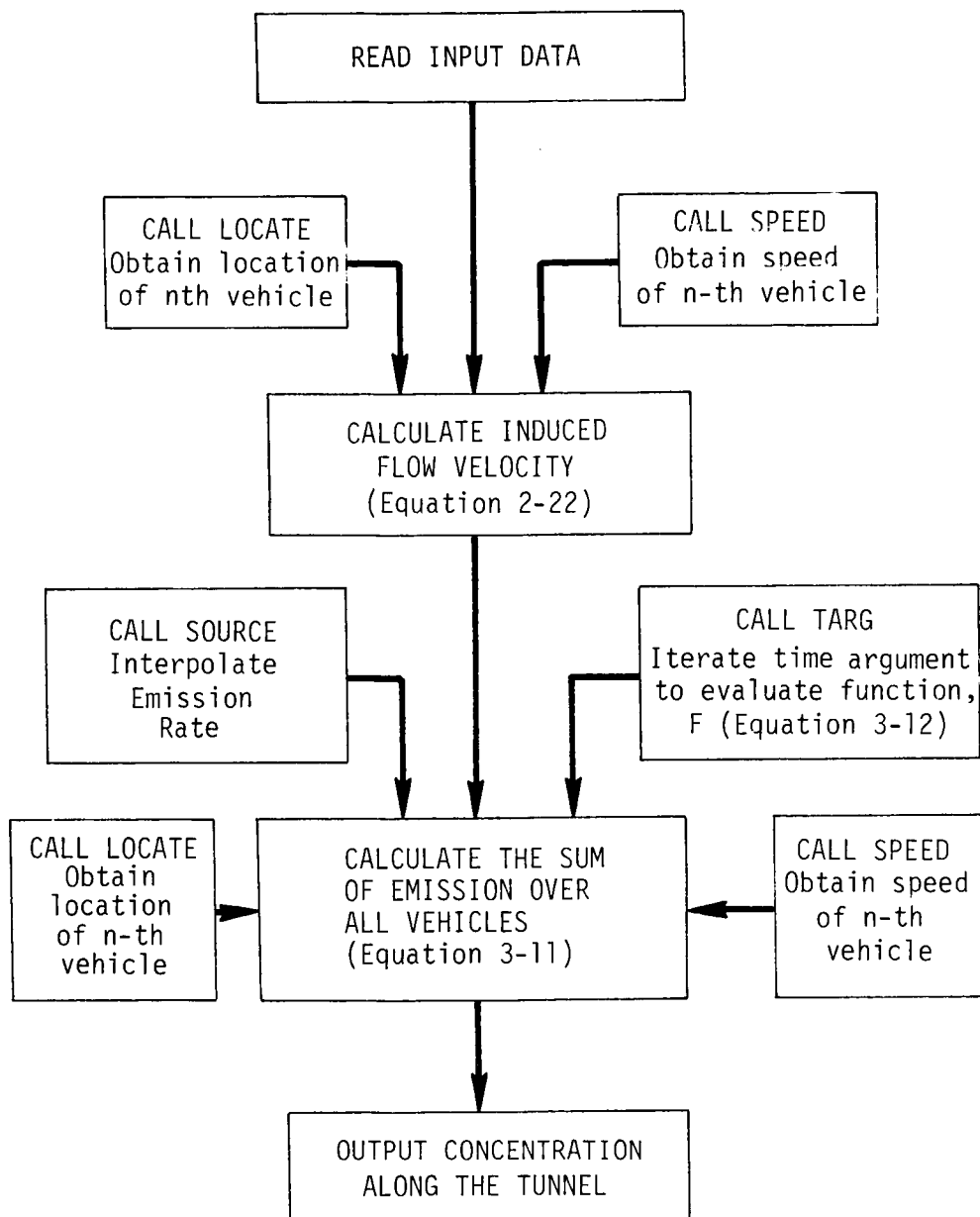


Figure 3-8. Organization of the TN. DOT/UTSI TRANS program.

CHAPTER IV

RESULTS AND DISCUSSION

Numerical results obtained in this study are transient pollutant concentrations along a highway tunnel. Example results are presented for the tunnel geometry and characteristics, traffic conditions, and traffic flow patterns listed in Table 4-1. The traffic stream is assumed to be made up of 80% LDV, 12% LDG, 4% HDD, and 4% HDG, which represent the expected peak traffic mix for Interstate I-40 through Memphis, Tennessee [2]. Emissions are calculated for conditions of 45 °F temperature with 20% cold start, and 27% hot start. Results were obtained for both 1980 and/or 1975 emission standards. The three gaseous pollutants, i.e., CO, NO_x, and C_nH_m, are discussed individually. The emission rates of the three gases are as shown in Figures 3-5, 3-6, and 3-7, pages 54 through 56.

The results of this example study are discussed under the two following categories: (1) results without turbulent mixing and (2) results with approximate turbulent mixing.

The traffic pattern in this study is a uniform traffic stream with a speed of 60 ft/sec, and vehicle spacing of 100 ft suddenly beginning to flow through the undisturbed air in the specified highway tunnel. The induced airflow builds up because of the "piston effect" or the drag on the air by the vehicles. Gases are exhausted along the tunnel by the vehicles, and propagated downstream due to the induced airflow. Eighty seconds from the time the first vehicle enters the tunnel, the induced airflow asymptotically approaches a steady state

TABLE 4-1
INPUT DATA FOR TRANSIENT MODEL BASE CASE

Tunnel Characteristics:	1. Tunnel length	1000 ft
	2. Cross-section area	300 ft ²
	3. Hydraulic diameter	20 ft
	4. Darcy total friction factor	0.03
Traffic Conditions:	1. Uniform traffic speed	60 ft/sec
	2. Spacing	100 ft
	3. Vehicle area	20 ft ²
	4. Vehicle drag coefficient	0.5
Flow Pattern:	1. Stall time	150 sec
	2. Stall position	500 ft
	3. Final speed after stall	0 ft/sec ²
	4. Final spacing after stall	25 ft
	5. Restart time	500 sec
	6. Acceleration rate	10 ft/sec ²

value of 16 fps. Traffic begins to stall in the middle of tunnel ($x = 500$ ft) at $t = 150$ sec. The first stalled vehicle decelerates at a rate of 20 ft/sec^2 , and the following vehicles decelerated to the congested situation at the appropriate deceleration rates. The induced air velocity decays very rapidly at first, and then more slowly. Traffic restart occurs at $t = 500$ sec with a 10 ft/sec^2 acceleration rate for the case under study. The entire history of the induced airflow is shown in Figure 4-1. Note, because the air is assumed incompressible the airflow is the same throughout the tunnel.

I. POLLUTION CONCENTRATION WITHOUT TURBULENT MIXING

The distributions of pollutant without smoothing due to turbulent diffusion are given in this section. The results are obtained from numerical solution of Equation 3-11. Figures 4-2, 4-3, and 4-4 show CO , NO_x , and C_nH_m concentration distributions along the tunnel for different times measured from the first vehicle entering the tunnel. When $t = 10$ sec, the first car has reached a distance $x = 600$ ft, and a total of six vehicles have entered the tunnel. The induced air velocity is $V = 2.14 \text{ ft/sec}$ at this time. As time increases, more vehicles enter the tunnel. The induced airflow increases such that the pollutant is now drawn downstream at a faster rate. However, the level of pollutant concentration increases because the vehicles are exhausting pollutants faster than they can be drawn from the tunnel by the induced airflow. At time greater than 100 sec, the induced air velocity becomes steady and since the traffic stream is uniform, the distribution of pollutant also becomes steady. Figures 4-5, 4-6, and 4-7 show the steady state solutions for all three gaseous pollutants

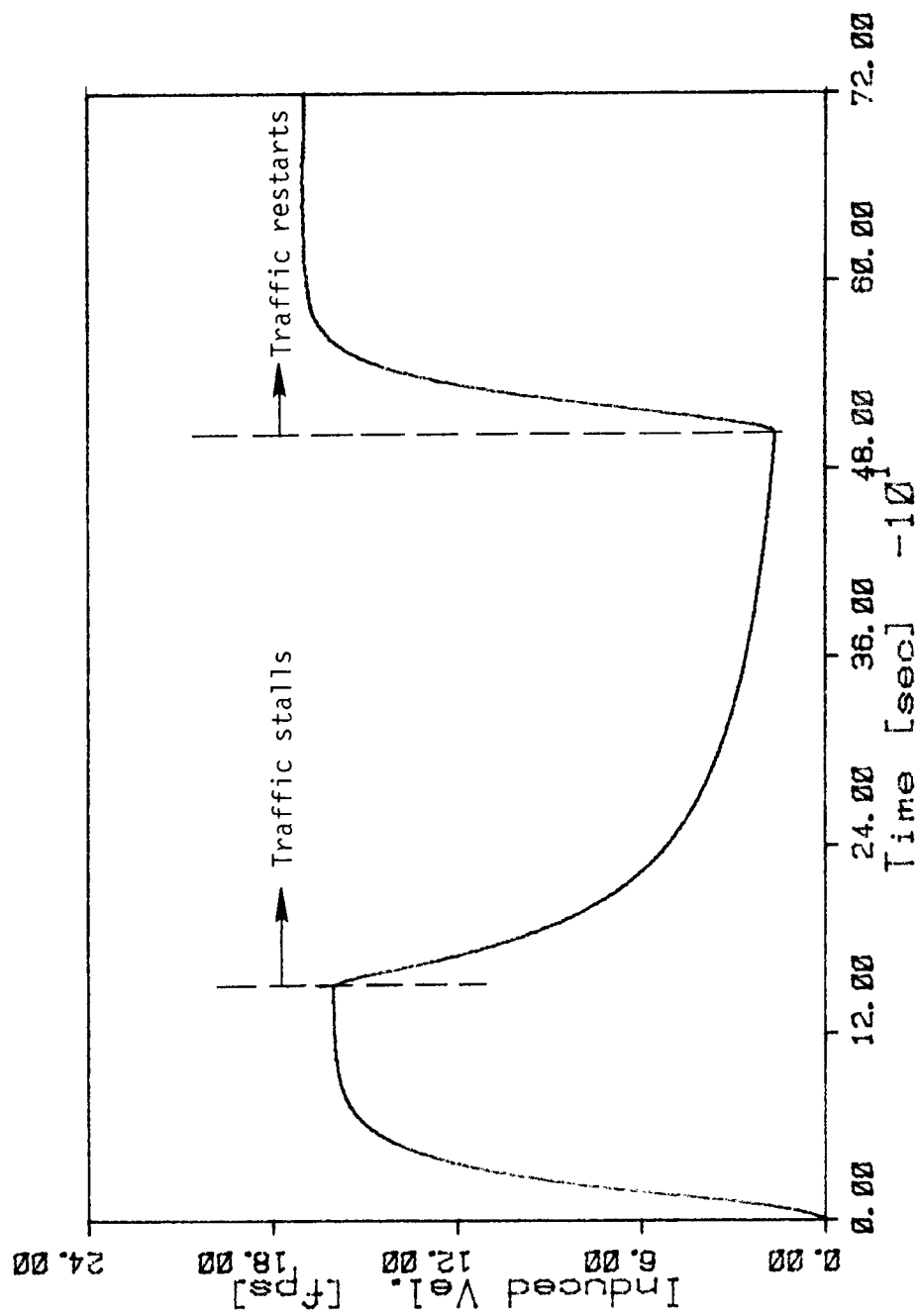


Figure 4-1. History of induced airflow velocity for base case.

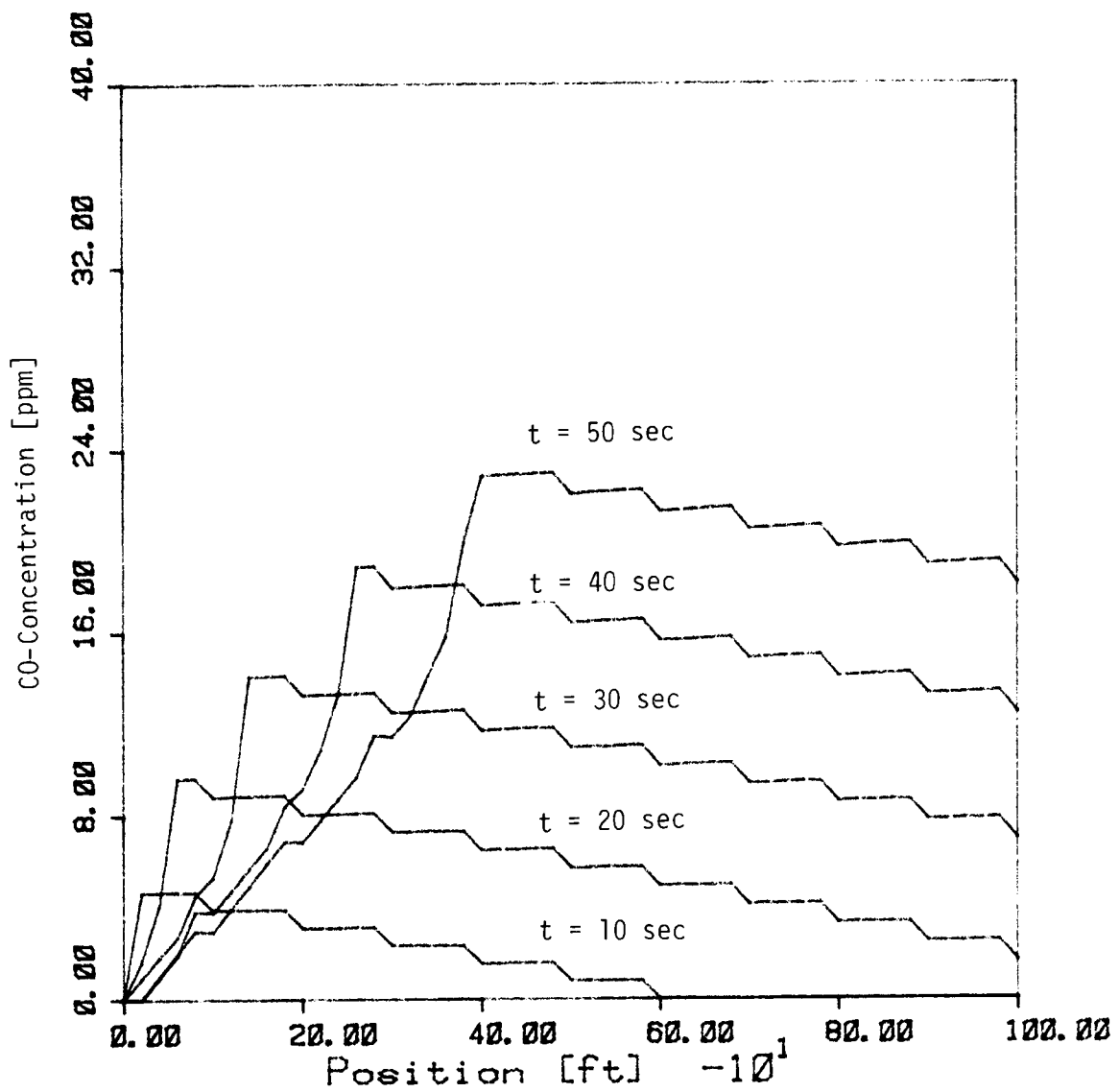


Figure 4-2. CO-concentration distribution from time 10 seconds to 50 seconds.

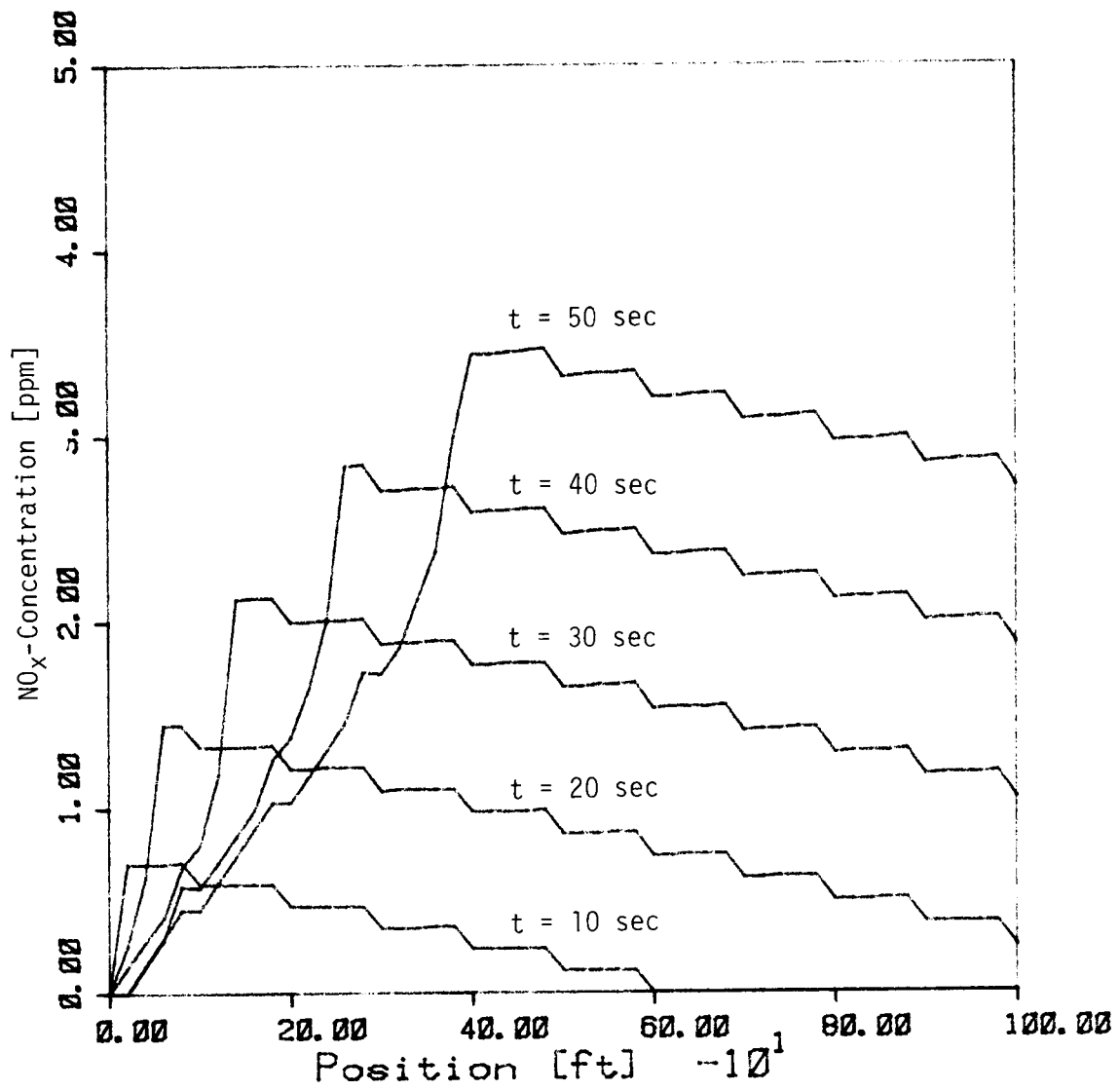


Figure 4-3. NO_x-concentration distribution from time 10 seconds to time 50 seconds.

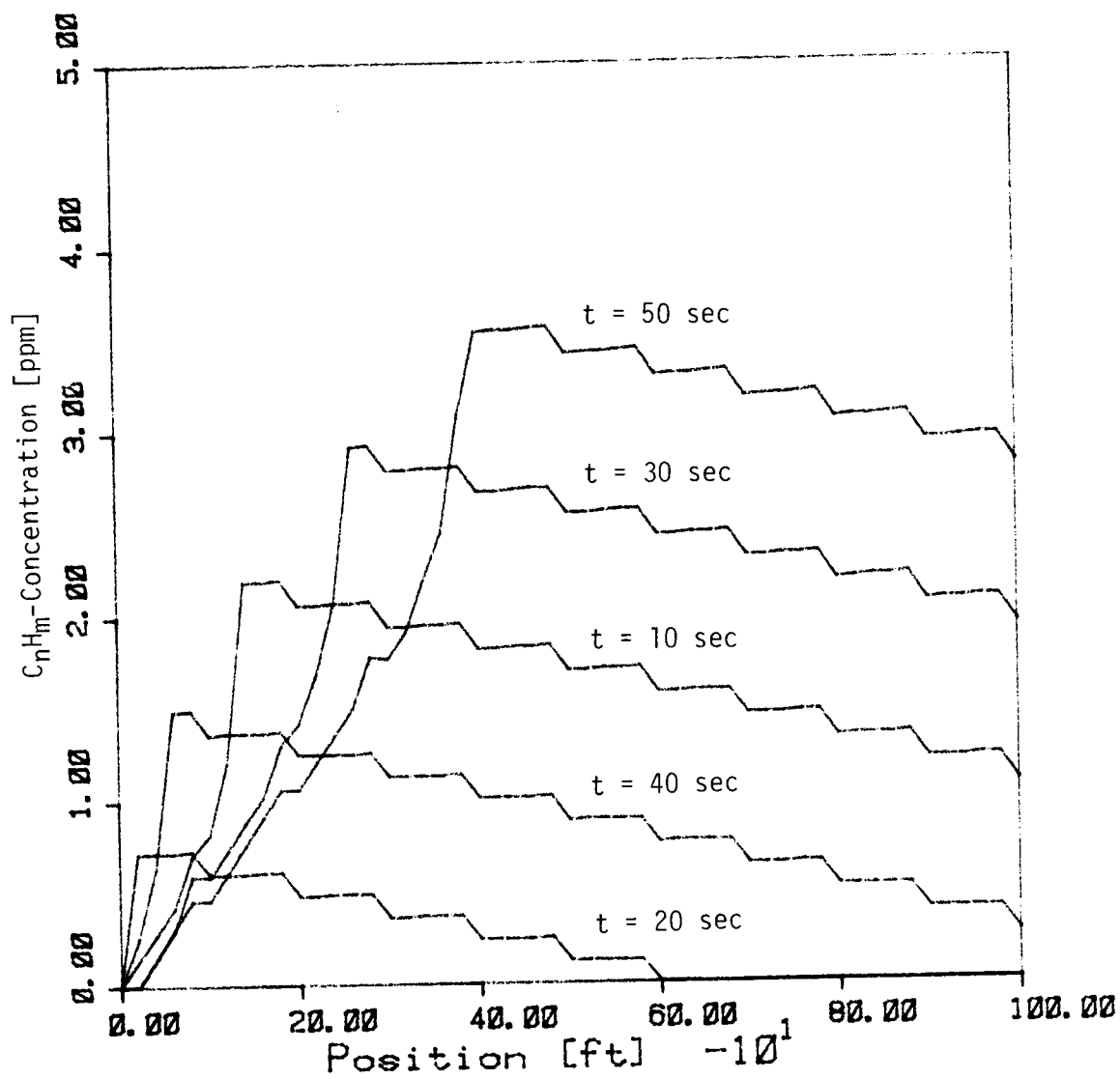


Figure 4-4. CnHm-concentration distribution from time 10 seconds to 50 seconds.

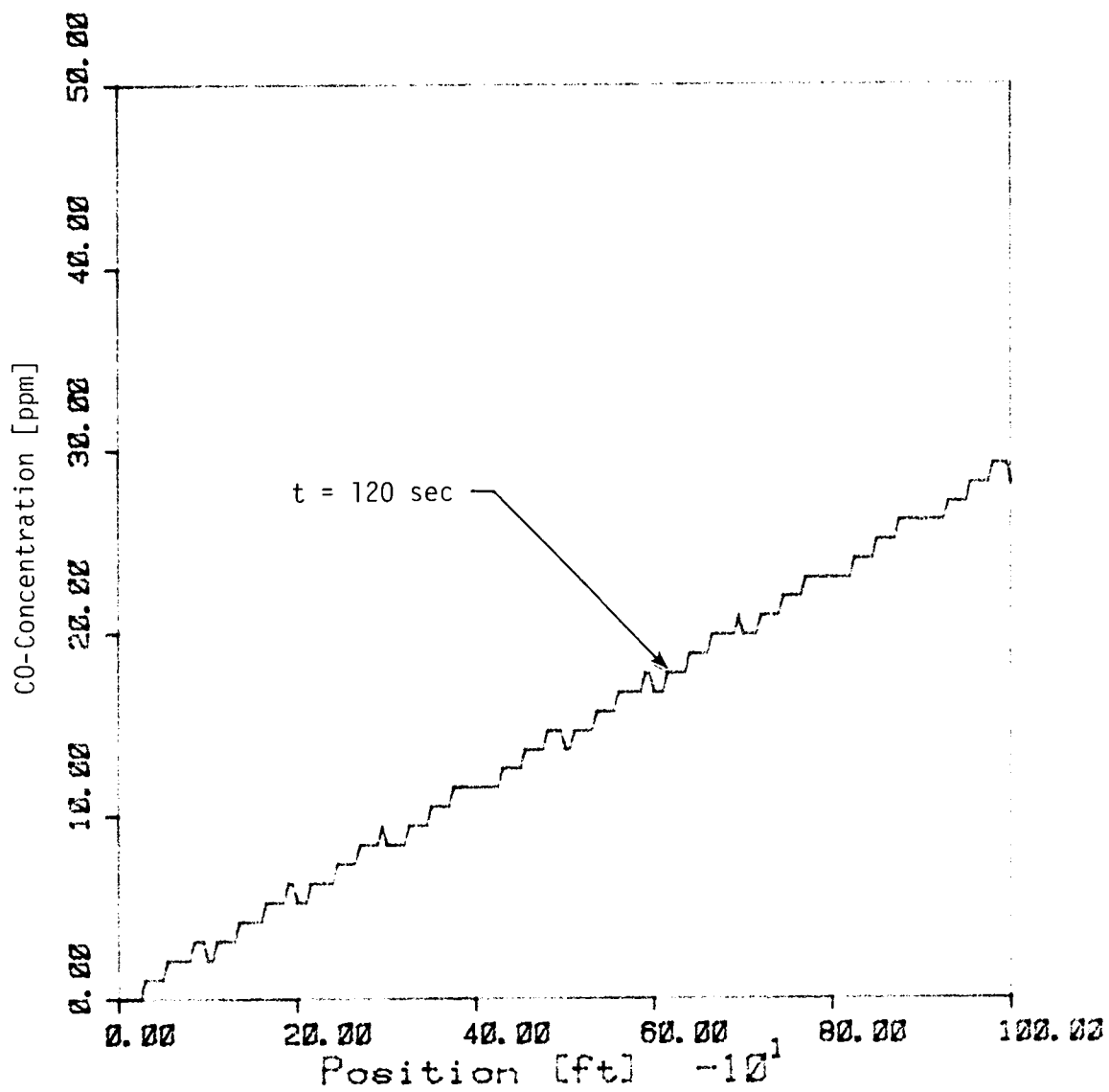


Figure 4-5. Steady state solution of CO-concentration distribution.

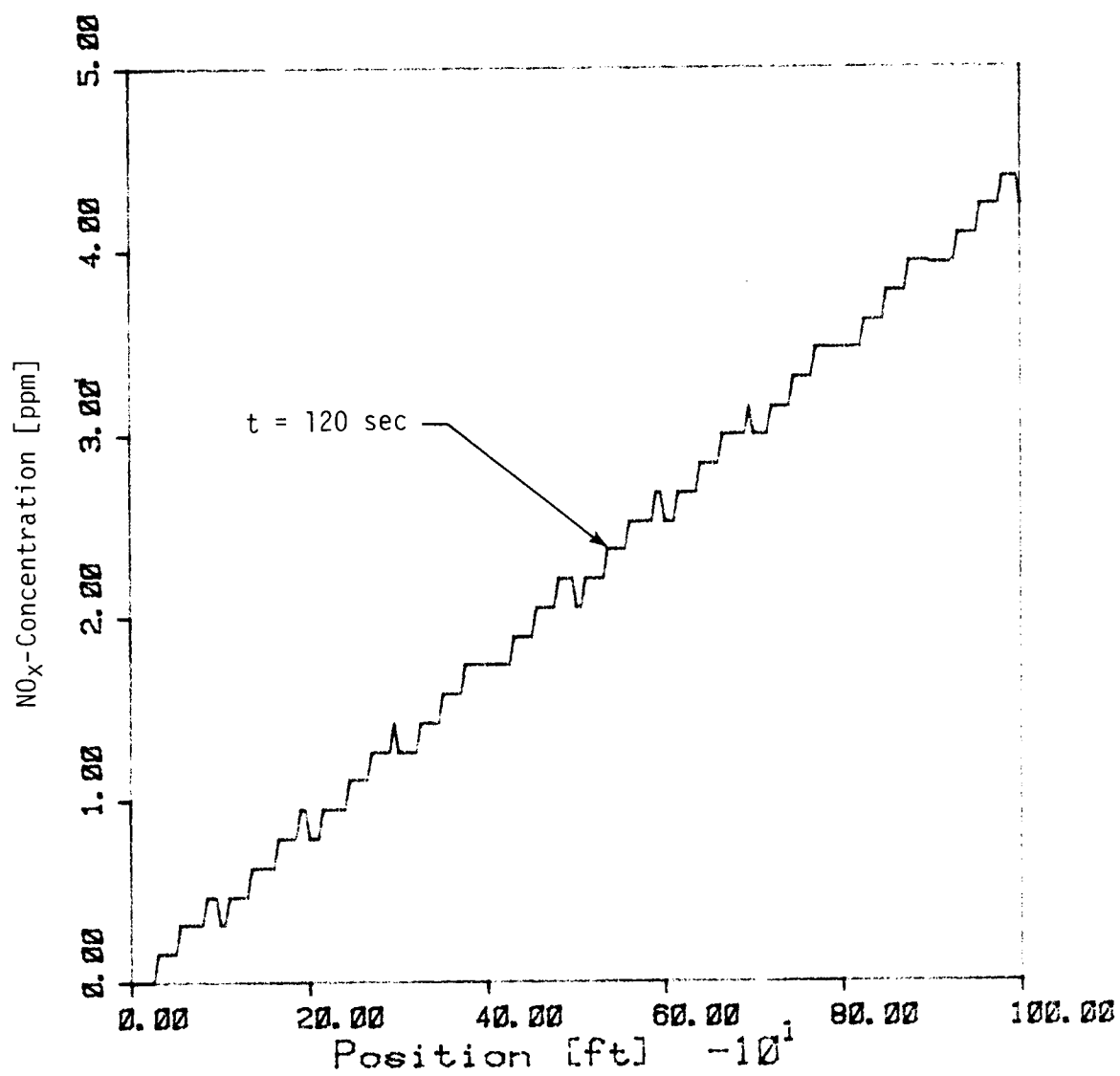


Figure 4-6. Steady state solution of NO_x concentration distribution.

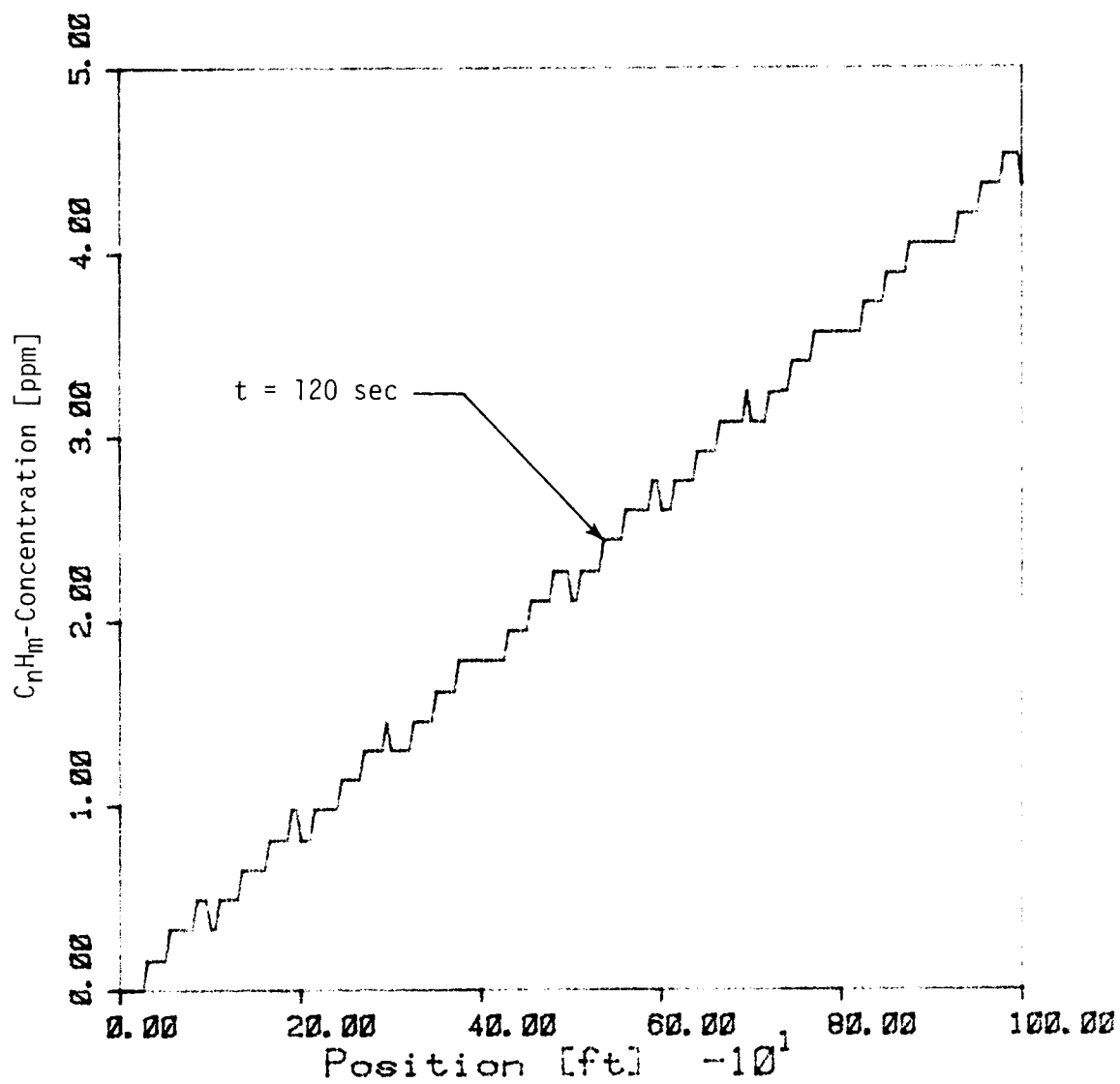


Figure 4-7. Steady state solution of C_nH_m concentration distribution.

at $t = 120$ sec.

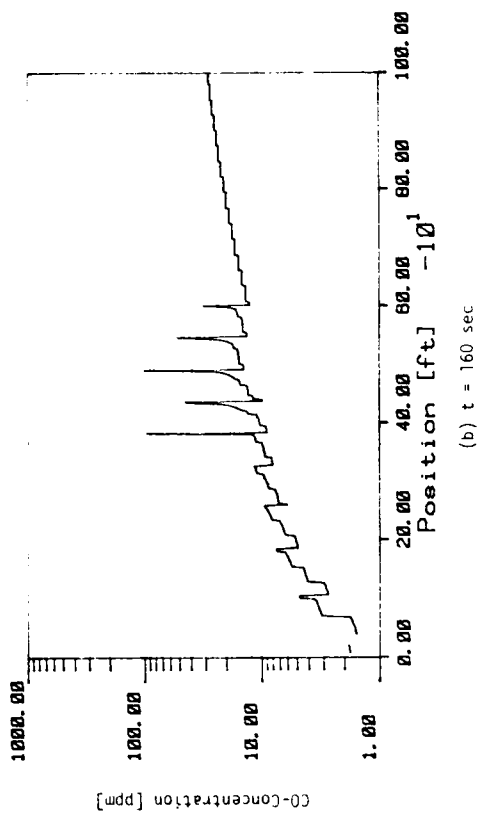
At $t = 150$ sec, an accident may be assumed to occur at the middle of the tunnel. Traffic begins to stall and the induced velocity decays. Figures 4-8, 4-9, and 4-10 illustrate the transient behavior of the pollutant distribution along the tunnel as the stall intensifies.

Interesting spikes are observed to occur in the concentration distribution. The intensity of these spikes is partly due to the numerical modeling technique but physically their occurrence is very real. To explain this effect, consider the equation governing the transient pollutant distributions, i.e., Equation 3-11. The term

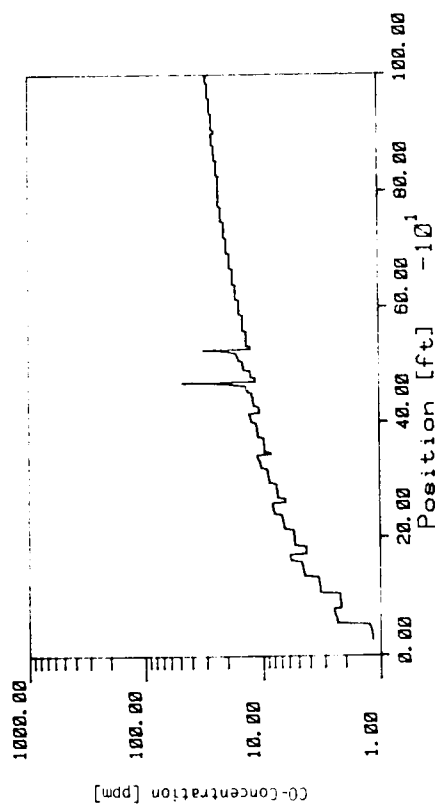
$$F_n(x + P_n - \int_0^t V dt) = \frac{1}{U_n(\tau) - V(\tau)}$$

in this equation where τ is found from iterating Equation 3-12. F_n is the inverse of the relative speed between the vehicle and the induced airflow. This term controls the source or rate of pollutant output. If the vehicle speed approaches the induced airspeed, F_n approaches infinity and a spike appears in the concentration at that point. Physically, if the relative speed between vehicle and induced air become small the concentration of pollutant in the air surrounding the vehicle become very large. Note, however, that turbulent diffusion will tend to reduce the intensity of the spike. Since turbulent mixing is not considered in the results discussed in this section, the spikes in the computed concentration distributions are larger than would be physically expected.

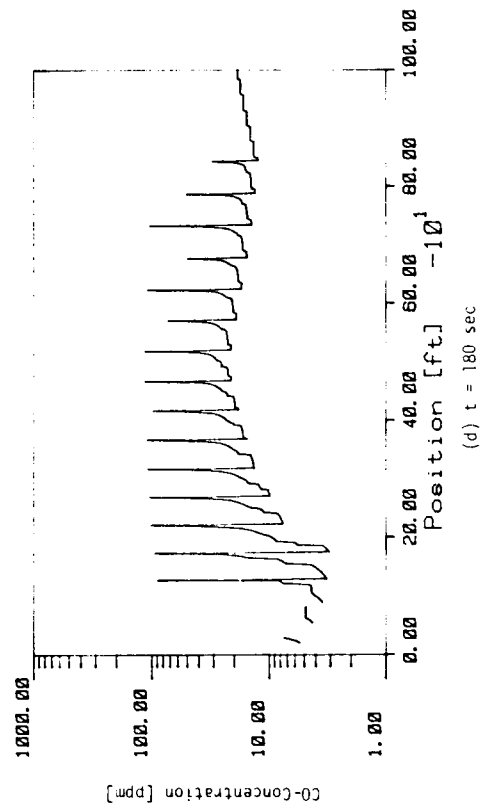
The spikes occur when the vehicles decelerate from 60 ft/sec to 0 at a faster rate than the induced flow velocity decays. Hence, a



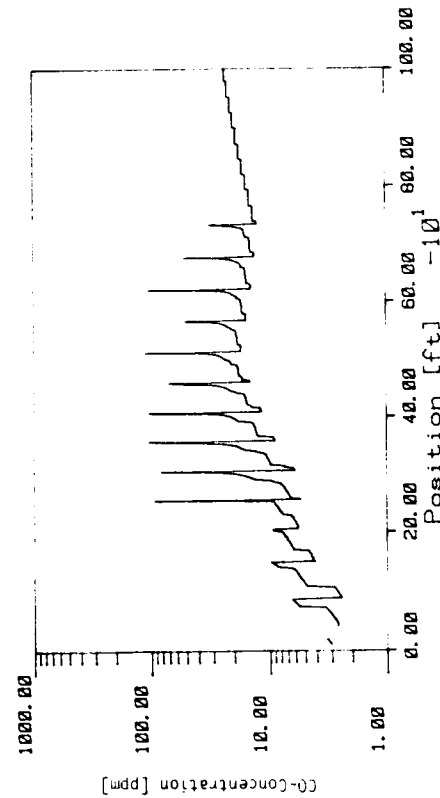
(a) $t = 155 \text{ sec}$



(b) $t = 160 \text{ sec}$



(c) $t = 170 \text{ sec}$



(d) $t = 180 \text{ sec}$

Figure 4-8. CO-concentration distribution without diffusion effect after traffic stalls at $t = 150 \text{ seconds}$.

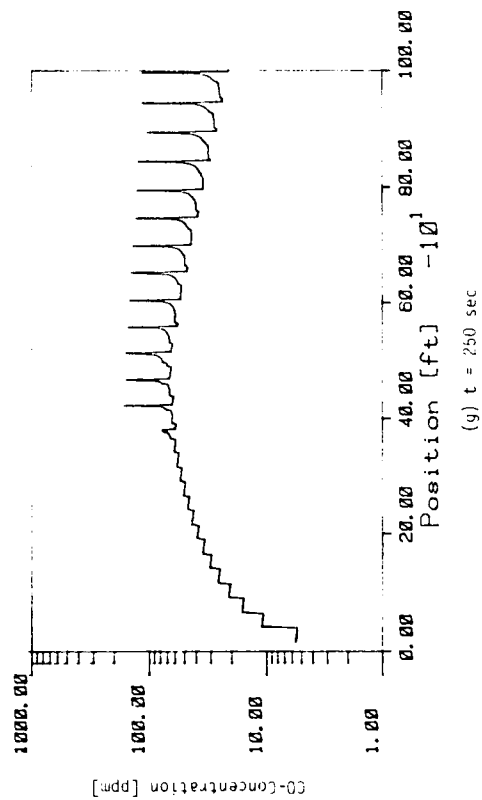
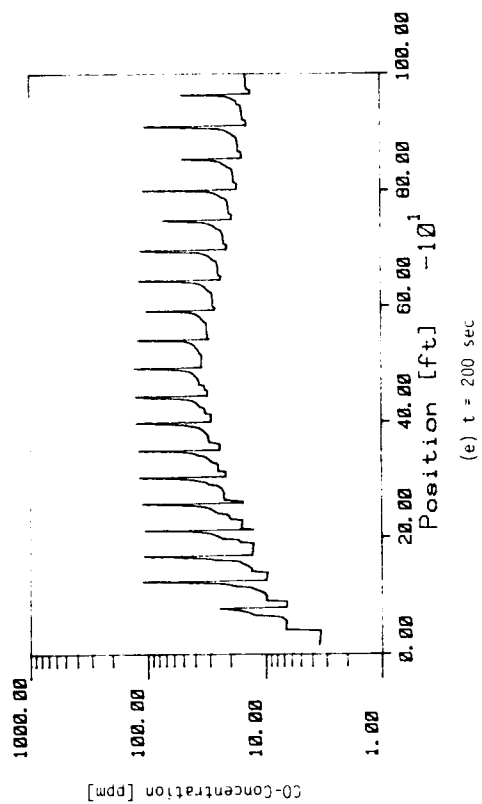
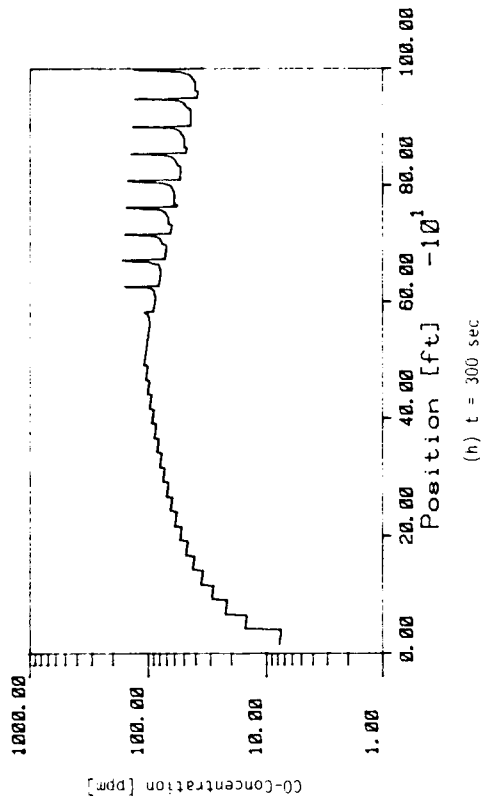
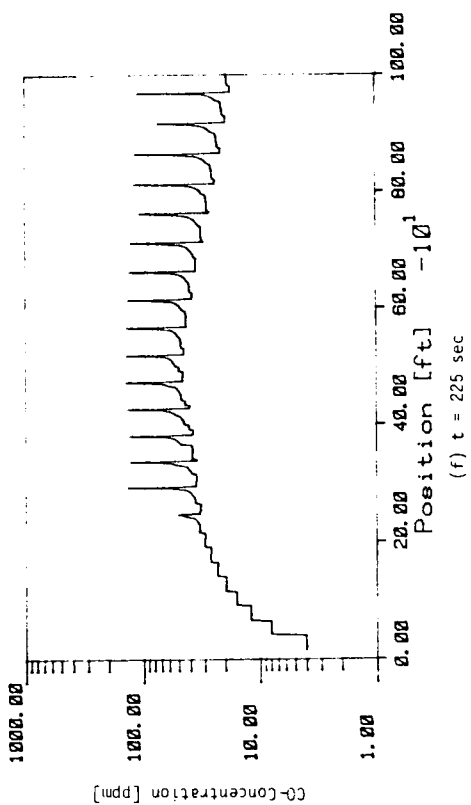


Figure 4-8. (Continued)

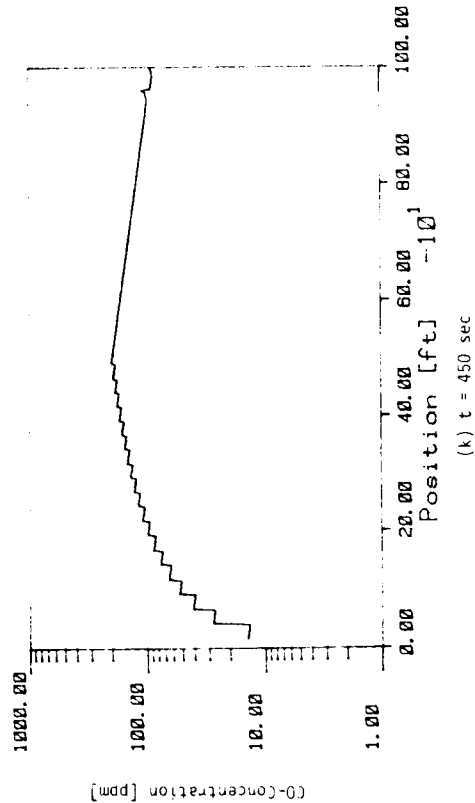
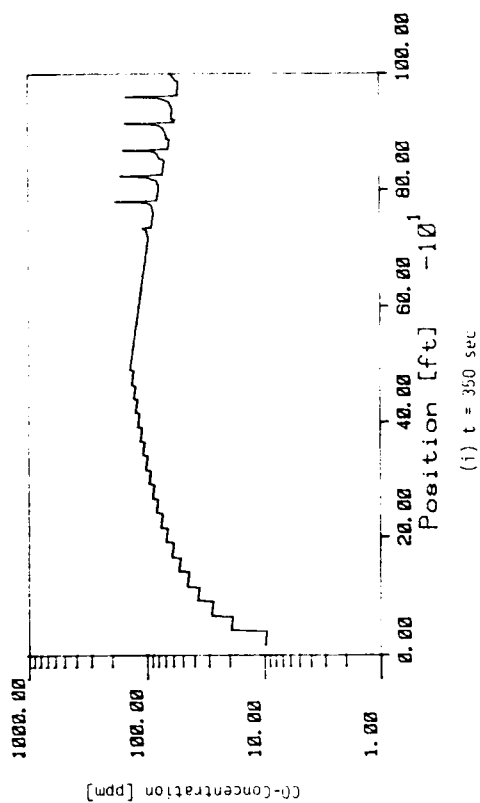
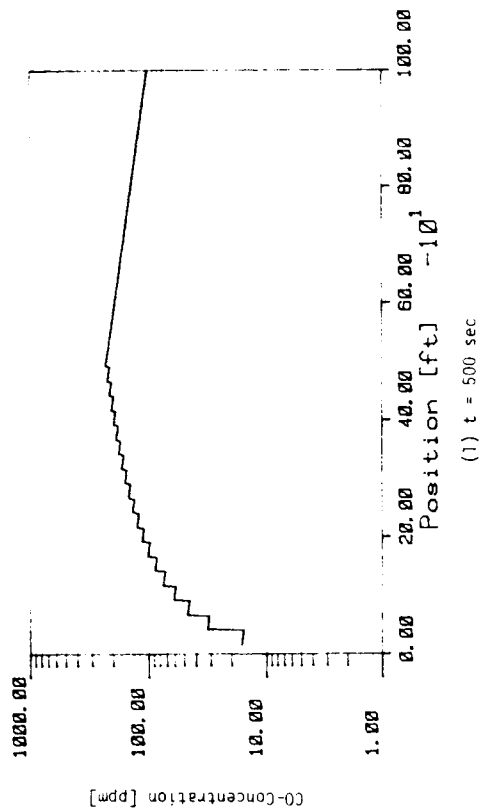
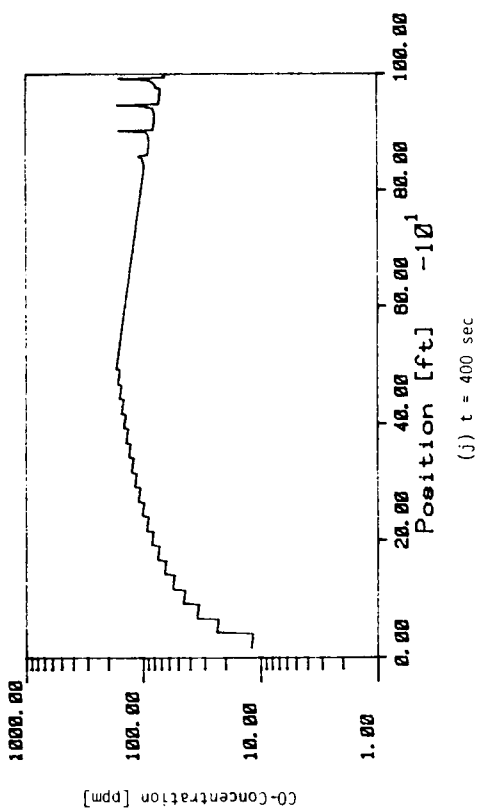


Figure 4-8. (Continued)

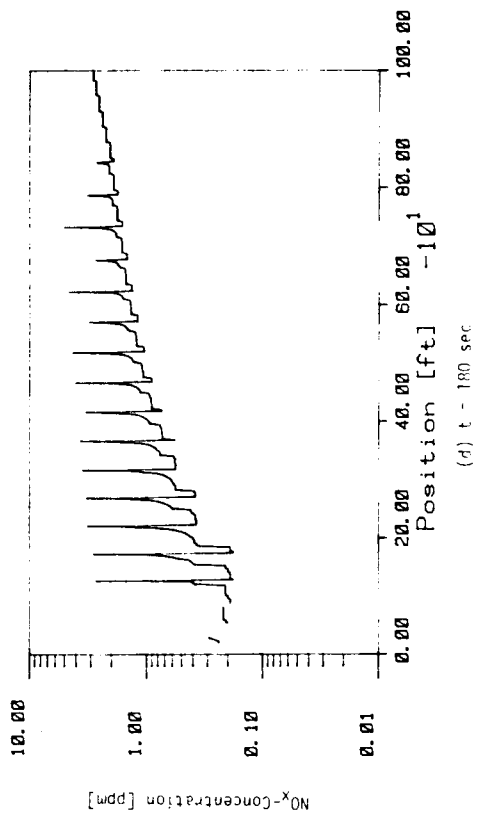
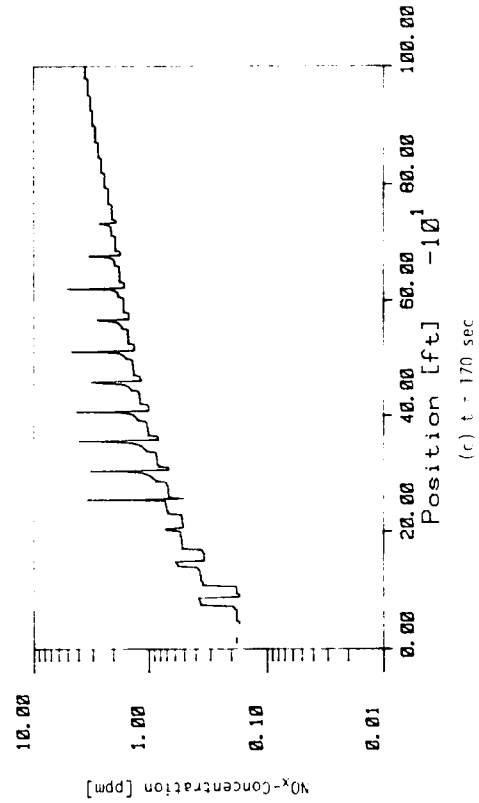
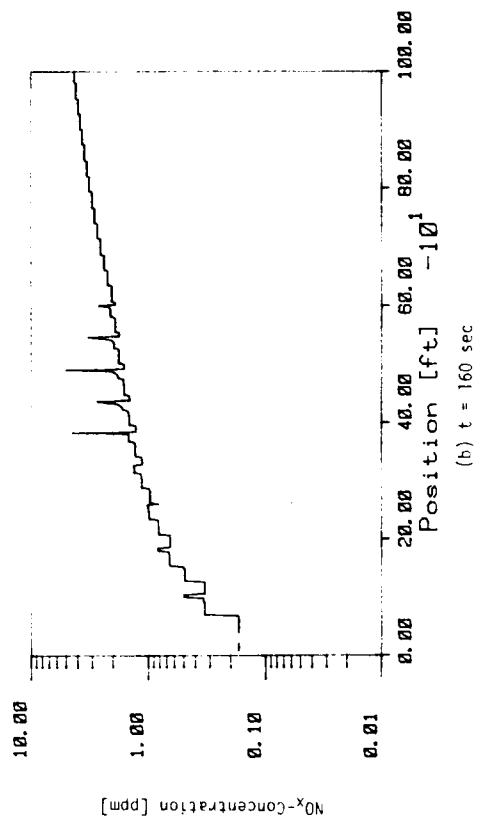
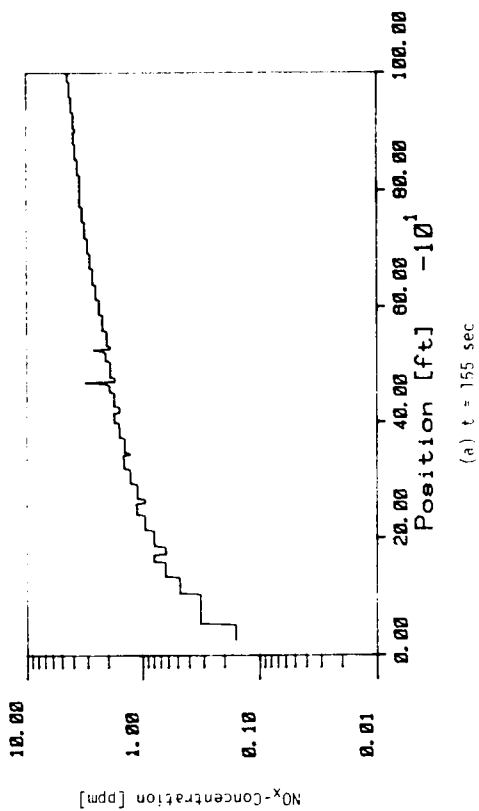


Figure 4-9. NO_x -concentration distribution without diffusion effect after traffic stall at $t = 150$ seconds.

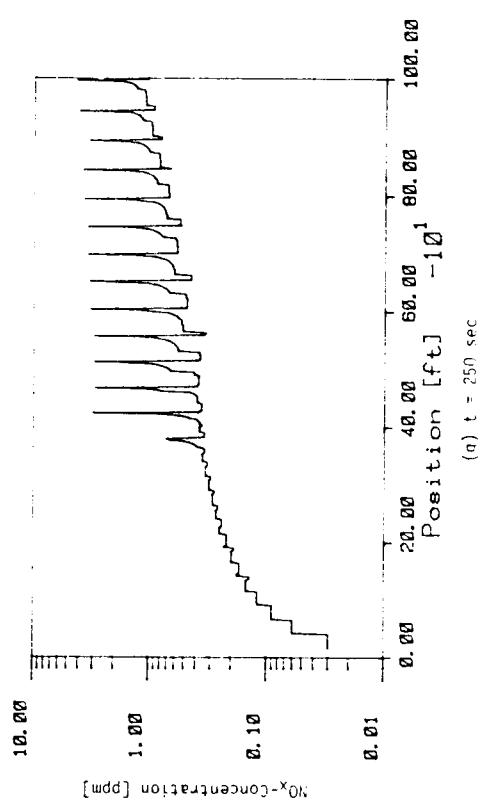
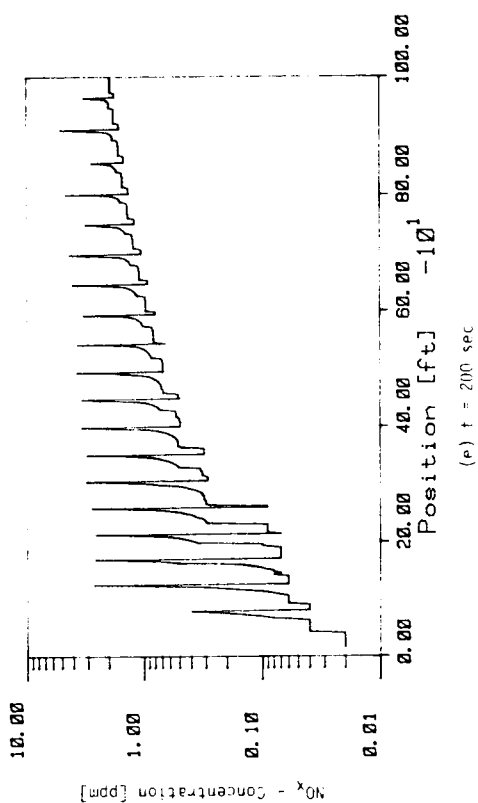
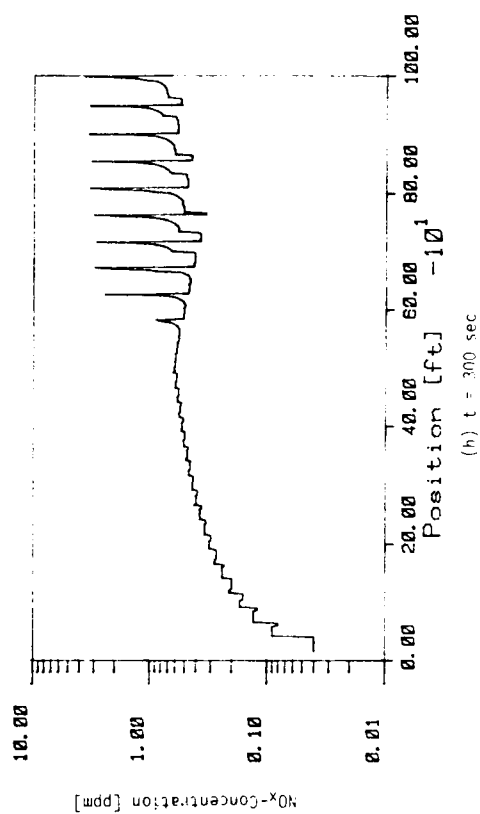
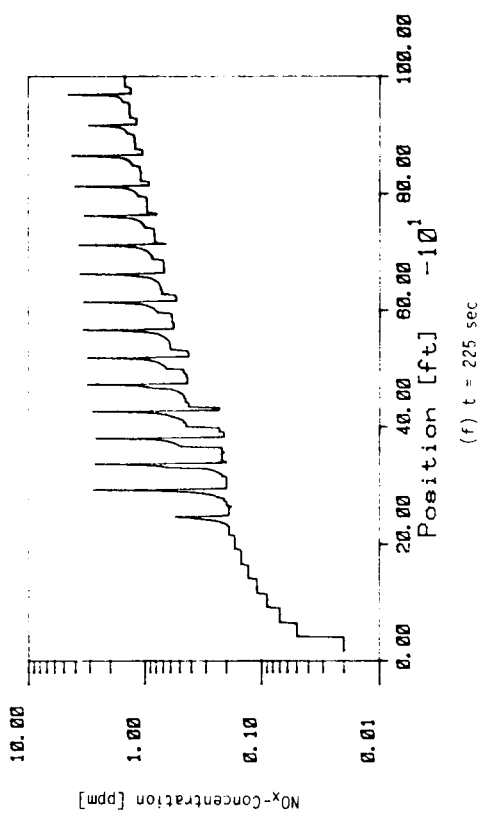


Figure 4-9. (Continued)

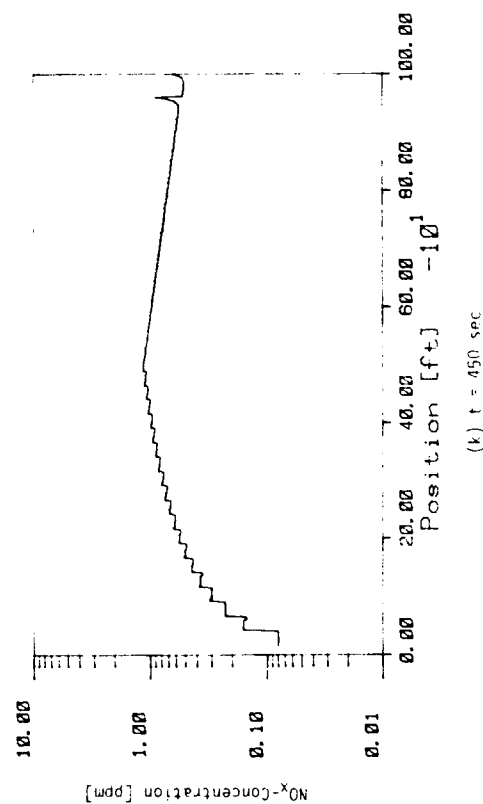
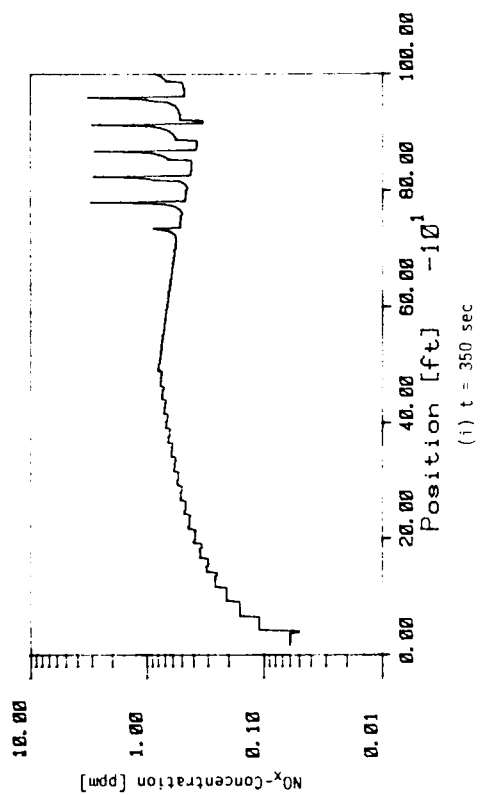
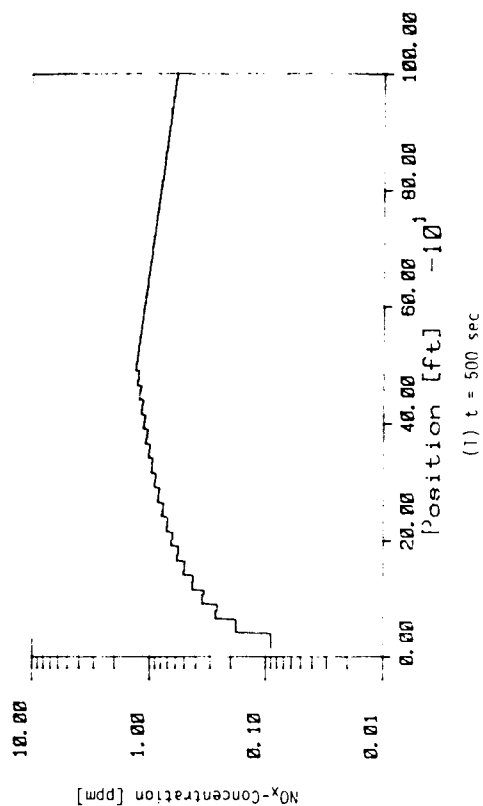
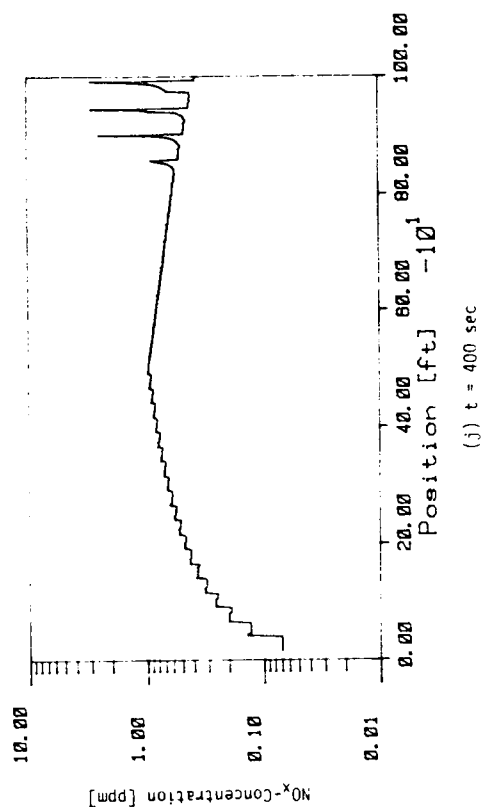


Figure 4-9. (Continued)

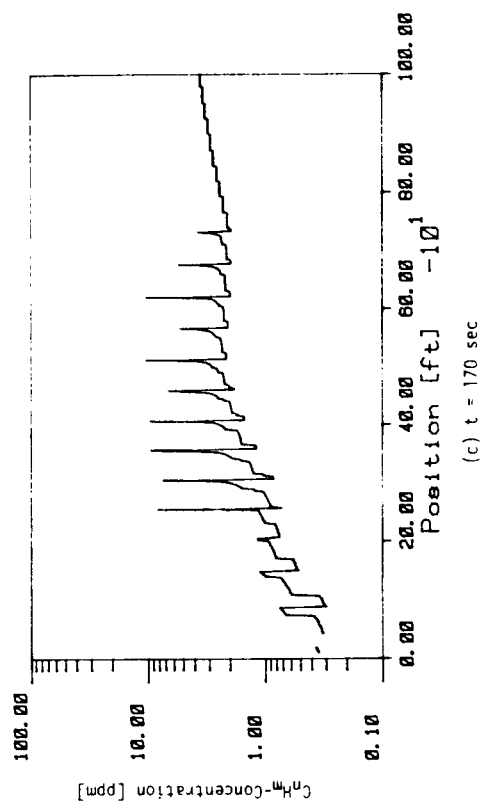
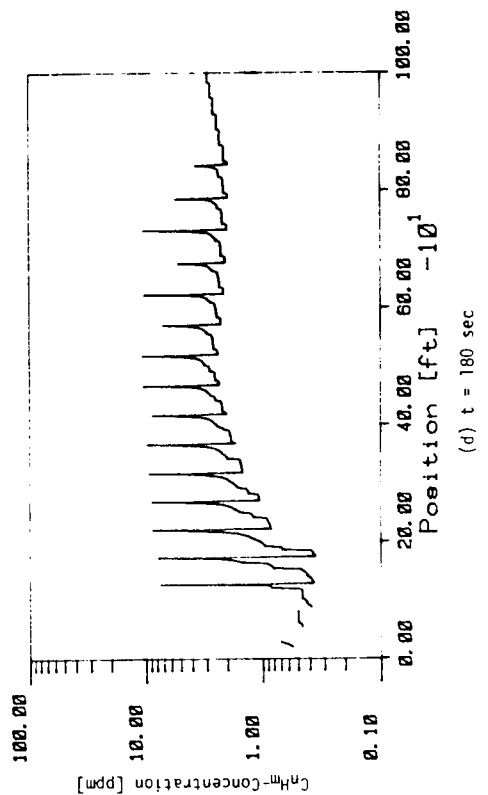
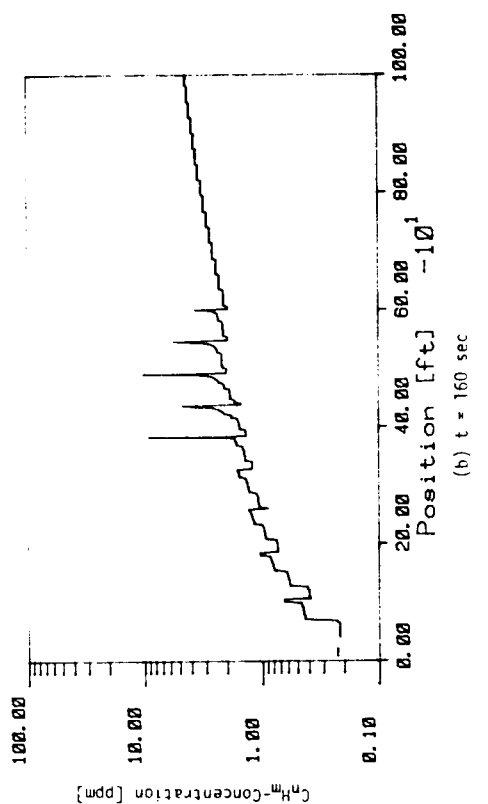


Figure 4-10. C_{nHm} -concentration distribution without diffusion effect after traffic stall at $t = 150 \text{ seconds}$.

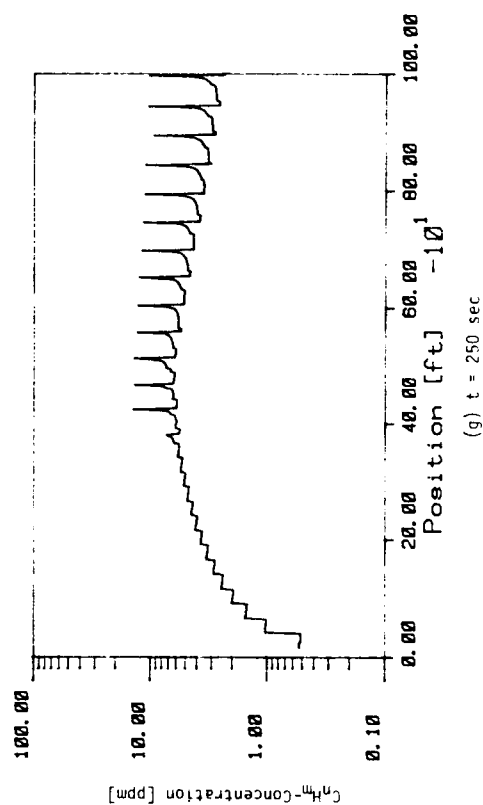
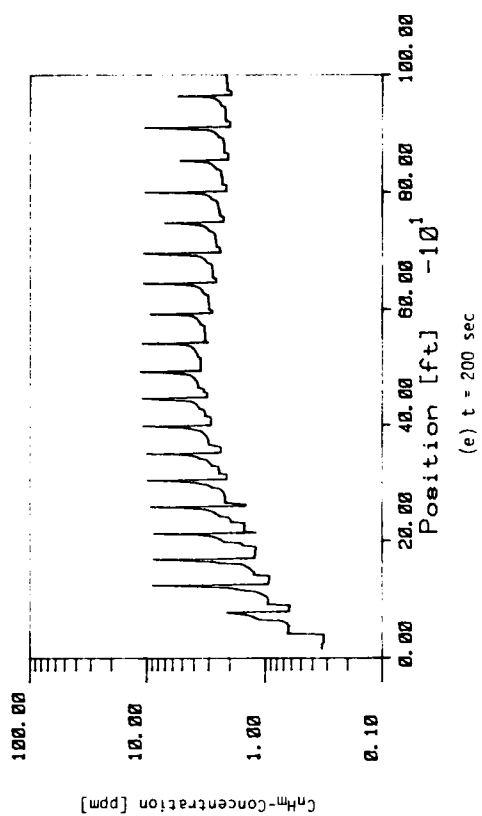
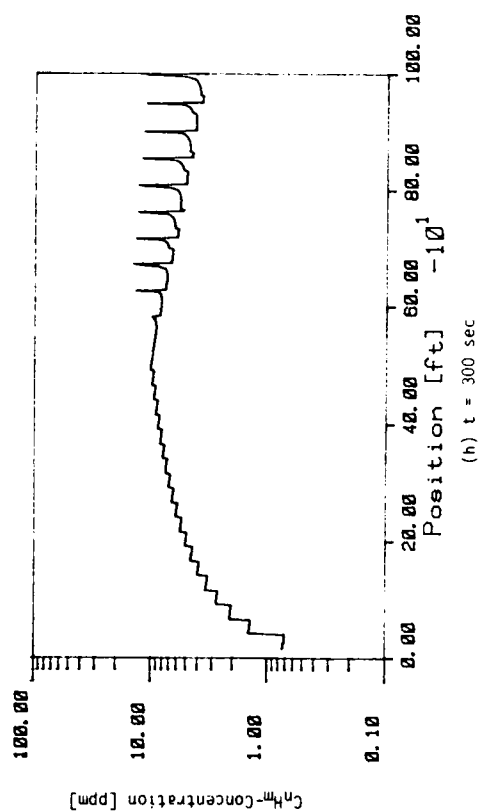
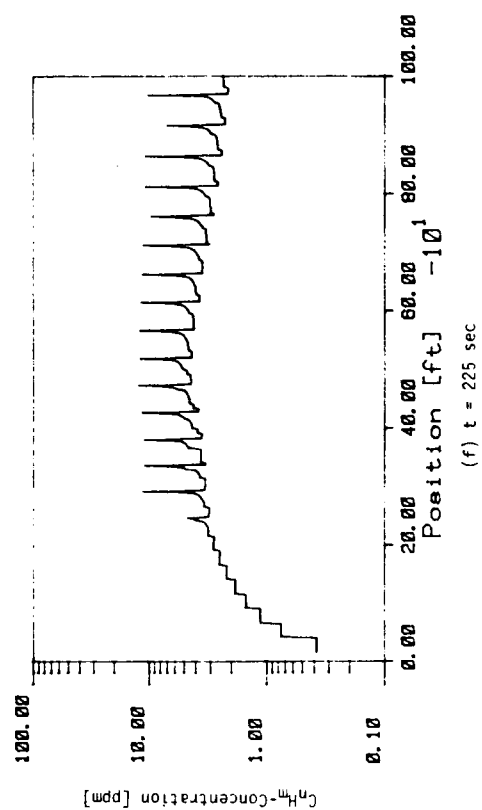


Figure 4-10. (Continued)

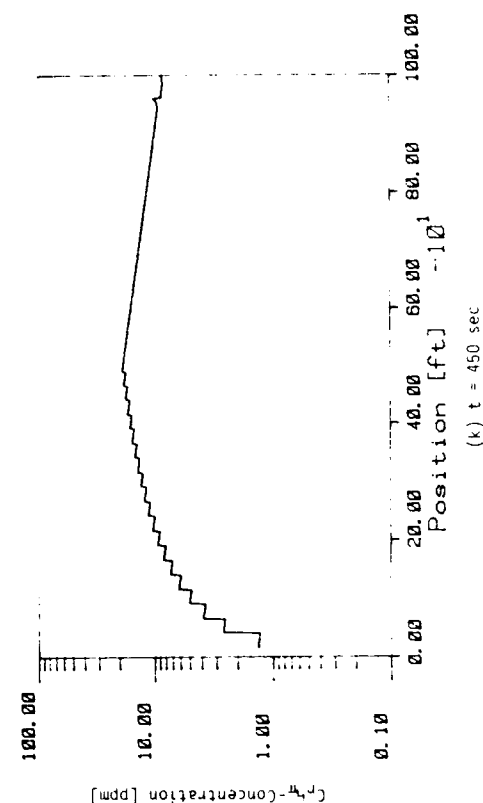
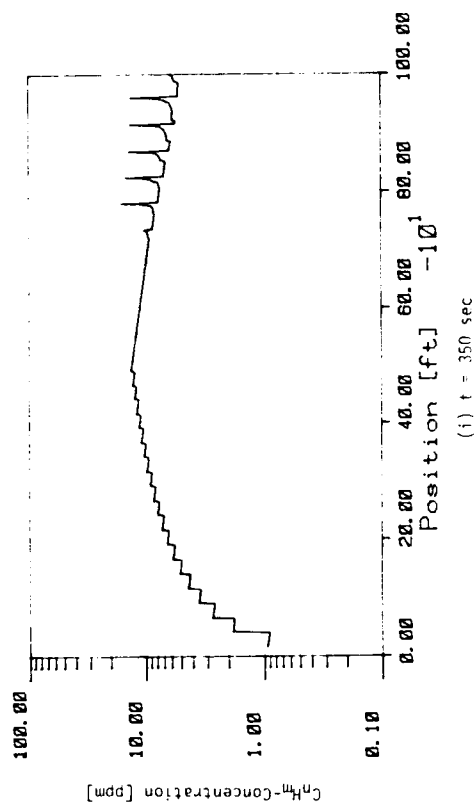
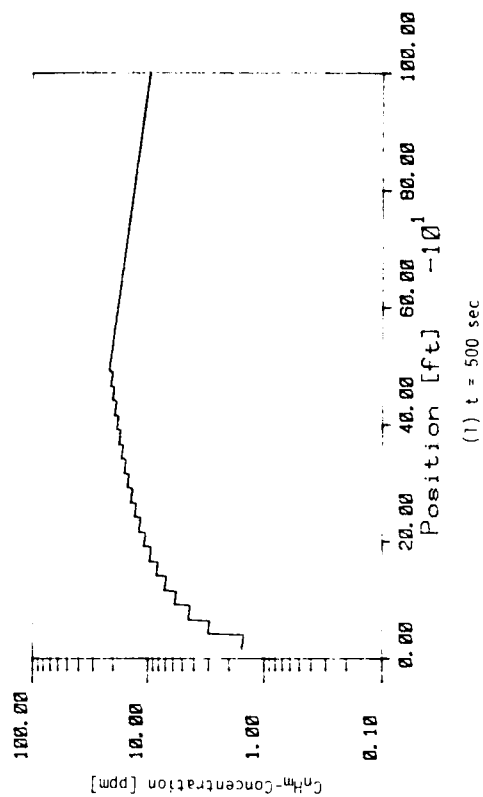
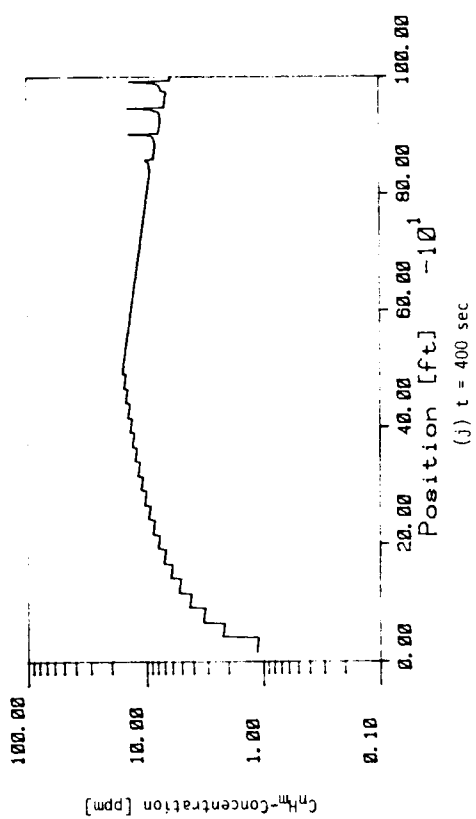


Figure 4-10. (Continued)

dramatically high concentration occurs for each vehicle when the value of the vehicle speed passes through the value of the induced airspeed.

Figure 3-8(a), where $t = 155$, represents the CO concentration distribution at 5 seconds after stall (the time of stall is 150 seconds). Two spikes appear in this figure, which indicates that two vehicles have either decelerated below the induced velocity or have stopped altogether. In Figure 4-8(b) where $t = 160$, more spikes appear, indicating that more vehicles have slowed below the speed of the induced air velocity. Figures 4-8(a) through (l) from $t = 155$ sec to $t = 500$ sec show CO concentration distributions without diffusion effects taken into account. These figures clearly show many spikes being generated and embedded in the air moving through the tunnel. Since there are no diffusion effects considered in the results presented, the spikes retain their shape and, owing to the induced airflow, the spikes are carried downstream and finally exit the tunnel.

In the distribution following the spikes, steps in the concentration distribution occur at each stalled vehicle. These steps occur because of the discrete numerical method of computing the pollutant concentration distributions i.e., the length of the tunnel is divided into Δx increments for numerical solution. This step size has a more profound effect on the solutions when traffic stalls. However, the influence of the step size is minimized when $\Delta x < L/S$ (i.e., tunnel length divided by vehicle spacing) for steady state condition or for a steady stream of vehicles passing through a tunnel of undisturbed air.

The step size, of course, strongly influences the magnitude of the spike in concentration which occurs during deceleration. As

discussed before, the concentration is theoretically infinite when the vehicle speed during deceleration equals the value of the induced velocity. This occurs due to the term $F_n = \frac{1}{U_n(\tau) - V(\tau)}$ in Equation 3-11. If the step size is too small, the computational scheme "blows up"; if the step size is not small enough, the magnitude of the spike is inaccurately predicted. Based on the conservation of mass of pollutants it is estimated that when the step size is chosen as $\Delta x = 2$ ft, the minimum difference of U_k and V in Equation 3-11 is less than ± 0.5 , i.e., $|U_k - V| \leq 0.5$.

Inspecting Figure 4-8(1), page 70, a smooth curve is observed in the tunnel section downstream of the stalled vehicles. The pollutant concentration in this part results from the exhaust gases emitted by the vehicles upstream being transported downstream by the remnants of the induced velocity which requires considerable time to decay to zero. Under stalled conditions, the number of vehicles in the tunnel is constant, i.e., $N = 20$ in this example. Since $U_n = 0$, thus q_n is constant in Equation 3-11, and therefore, the magnitude of $\gamma(x,t)$ is a function F_n only. $F_n = \frac{1}{U(\tau) - V(\tau)}$, since $U(\tau) = 0$ at complete stall, $F_n = -\frac{1}{V(\tau)}$. The value of $V(\tau)$ decreases exponentially after the traffic stall occurs. In the semi-logarithm coordinate, Figure 4-8(1), the curve is straight and maintains the same trend with increasing time.

Physically, this implies that the concentration which is increasing in the upstream section due to the exhaust from the stalled vehicles drifts downstream with the slowly decaying induced velocity. The concentration continues to rise in both sections, however; if the stall lasts for a very long period, a discontinuity in the

concentration profile would grow at the position in the tunnel where the first stalled vehicle is located. That is, without any induced flow, the concentration in the section containing the stalled vehicles would increase from the exhaust emission; but in the section without vehicles, it would simply remain stagnant. At the low induced velocity, diffusion would of course smooth out the concentrations. An approximate correction for diffusion is discussed subsequently.

Figures 4-9 and 4-10, pages 73 through 78, show nearly identical results for NO_x and C_nH_m (hydrocarbon) respectively. At a time of $t = 500$ seconds, the traffic begins to move once more. The induced airflow builds up again as shown in Figure 4-1, page 62. The high concentrations of pollutants which have accumulated from the congested traffic, with no airflow in the tunnel are now once again diluted by the induced airflow drawing in fresh air. Vehicles begin to leave the tunnel and the vehicle emission rate decreases with increasing traffic speed, at least for CO_2 and C_nH_m (NO_x is discussed later). This effect coupled with the induced airflow drawing pollutant out of the tunnel results in the concentration levels decreasing. The pollutant concentration thus, after several seconds returns to steady state conditions. Figures 4-11, 4-12, and 4-13 show the CO , NO_x , and C_nH_m concentration distributions, respectively. These figures illustrate that only 100 seconds (from 500 to 600 seconds) are required to dilute the high concentration which occurs during stall.

The general characteristics of the curves shown in Figure 4-11 can be described as follows. Comparing Figures 4-11(a) and (c), the high concentrations near the entrance are diluted first (time equal to 535 seconds) as the traffic begins to move. Actually, in the case

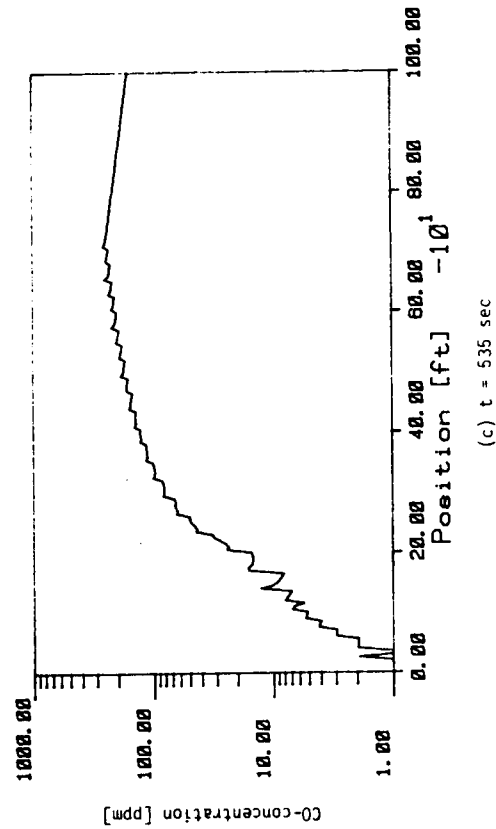
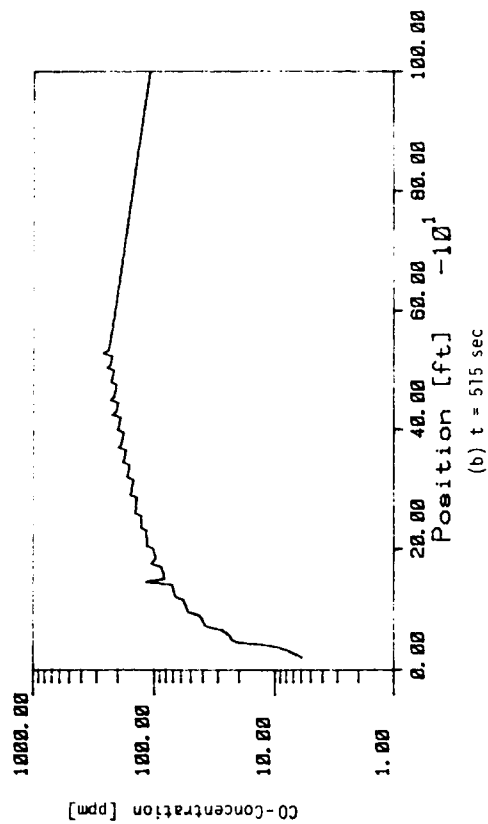
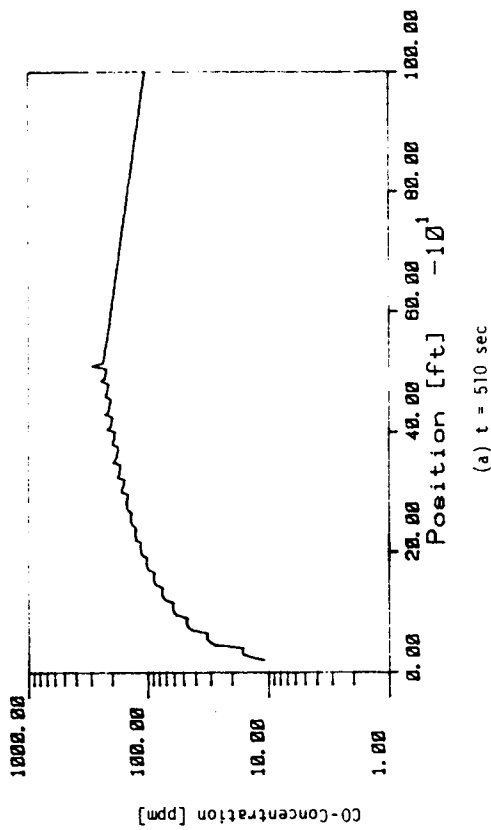


Figure 4-11. CO-concentration distribution without diffusion effect after traffic restart at $t = 500$ seconds.

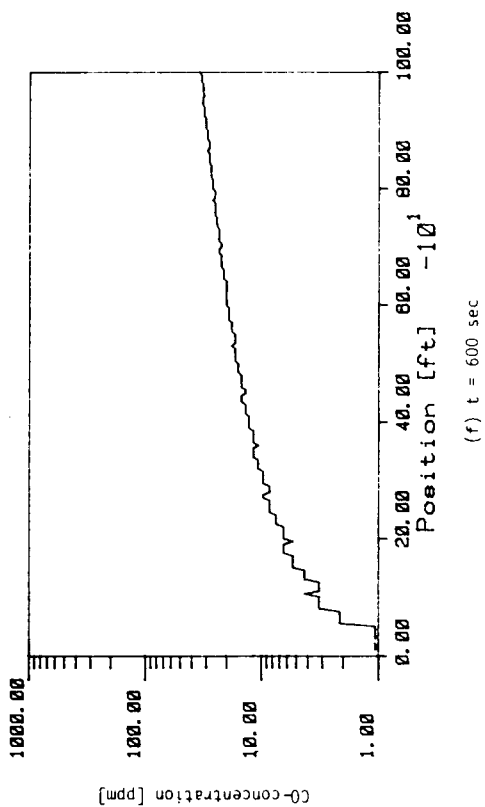
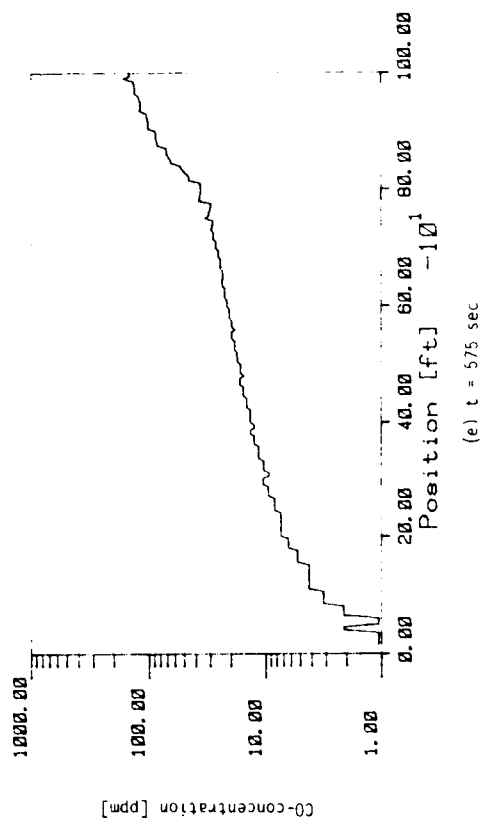
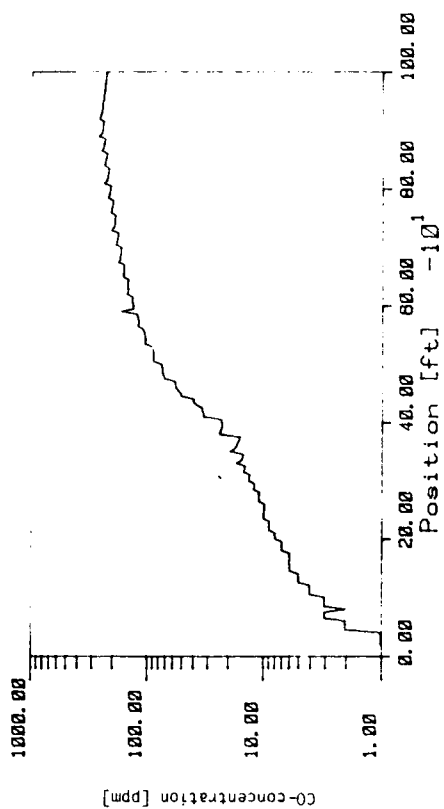


Figure 4-11. (Continued)

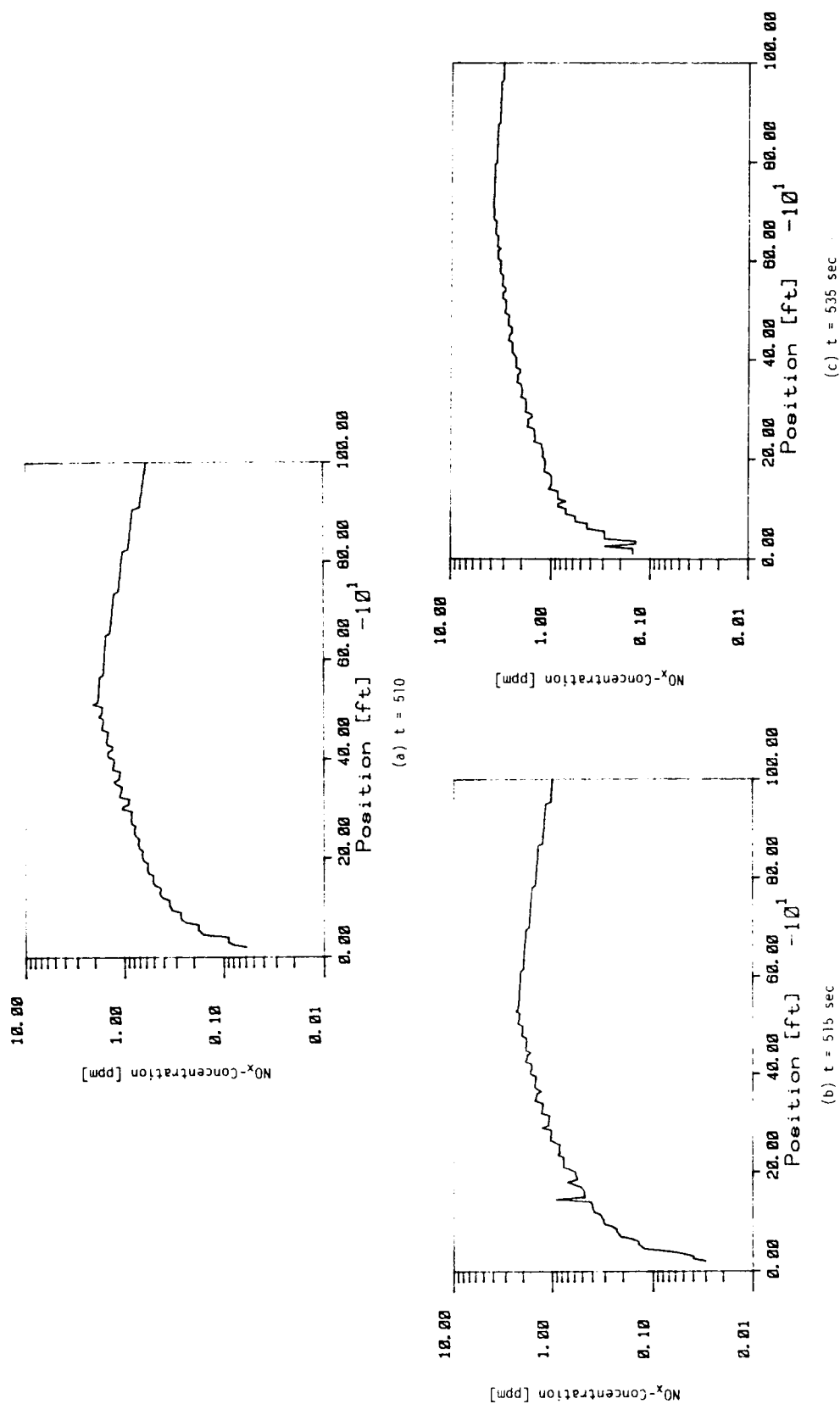
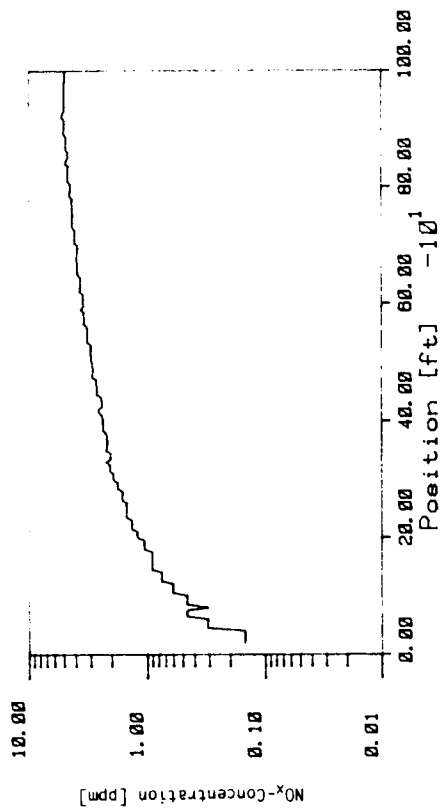
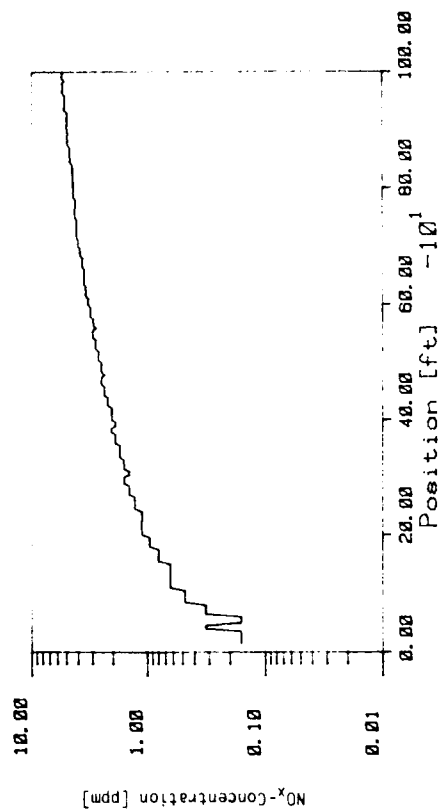


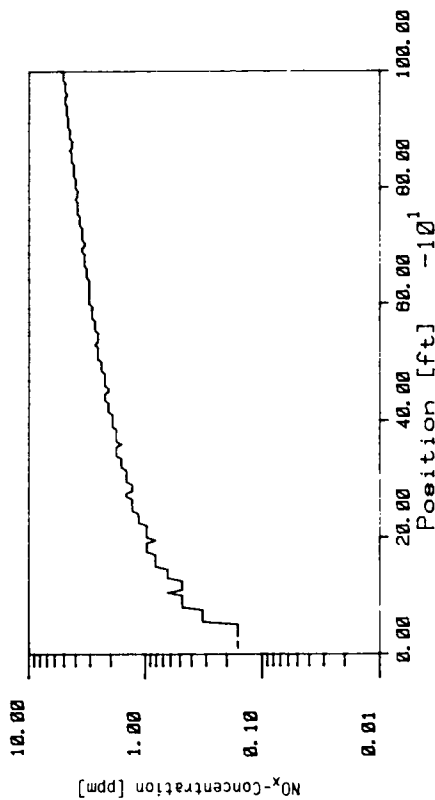
Figure 4-12. NO_x -concentration distribution without diffusion effect after traffic restart at $t = 500$ seconds.



(d) $t = 550$ sec



(e) $t = 575$ sec



(f) $t = 600$ sec

Figure 4-12. (Continued)

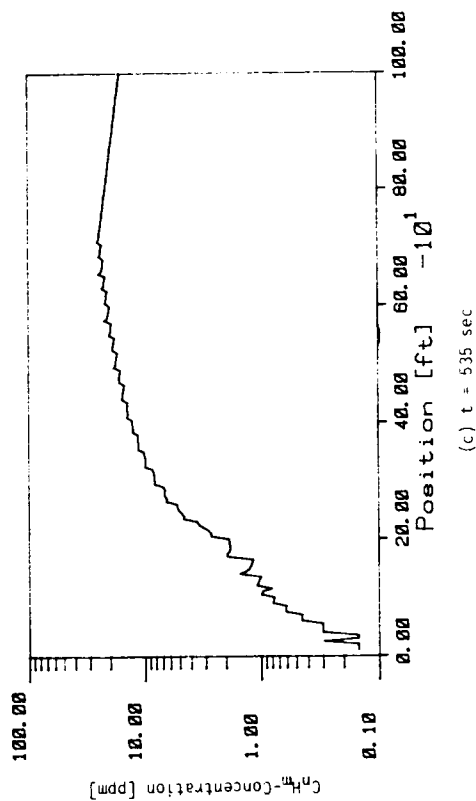
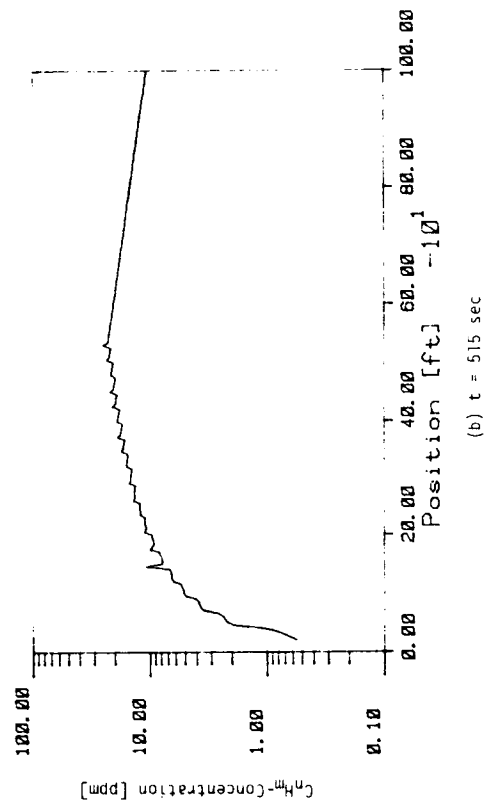
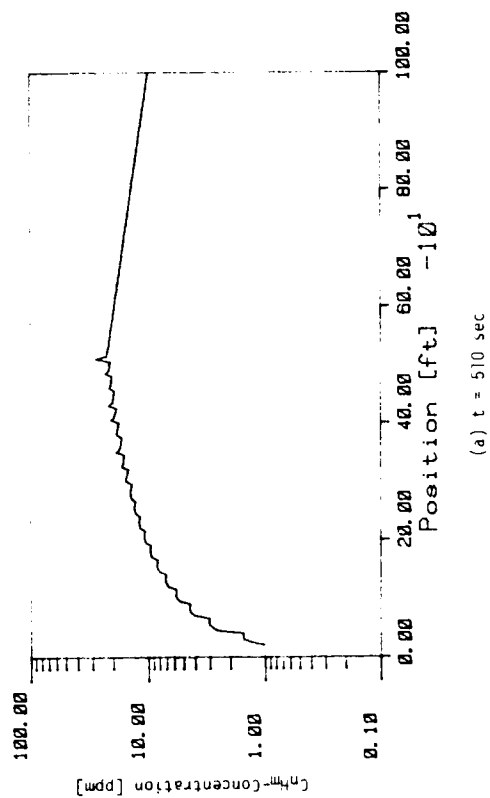


Figure 4-13. C_{nHm} -Concentration distribution without diffusion effect after traffic restart at $t = 500 \text{ seconds}$.

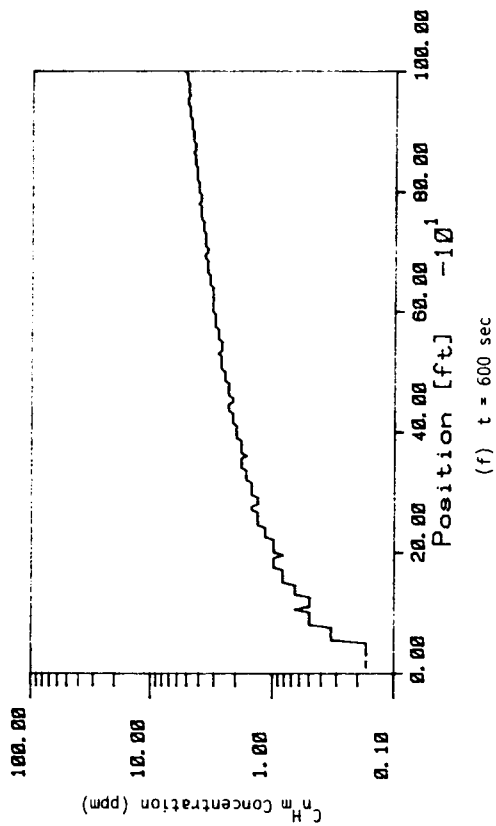
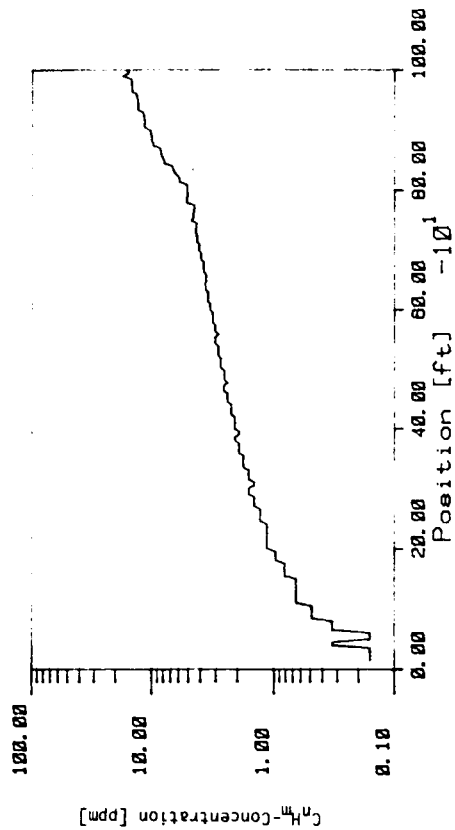
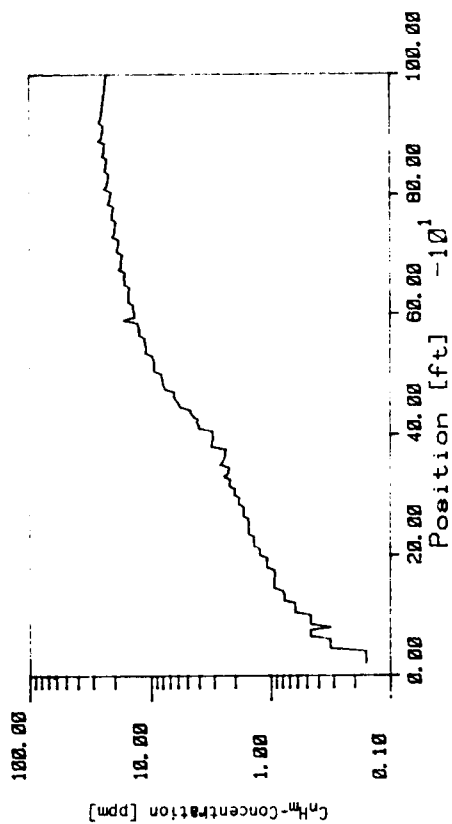


Figure 4-13. (Continued)

studied, the traffic pattern has become uniform by time $t = 535$ sec. Although the induced air velocity at $t = 535$ sec ($V = 12$ fps), has not yet reached steady state, see Figure 4-1, page 62, the maximum value of CO concentration has moved from $x = 510$ ft (at $t = 510$ sec) to $x = 710$ ft (at $t = 535$ sec) due to the limited build up flow. As the induced velocity increases toward its steady state value, the high concentrations of pollutants which accumulated during congested conditions move downstream finally exiting the tunnel at approximately $t = 550$ sec (see Figures 4-11(b) through (d)).

The $C_n H_m$ concentration distributions in Figure 4-13 behave very much like the CO concentration distribution. The NO_x distribution shown in Figure 4-12, on the other hand, is different from either the CO or $C_n H_m$ concentrations. This difference is due to the fact that the exhaust rates of CO and $C_n H_m$ decrease with increasing vehicle velocity, Figures 3-5 and 3-7, pages 54 and 56, whereas the exhaust rate of NO_x increases or remains constant with vehicle speed, Figure 3-6, page 55. The exhaust rate of NO_x , Gram/Veh-Hour = [Gram/Veh-Mile] $\times$ [Mile/Hour] is proportional to vehicle speed. Thus, when the traffic slows due to congestion the NO_x concentration does not increase as drastically as that of CO and $C_n H_m$. On the other hand, as the traffic begins to move, the NO_x concentration increases as vehicle speed increases. Thus, the initial decrease in concentration that moves downstream observed in Figures 4-11 and 4-13 does not occur in Figure 4-12.

II. RESULTS INCLUDING TURBULENT MIXING EFFECTS

Since the flow in highway tunnels is highly turbulent, turbulent

diffusion will influence the concentration distributions, particularly at low induced velocities. An approximate correction for axial turbulent diffusion was discussed in Chapter III. The turbulent mixing processes of interest to this study will be strongly influenced by the vehicle wake which will have a typical length scale imposed by tunnel dimensions. How concentration distribution will be influenced by the interaction between the wake and exhaust of the different vehicles in the tunnel is not known. The estimated effect, based on the analytical technique described in Chapter III, is shown in Figure 4-14. Figure 4-14 compares the results before smoothing and after smoothing. In this case $t = 200$ sec after stall which occurred at $t = 150$ sec, the first stalled vehicle has stopped at $x = 490$ ft, and the following vehicles stop successively. The smooth or turbulent mixed concentration profile may be explained as follows. There is no vehicle at a position downstream of $x = 490$ ft, i.e., the exhaust plume sources of turbulent mixing only exist from the entrance to the position of the first stopped vehicle. The spike in concentration generated by the first stalled vehicle is just exiting the tunnel and is only mixed by the wake created by this first stalled vehicle. The last spike is also only mixed one time because it has just been generated by the last vehicle into the tunnel.

Figures 4-15, 4-16, and 4-17 show the smoothed concentration profiles of CO , NO_x , and C_nH_m , respectively, at 15 second time intervals from traffic first entering the undisturbed air in a highway tunnel to 75 seconds. The steady state solution of CO concentration is also shown in Figure 4-15. Figure 4-18 represents the CO concentration distribution for various times after stall. The maximum CO

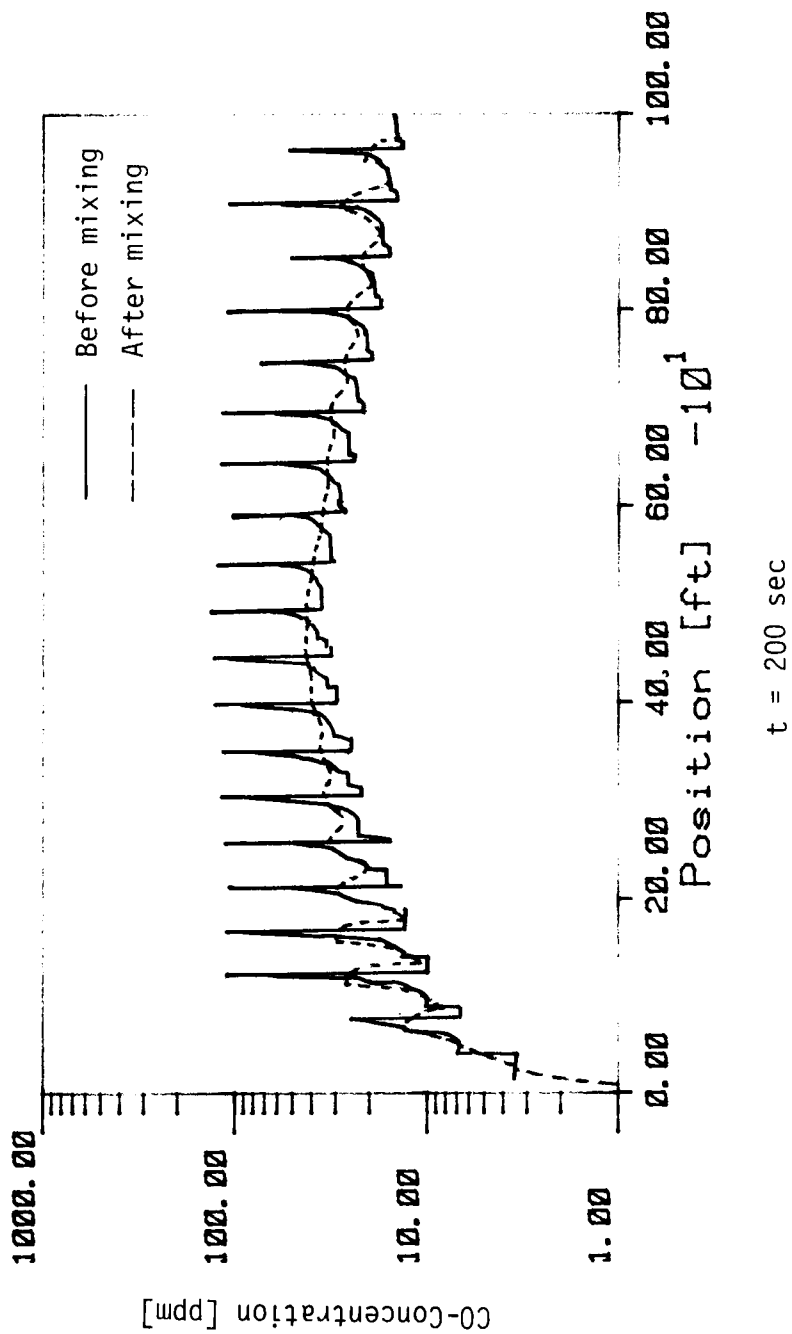


Figure 4-14. Comparison of CO-concentration distribution before mixing and after mixing based on the approximate analytical model of axial turbulent mixing (50 seconds after stall).

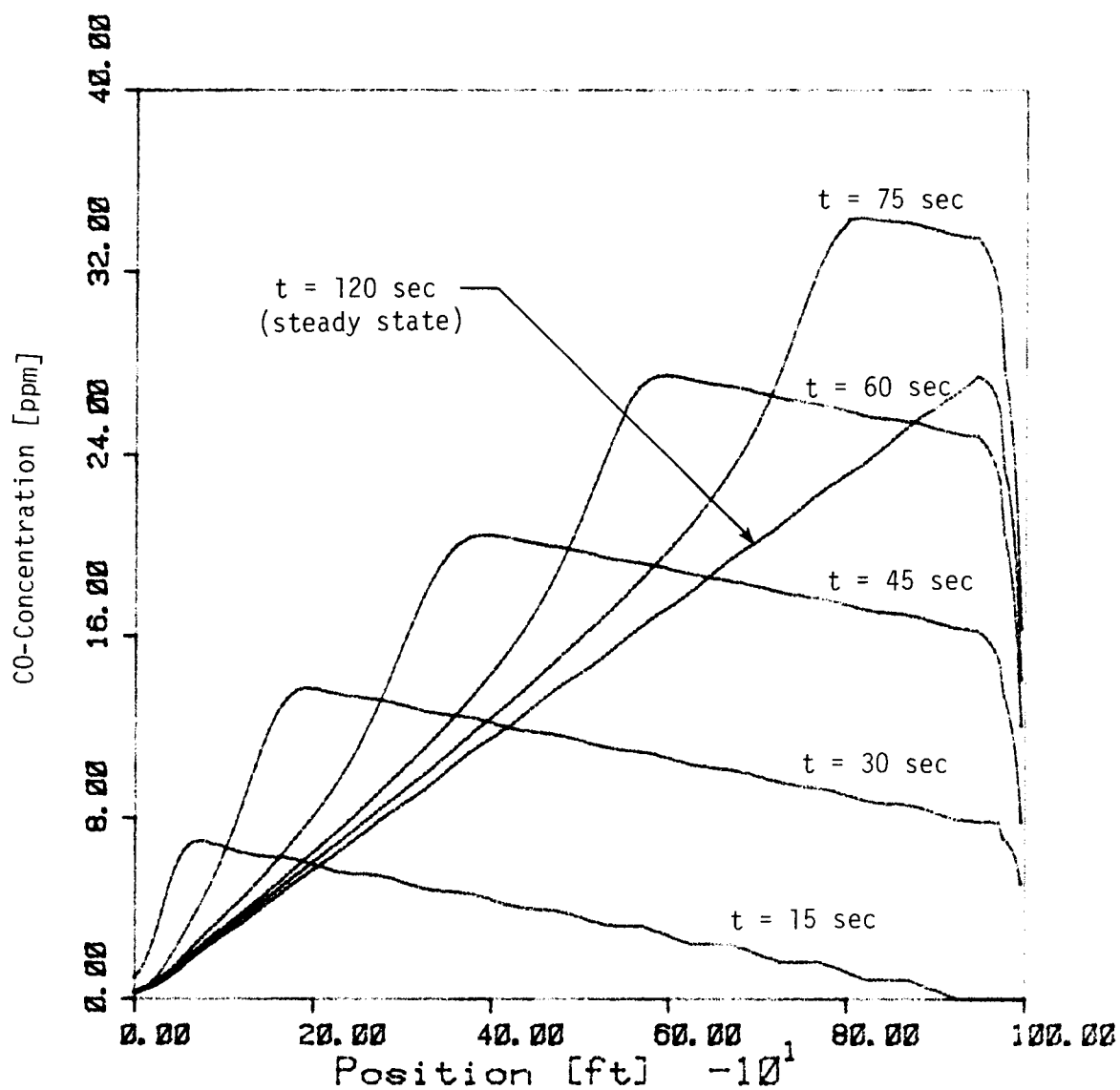


Figure 4-15. CO-concentration distribution for 15 second time interval from $t = 15$ to $t = 75$ seconds after considering turbulent mixing. (When $t = 0$ there is no vehicle in tunnel, and when $t = 120$ seconds the distribution has reached steady state, input data in Table 4-1, page 60.

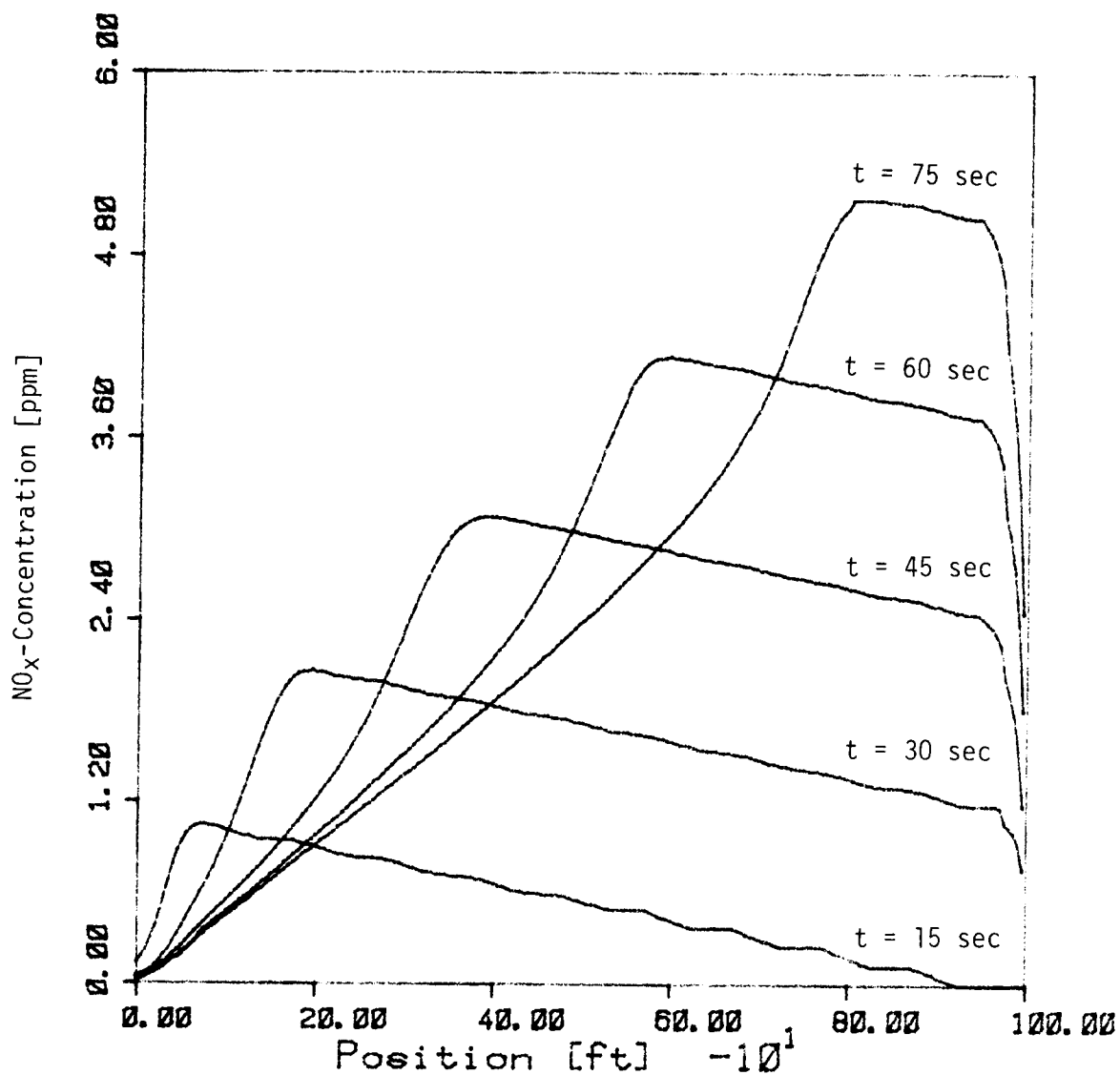


Figure 4-16. NO_x-concentration distribution for 15 second time interval from t = 15 to 75 seconds after considering turbulent mixing. (When t = 0 there is no vehicle in tunnel, input data in Table 4-1, page 60.)

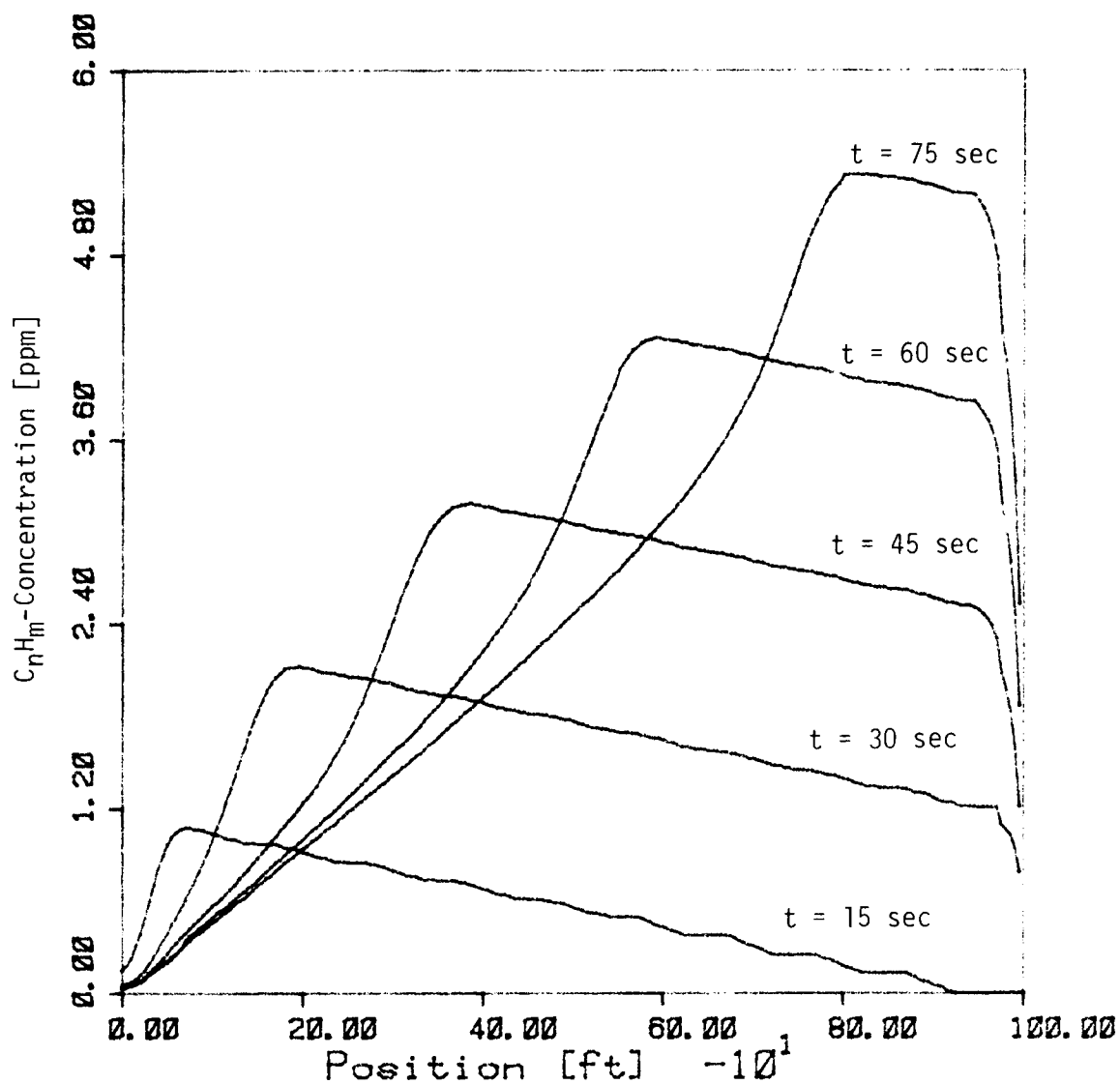


Figure 4-17. C_nH_m -concentration distribution for 15 second time interval from $t = 15$ to 75 seconds after considering turbulent mixing. (When $t = 0$ there is no vehicle in tunnel, input data in Table 4-1, page 60.)

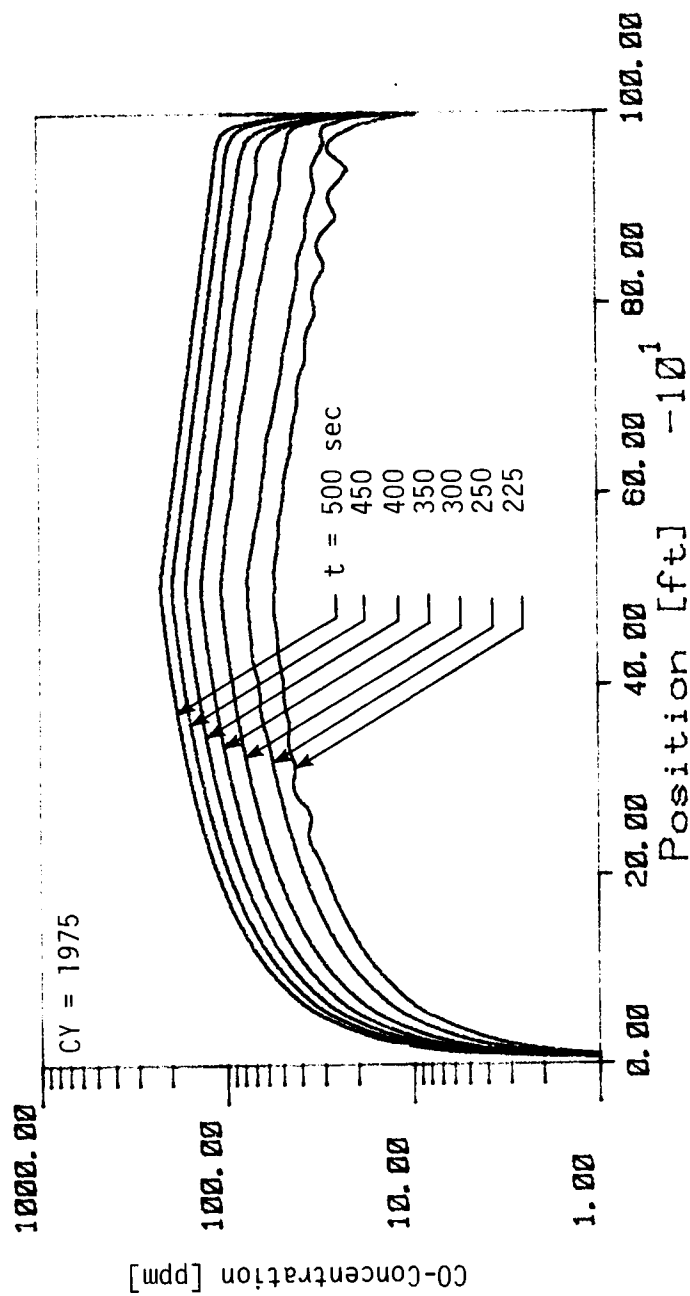


Figure 4-18. CO-concentration distribution for 1975 emission rate when traffic is congested. (The traffic stalls at $t_s = 150$ seconds, $x_s = 500$ feet, input data in Table 4-1, page 60.)

concentration of 230 ppm occurs when $t = 500$ sec (350 seconds after stall). The oxides of nitrogen (NO_x) concentration distribution from $t = 225$ sec to $t = 500$ sec are represented in Figures 4-19 and, in turn, Figure 4-20 shows the distribution of hydrocarbons (C_nH_m) concentration for various time. The behavior of the C_nH_m distribution is similar to CO distribution (Figures 4-18 and 4-20). This is because the variation of emission rate with vehicle speed is the same for both gases (Figures 3-5 and 3-7, pages 54 and 56).

Figure 4-21 represents the CO distribution after traffic restart (at $t = 500$ sec) with the approximation for turbulent mixing in effect. The high CO concentration which accumulated during traffic congestion is quickly carried out of the tunnel by the combined induced flow and turbulent diffusion and decay rapidly to the steady state value under normal operating conditions. Figure 4-22 shows the distribution of the NO_x concentration after traffic restart. It is interesting to note that for NO_x the concentration increases with time. This result is different from that for CO and C_nH_m because the emission rate of NO_x does not behave the same with vehicle speed as does CO or C_nH_m (see Figures 3-5 and 3-6, pages 54 and 55). Figure 4-23 shows the result of C_nH_m concentration after traffic restart. Finally, Figures 4-24 through 4-26 are presented to show the behavior of CO, NO_x , C_nH_m concentration distribution for emissions based on 1980 standards. The trends are the same in all cases although the overall level of concentration is somewhat lower.

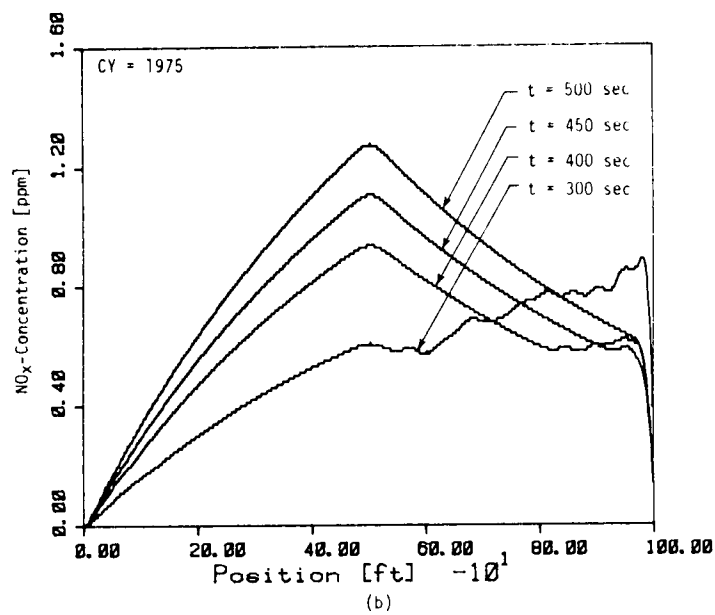
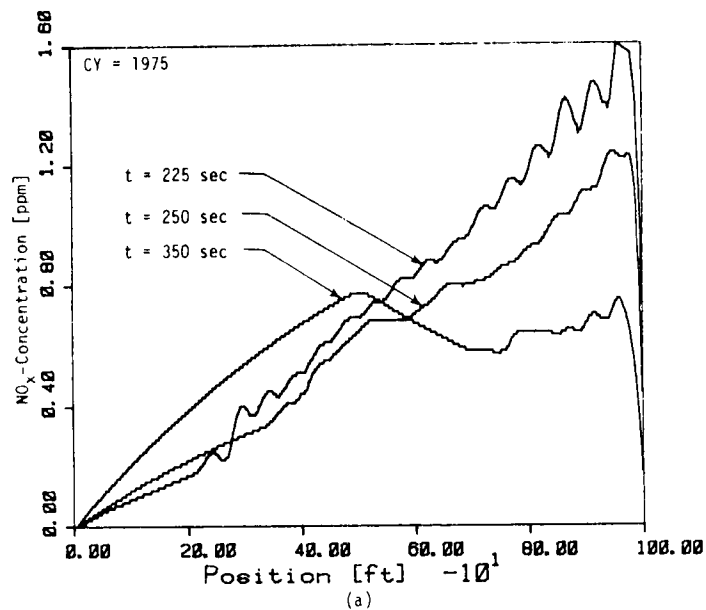


Figure 4-19. NO_x -concentration distribution for 1975 emission rate when traffic is congested. (The traffic stalls at $t_s = 150$ seconds, $x_s = 500$ feet, input data in Table 4-1, page 60.)

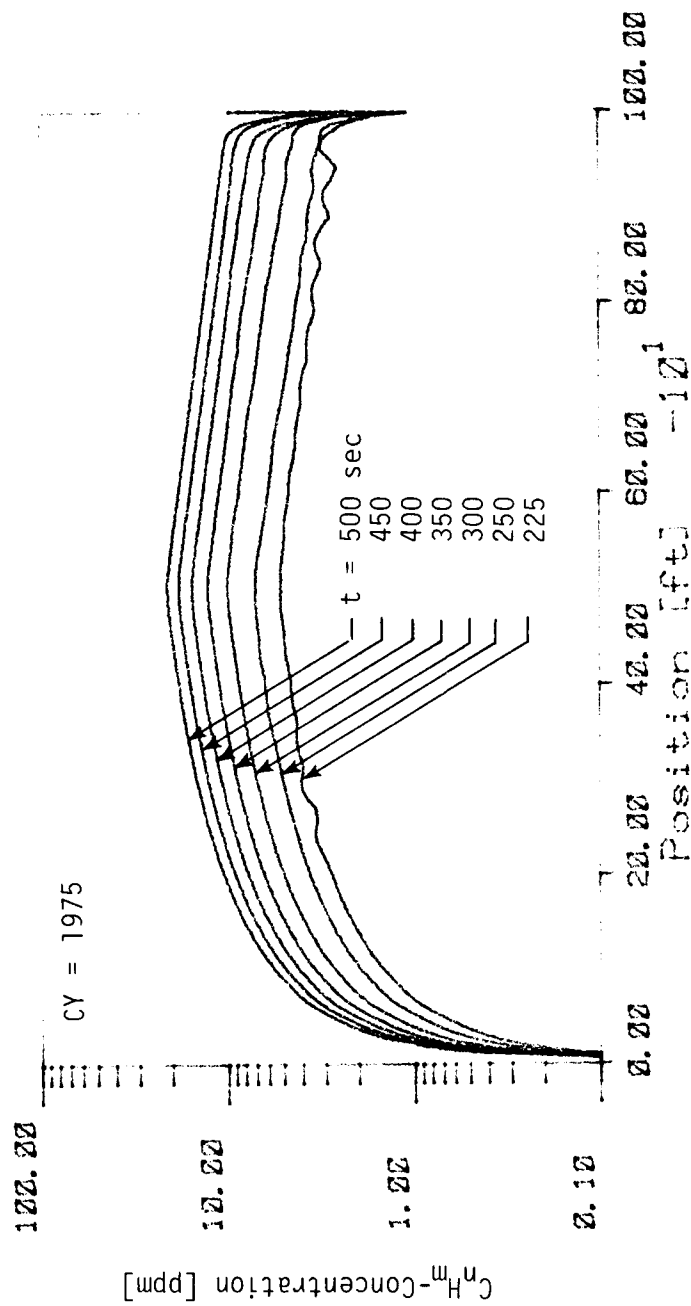


Figure 4-20. C_{H_m} -concentration distribution for 1975 emission rate when traffic is congested. (The traffic stalls at $t_s = 150$ seconds, $x_s = 500$ feet, input data in Table 4-1, page 60.)

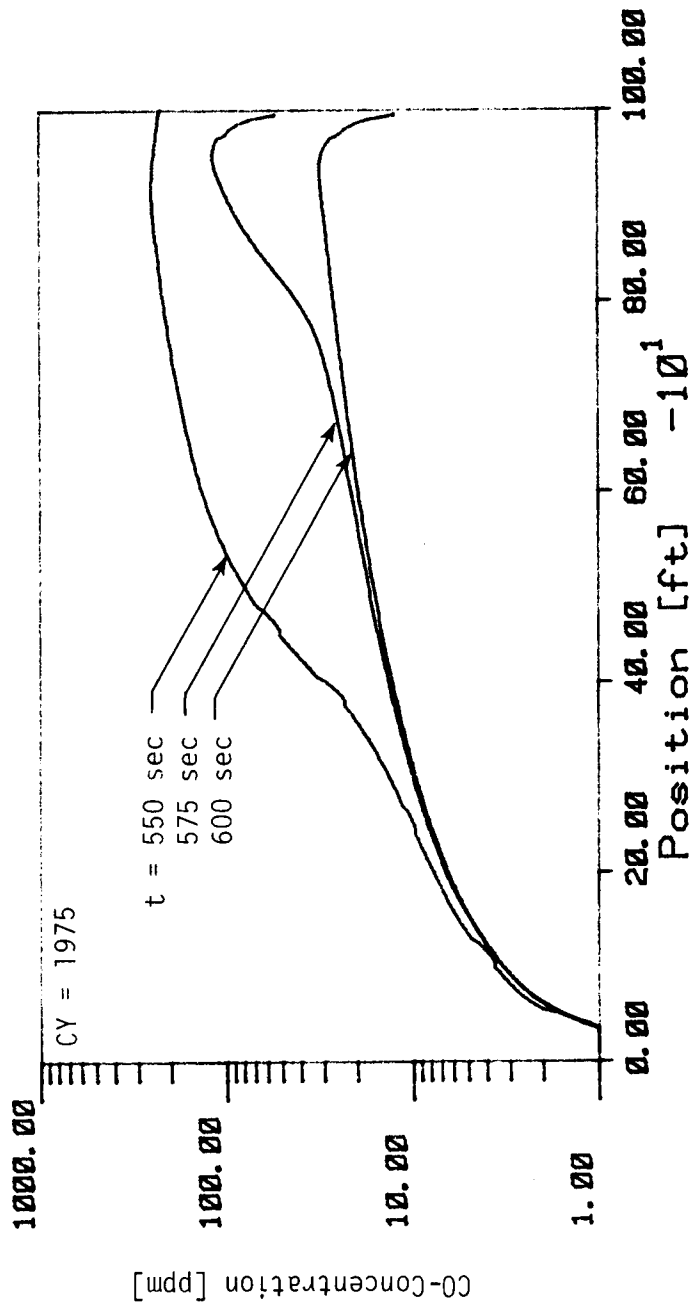


Figure 4-21. CO-concentration distribution for 1975 emission rate when traffic restarted. (Traffic restarts at $t = 500$ seconds, input data in Table 4-1, page 60.)

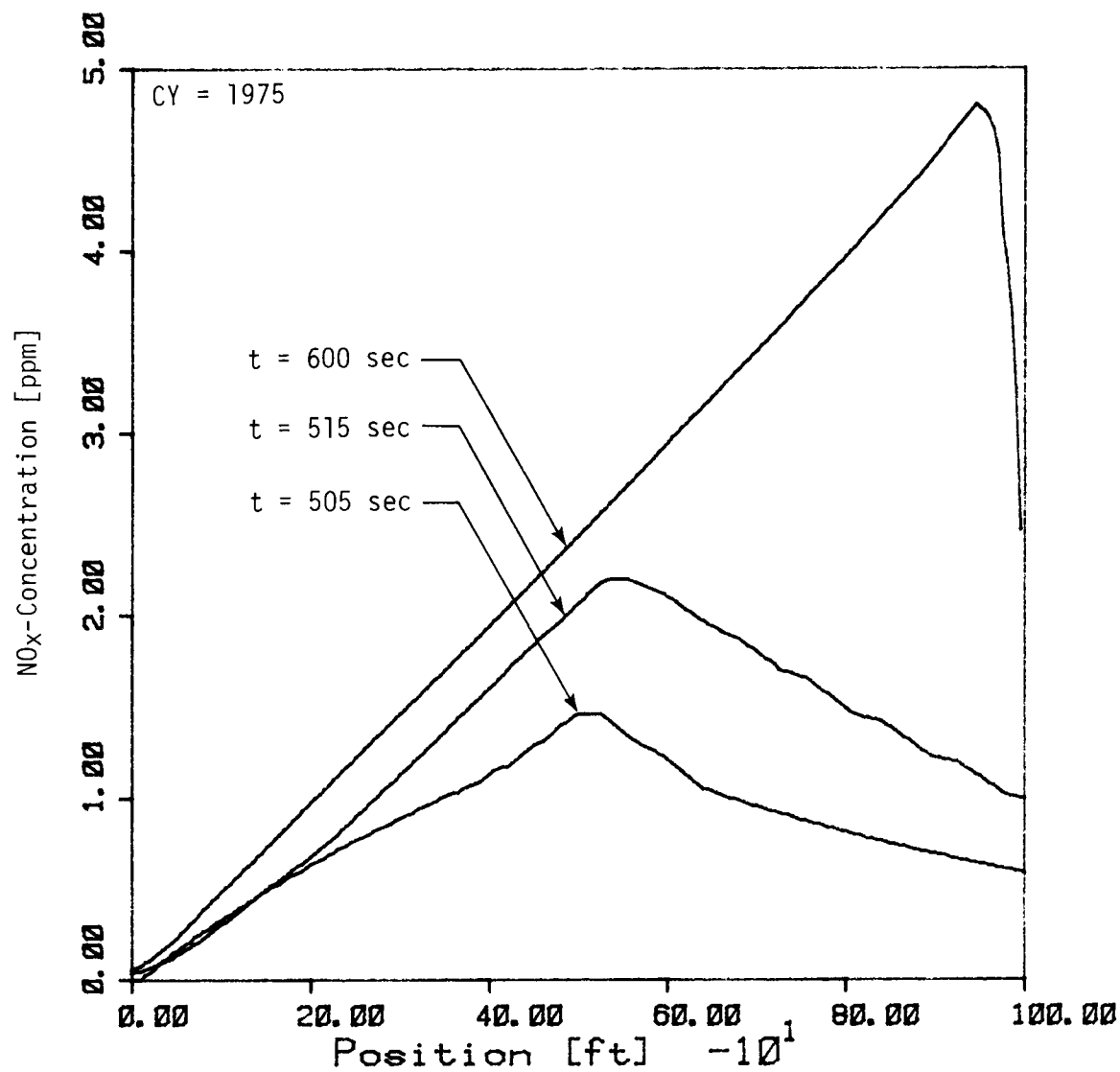


Figure 4-22. NO_x-concentration distribution for 1975 emission rate when traffic restarted. (Traffic restarts at t = 150 seconds, input data in Table 4-1, page 60.)

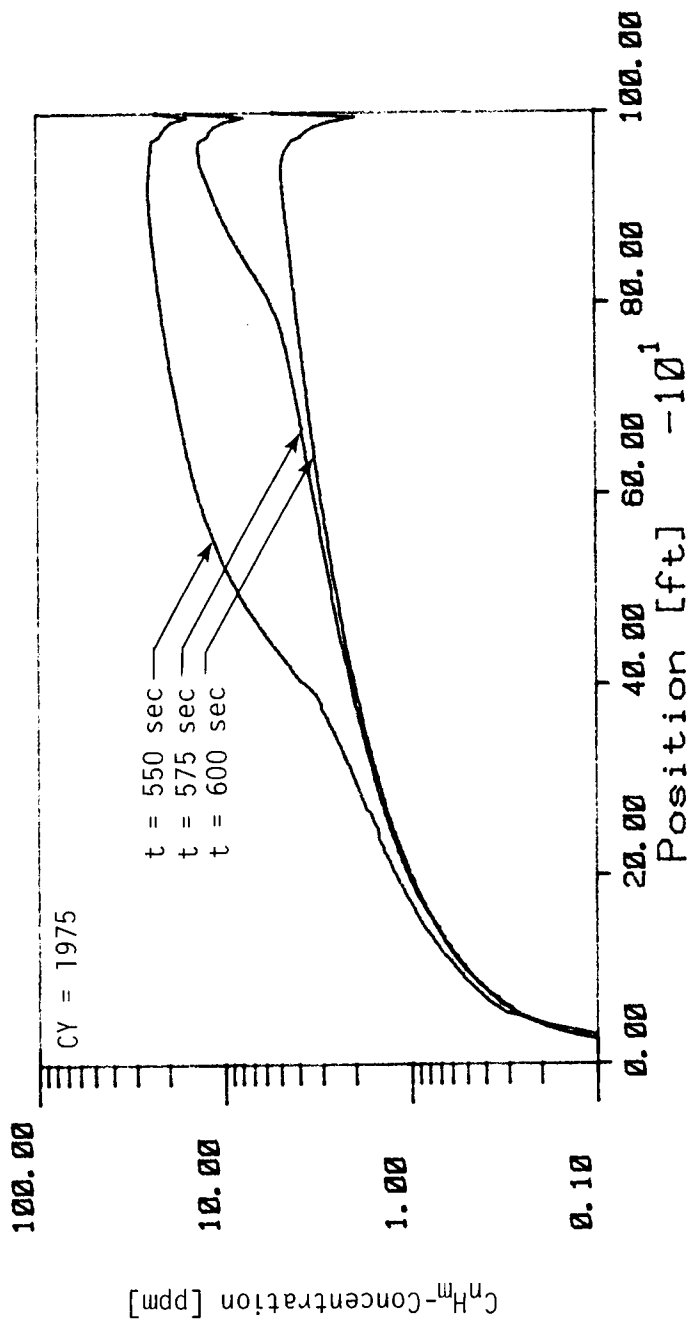


Figure 4-23. C_nH_m -concentration distribution for 1975 emission rate when traffic restarted. (Traffic restarts at $t = 500$ seconds, input data in Table 4-1, page 60.)

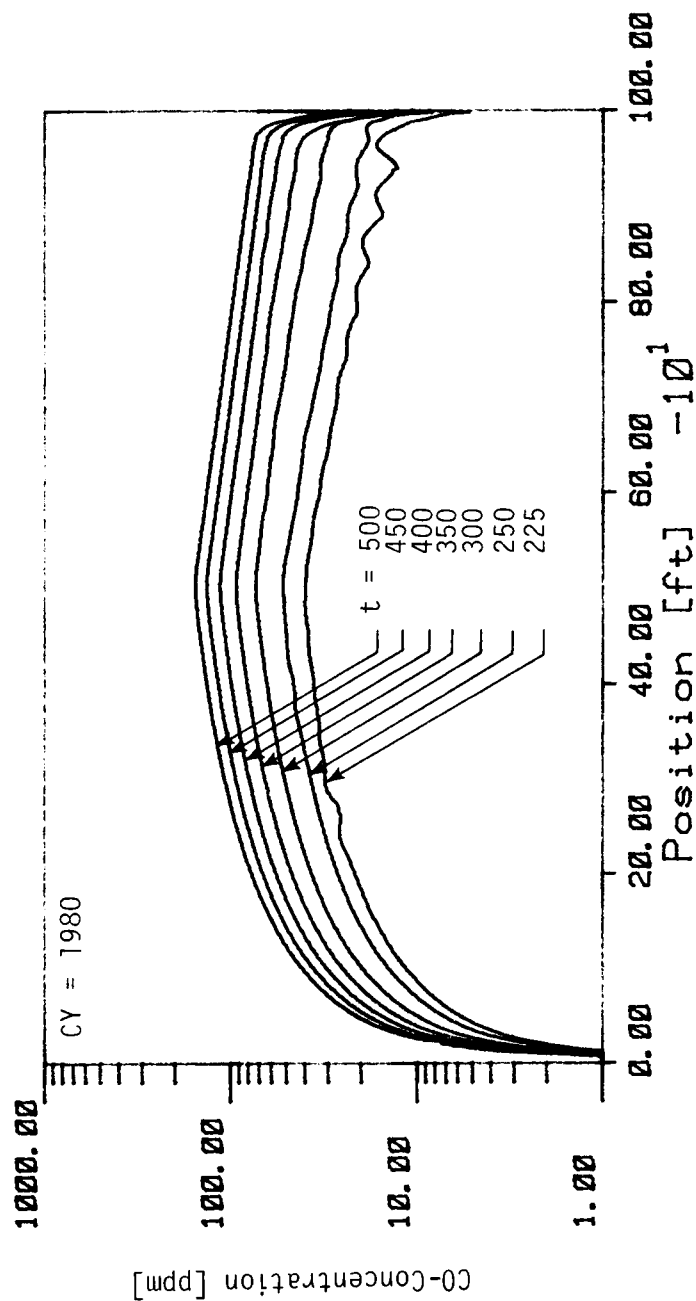


Figure 4-24. CO-concentration distribution for 1980 emission rate when traffic is congested. (Traffic stalls at $t_s = 150$ seconds, $x_s = 500$ feet, input data in Table 4-1, page 60.)

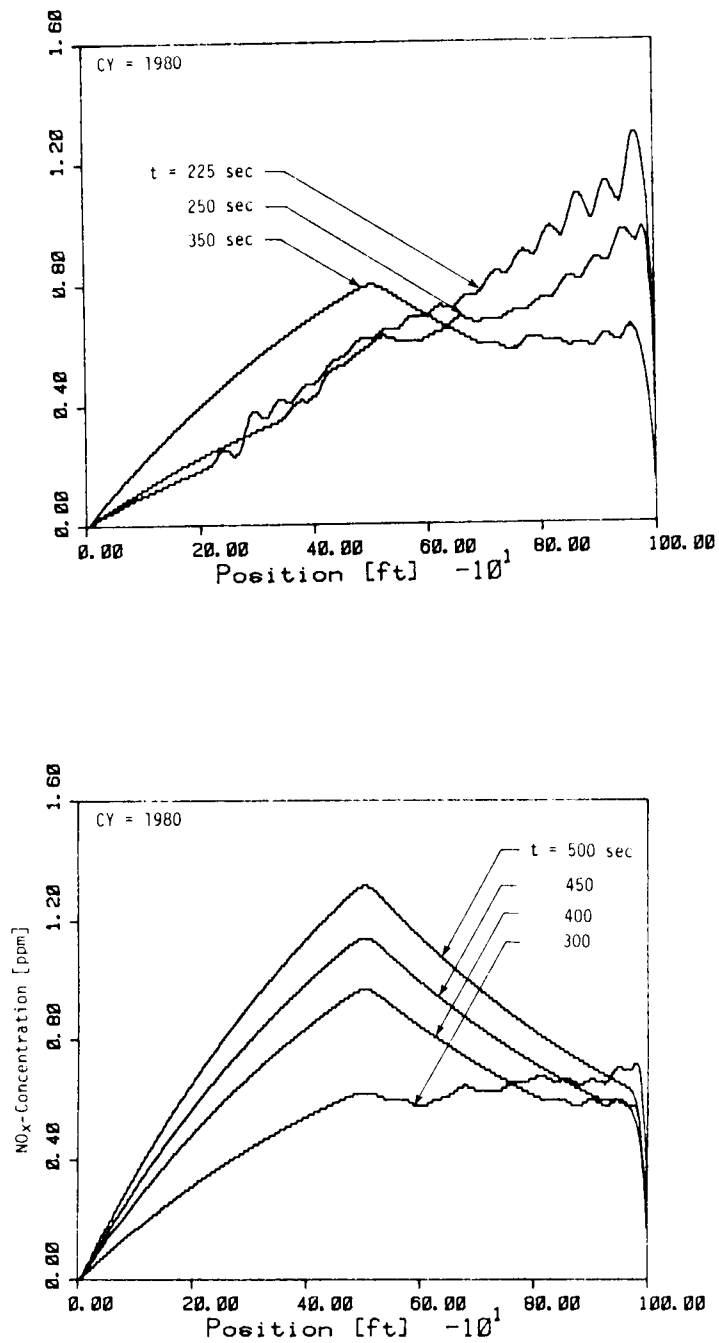


Figure 4-25. NO_x -concentration distribution for 1980 emission rate when traffic is congested. (Traffic stalls at $t_s = 150$ seconds, $x_s = 500$ feet, input data in Table 4-1, page 60.)

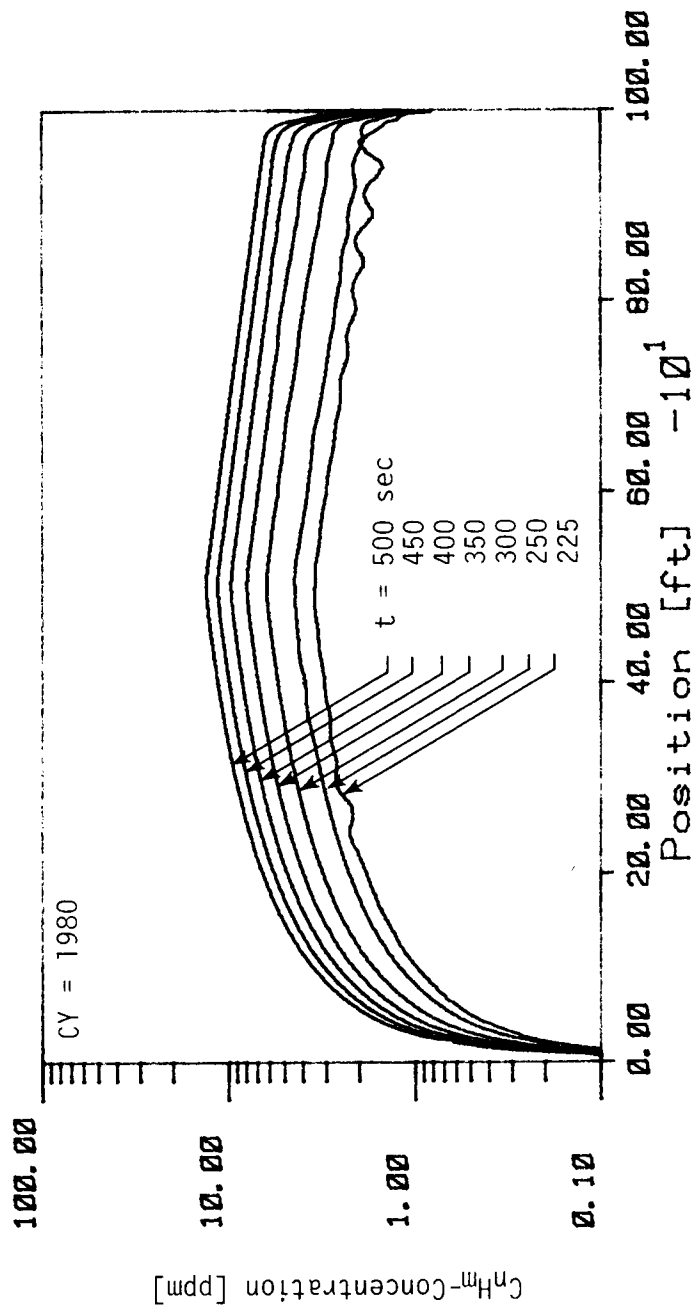


Figure 4-26 C_{nH_m} - concentration distribution for 1980 emission rate when traffic is congested. (Traffic stalls at $t_s = 150$ seconds, $x_s = 500$ feet, input data in Table 4-1, page 60.)

CHAPTER V

CONCLUSIONS

Transient model and associated computer program for computing the concentration distribution of pollutant along the tunnel for a wide range of traffic patterns including random distribution of vehicles from start, stall, slowdown and/or restart is developed. The computer program also allows for arbitrary length of tunnel, arbitrary tunnel cross-section area, traffic rate, and vehicle emission rates. The program provides the design engineer with criteria as to the rate of pollution accumulation and as to when concentration levels may exceed the safety limits due to traffic stall. Also, the rate of dilution in concentration following traffic restart can be predicted.

The program rigorously includes only convective transport of pollutants, however; an approximate modelling of turbulent mixing is included and provides meaningful predictions of the effects of turbulent mixing within the tunnel.

The variation of the induced airflow within the tunnel is the major factor controlling the growth and decay of pollutant concentration levels with time. The induced velocity is a function of vehicle speed, vehicle density, vehicle drag coefficient, tunnel length, blockage ratio, and tunnel wall friction. Under typical peak traffic situation (1500 ~ 2000 Veh/hr-lane) approximately 2 minutes are required to reach a steady state pollution level in tunnels of 800 ft to 1500 ft in length. The steady state induced velocity is approximately 30% of the steady traffic speed for peak traffic conditions.

With the induced airflows known as a function of time, the air quality in the tunnel is found for estimated values of emission rates. The emission rate is a function of the vehicle design, condition of the engine, and operating condition, i.e., idle acceleration, cruise, and deceleration. The reported results are for the emission rate of a traffic mix of 80% light-duty vehicles, 12% light-duty vehicles, 12% light-duty gas vehicles, 4% heavy-duty gas vehicles, and 4% heavy-duty diesel vehicles.

It should be emphasized that the tunnel airflows are highly turbulent due both to high Reynolds number and to local fluctuations caused by vehicle mixing effects. A turbulent mixing is proposed which gives realistic turbulent smoothing of the convective governed profiles.

The hazardous level of 125 ppm of CO concentration exceeds in roughly 3 ~ 5 minutes due to a complete stop traffic jam in a 1000 ft tunnel. It is concluded that for the traffic flow conditions considered in this study, an emergency ventilation system is a necessity for maintaining pollution concentration below hazardous levels during a major traffic stall.

Possible traffic control systems which restrict the rate of traffic entering the tunnel as traffic speeds decrease can be developed utilizing the computer program developed herein as a design tool.

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BIBLIOGRAPHY

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APPENDIXES

APPENDIX A

DERIVATION OF DECELERATE RATE

Consider a uniform traffic stream with speed U . The first vehicle stalls at time t_s with a deceleration rate D_s , and decelerates to a final speed U_f . The following vehicles decelerate with a reaction time t_R delay between each vehicle let $k = 1$ be the first vehicle which enters the initially undisturbed air in the tunnel at $t = 0$. Therefore, if the time, t_s , at which stall begins and the position, x_s , at which it first occurs are specified then, the number of the first stalled vehicle (i.e., K_s) can be calculated as:

$$K_s = (Ut_s - x_s)/S + 1 \quad (A1.1)$$

The position of K_s vehicle is P_s at time t .

$$P_s = Ut_s - (K_s - 1)S + \frac{1}{2}(U^2 - U_f^2)/D_s + U_f(t - t_f) \quad (A1.2)$$

where U and S are the speed and spacing of uniform traffic pattern respectively. D_s is deceleration rate of the first stall vehicle K_s .

t_f is the time when the first stall vehicle K_s reaches to final speed U_f . t_f can be written as:

$$t_f = t_s + (U - U_f)/D_s \quad (A1.3)$$

Similarly, the time from when the K -th vehicle stalled to reach the final speed U_f is t_k .

$$t_k = t_s + (K - K_s)t_R + (U - U_f)/D_k \quad (A1.4)$$

where the unknown D_k is the deceleration rate of K-th vehicle. The position of K-th vehicle at time t is P_k .

$$P_k = U(t_s + (K - K_s)t_R) + \frac{1}{2}(U^2 - U_f^2)/D_k - (K - 1)S + U_f(t - t_k) \quad (A1.5)$$

If the final spacing after the traffic stall has occurred is, say S_f , then, the distance between K and K_s (the first stalled vehicle) can be written as:

$$P_k - P_s = (K - K_s)S_f \quad (A1.6)$$

Subtracting Equation A1.5 from Equation A1.2, then we have

$$P_x - P_s = U(K_s - K)t_R - (K_s - K)S + \frac{1}{2}\left(\frac{1}{D_k} - \frac{1}{D_s}\right)(U^2 - U_f^2) + U_f(t_k - t_f) \quad (A1.7)$$

Equation A1.7 is equal to Equation A1.6. Substitute t_f and t_k from Equation A1.3 and A1.4 gives:

$$\begin{aligned} (K - K_s)S_f = & U(K_s - K)t_R - (K_s - K)S + \frac{1}{2}\left(\frac{1}{D_k} - \frac{1}{D_s}\right)(U^2 - U_f^2) \\ & + U_f[(K - K_s)t_R + (U - U_f)\left(\frac{1}{D_k} - \frac{1}{D_s}\right)] \end{aligned} \quad (A1.8)$$

Regrouping,

$$\left(\frac{1}{D_k} - \frac{1}{D_s}\right)\left[\frac{1}{2}(U^2 - U_f^2) - U_f(U - U_f)\right] = (K_s - K)[(U - U_f)t_R + S_f - S]$$

Finally, the deceleration rate of the K-th vehicle, D_k , is:

$$D_k = \frac{D_s}{1 + 2(K_s - K)D_s[(U - U_f)t_R + S_f - S]/(U - U_f)^2} \quad (A1.9)$$

APPENDIX B

DERIVATION OF POLLUTANT MASS TRANSPORT EQUATION

MASS BALANCE

The conservation of mass for a given pollutant in a longitudinal element of the tunnel air control volume is illustrated in Figure 3-1, page 40. Based on a mass balance analysis the governing equation for concentration of a given pollutant in the volume element can be written as:

$$\begin{aligned}
 \text{Adx} \frac{\partial \gamma}{\partial t} = & \underbrace{A[\gamma V - v \frac{\partial \gamma}{\partial x}]_x}_{\text{mass flow in c.v.}} - \underbrace{A[\gamma V - v \frac{\partial \gamma}{\partial x}]_{x+dx}}_{\text{mass flow out c.v.}} \\
 & + \underbrace{S_v \text{Adx}}_{\text{source}} + \underbrace{R \text{Adx}}_{\text{chemical reaction}}
 \end{aligned} \tag{A2.1}$$

where γ is pollutant concentration, A is cross-section area, V is the induced flow velocity, v is concentration diffusivity.

$$\frac{\partial \gamma}{\partial t} = - \frac{\partial(\gamma V)}{\partial x} + \frac{\partial}{\partial x}(v \frac{\partial \gamma}{\partial x}) + S_v + R \tag{A2.2}$$

since, assuming v is constant, and neglect chemical reaction R . The induced air velocity is a function of time only and therefore, Equation A2.2 becomes:

$$\frac{\partial \gamma}{\partial t} = - V \frac{\partial \gamma}{\partial x} + v \frac{\partial^2 \gamma}{\partial x^2} + S_v \tag{A2.3}$$

Diffusive effects can in general be neglected compared to convective

effects in the tunnel and Equation A2.3 then becomes:

$$\frac{\partial \gamma(x,t)}{\partial t} = -V(t) \frac{\partial \gamma(x,t)}{\partial x} + S_v(x,t) \quad (A2.4)$$

The analytical expression for the source term S_v discussed in Chapter III is:

$$S_v(x,t) = \sum_{n=1}^{\infty} q_n(x,t) H(t-t_n) \delta(x - (\int_0^t U_n(t') dt' - P_n)) \quad (3.5)$$

where $q_n(x,t)$ is the exhaust rate of n -th vehicle t_n is the time the n -th vehicle enters the tunnel and $U_n(t)$ is the speed of the n -th vehicle. The function H is Heaviside unit function defined as:

$$H(t - t_n) = \begin{cases} 1 & \text{when } t \geq t_n \\ 0 & \text{when } t < t_n \end{cases}$$

and $\delta(x)$ is the Delta function defined as:

$$\delta(x) = 0; \quad x \neq 0$$

$$\int_{-\infty}^{\infty} \delta(x) f(x) dx = f(0)$$

Substituting Equation 3.5, page 54, into Equation A2.4 gives:

$$\frac{\partial \gamma(x,t)}{\partial t} = -V(t) \frac{\partial \gamma(x,t)}{\partial x} + \sum_{n=1}^{\infty} q_n(x,t) H(t - t_n) \delta(x - (\int_0^t U_n dt' - P_n)) \quad (A2.5)$$

Let us transform the coordinate system from (x,t) to (ξ, τ)

$$\tau = t; \quad \xi = x - \int_0^t V(t) dt \quad (A2.6)$$

Equation A2.5 becomes:

$$\frac{\partial \gamma(\xi, \tau)}{\partial \tau} = -AV(\tau) \frac{\partial \gamma(\xi, \tau)}{\partial \xi} \frac{\partial \xi}{\partial x} + \sum_{n=1}^{\infty} q_n(\xi, \tau) H(\tau - \tau_n) \cdot \delta \int_0^{\tau} (U_n - V) dt - (\xi + P_n) \quad (A2.7)$$

Relative to the moving coordinate (ξ, τ) , $V(\tau) = 0$. Equation A1.7 thus, further reduces to:

$$\frac{\partial \gamma(\xi, \tau)}{\partial \tau} = \sum_{n=1}^{\infty} q_n(\xi, \tau) H(\tau - \tau_n) \delta \left(\int_0^{\tau} (U_n - V) dt' - (\xi + P_n) \right) \quad (A2.8)$$

Integrating both sides of Equation A1.8

$$\begin{aligned} \gamma(\xi, \tau) - \gamma(\xi, 0) &= \sum_{n=1}^{\infty} \int_0^{\tau} q_n(\xi, \tau') H(\tau' - \tau_n) \delta \left(\int_0^{\tau'} (U_n - V) dt' - (\xi + P_n) \right) d\tau' \\ &= \sum_{n=1}^{\infty} \int_{\tau_n}^{\tau} q_n(\xi, \tau') \delta \left(\int_0^{\tau'} (U_n - V) dt' - (\xi + P_n) \right) d\tau' \\ &= \sum_{n=1}^{\infty} \int_{\tau_n}^{\tau} q_n(\xi, \tau') (D_n(\tau') - (\xi + P_n)) d\tau' \quad (A2.9) \end{aligned}$$

where

$$D_n(\tau') = \int_0^{\tau'} (U_n(t') - V(t')) dt' \quad (A2.10)$$

Now let

$$\eta = D_n(\tau') - (\xi + P_n)$$

$$d\eta = \frac{dD_n(\tau')}{d\tau'} d\tau' \quad (A2.11)$$

and

$$d\tau' = \frac{d\eta}{dD_n(\tau')/d\tau'} \quad (A2.12)$$

From Equation A2.11:

$$D_n(\tau') = \eta + \xi + P_n \quad (A2.13)$$

Defining:

$\zeta = \xi + P_n$, Equation A2.13 becomes:

$$D_n(\tau') = \eta + \zeta \quad (A2.14)$$

Also, τ can be expressed as a function of $D_n(\tau')$ i.e., $\tau' = \tau'(D_n)$

which means $\tau' = \tau'(\zeta, \eta)$. Define $F(\tau')$ as:

$$F(\tau') = \frac{1}{dD_n(\tau')/d\tau'} \quad (A2.15)$$

and also changing the lower limit τ_n and the upper limit τ of Equation A2.9 to η ; where Equation A2.14

and

$$\begin{aligned} \eta &= D_n(\tau) - \zeta && \text{when } \tau' = \tau_n \\ \eta &= D_n(\tau) - \zeta && \text{when } \tau' = \tau \end{aligned} \quad (A2.16)$$

The exhaust rate q_n in Equation A2.9 is a function of ξ, τ' , that is equivalent to function of ζ and n , hence, $q_n = q_n(\zeta, n)$. Substituting Equation A2.11, A2.12, A2.15, and A2.16 into Equation A2.9 gives:

$$\gamma(\xi, \tau) - \gamma(\xi, 0) = \sum_{n=1}^{\infty} \int_{D_n(\tau_n) - \zeta}^{D_n(\tau) - \zeta} q_n(\zeta, n) F_n(\zeta, n) \delta(n) dn \quad (A2.17)$$

The Delta function in Equation A2.17 can be integrated and becomes the Heaviside function.

$$\gamma(\xi, \tau) - \gamma(\xi, 0) = \sum_{n=1}^{\infty} q_n(\zeta) F_n(\zeta) [H(D_n(\tau) - \zeta) - H(D_n(\tau_n) - \zeta)] \quad (A2.18)$$

Because $\zeta = \xi + P_n$, Equation A2.18 becomes:

$$\gamma(\xi, \tau) - \gamma(\xi, 0) = \sum_{n=1}^{\infty} q_n(\zeta) F_n(\zeta) [H(D_n(\tau) - \xi - P_n) - H(D_n(\tau_n) - \xi - P_n)] \quad (A2.19)$$

From Equation A2.10

$$D_n(\tau_n) = \int_0^{\tau_n} (U_n - V) dt'$$

hence:

$$P_n = \int_0^{\tau_n} U_n dt'$$

so we have:

$$D_n(\tau_n) - P_n = - \int_0^{\tau_n} V dt' \quad (A2.20)$$

Substitute Equation A2.20 into Equation A2.19 gives:

$$\gamma(\xi, \tau) - \gamma(\xi, 0) = \sum_{n=1}^{\infty} q_n(\zeta) F_n(\zeta) \left[H(D_n(\tau) - \xi - P_n) - H\left(-\xi - \int_0^{\tau_n} V dt'\right) \right]$$

Using Equation A2.6 to transfer from the (ξ, τ) coordinate back to the (x, t) coordinates, and defining $\zeta = \xi + P_n$, results in:

$$\begin{aligned} \gamma(x, t) - \gamma_i\left(x - \int_0^t V dt\right) &= \sum_{n=1}^{\infty} q_n\left(x + P_n - \int_0^t V dt\right) F_n\left(x + P_n - \int_0^t V dt\right) \\ &\quad \cdot \left[H\left(\int_0^t U_n dt - (x + P_n)\right) - H\left(-x + \int_{t_n}^t V dt\right) \right] \end{aligned} \quad (A2.21)$$

This is final form of governing equation for transient pollutant mass transport within a highway tunnel.

APPENDIX C

TN. DOT/UTSI TRANS PROGRAM LISTING

TN. DOT/UTSI TRANS is written in standard FORTRAN IV, run on the VAX II at The University of Tennessee Space Institute. Data is read into the program from 'DOT.IN' file in main program.

READ (5, 110) XL, A, TREF, DELT, NT

where XL is tunnel length

A is cross-section area of tunnel.

TREF is first evaluation time.

DELT is time interval between two time step.

NT is number of time of evaluation.

READ (5, 120) U, S, UF, SPACE, ACCEL

where U is uniform traffic speed.

S is uniform traffic spacing.

UF is final speed after stall.

SPACE is final spacing after stall.

ACCEL is acceleration rate

READ (5, 130) NX, N, NYEAR

where NX is number of points to be evaluated along the tunnel.

N is number of vehicle.

NYEAR is calendar year of emission standard.

READ (5, 140) TSTALL, XSTALL, TSTART

where

TSTALL is traffic stall time.

XSTALL is traffic stall position in tunnel.

TSTART is traffic restart time.


```

DO 20 J=1,NT
TIME(J) = TREF+(J-1)*DELT
T2=TIME(J)
N1=1
DO 21 I=1,NXP1
TT2=0.
X(I)=XL-(I-1)*DELT
NF = N1
SUM1=0.
SUM2=0.
SUM3=0.
DO 30 K=NF,KT
TI = TN(K)
IF(T1.GT.T2) GO TO 30
CALL LOCATE(K,T2,P)
PUS = P
C**** OBTAIN INITIAL LOCATION OF N-TH VEHICLE
CONTINUE
30 GAMMA(I,J) GIVES IN PARTS PER MILLION
C**** AIR DENSITY IS 34.7 GRAM/CUB. FT
C**** GAMMA(I,J,1)=SUM1*1000000./34.7
GAMMA(I,J,2)=SUM2*1000000./34.7
GAMMA(I,J,3)=SUM3*1000000./34.7
CONTINUE
21 CONTINUE
DO 50 J=1,NT
WRITE(6,320) TIME(J)
WRITE(6,330)
DO 50 I=1,NXP1
50 WRITE(6,340) X(I),GAMMA(I,J,1),GAMMA(I,J,2),GAMMA(I,J,3)
110 FORMAT(4F10.2,110)
120 FORMAT(5F10.2)
130 FORMAT(3110)
140 FORMAT(3F10.2)
200 FORMAT(3X,'TRANSIENT MODEL OF HIGHWAY TUNNEL OUTPUT',//)
210 FORMAT(1X,'TUNNEL LENGTH=',F8.2,4X,'TUNNEL AREA=',F8.2,4X,
1'UNIFORM TRAFFIC VEL=',F8.2,/,1X,'INITIAL SPACING=',F8.2,4X,
2'U-STALL=',F8.2,4X,'S-STALL=',F8.2)
220 FORMAT(1X,'ISIALL=',F8.2,4X,'XSTALL=',F8.2,'TSTART=',F8.2,4X,
1'CALEN. YEAR=',15)
310 FORMAT(2X,'XSTALL=',F10.2,4X,'XSTALL=',F10.2,'TSTART=',F10.2,4X,
1'YEAR=',15,/)
320 FORMAT(//,10X,'TIME=',F10.3)
330 FORMAT(1X,'POSITION F1',2X,'GAMMA-CU',2X,'GAMMA-NUX',2X,
1'GAMMA-HC')
340 FORMAT(4F10.2)
STOP
END

```

```

SUBROUTINE PLUME(K,I,T1,T2)
COMMON /H1/T(1000),V(1000),VINT(1000),TN(1000),TIME(10),X(501)
COMMON /H2/XL,A,TREF,DELT,NIAB,NT,SPACE,UF,N,NX,S,U
COMMON /H3/ISTALL,XSTALL,KSTALL,TSTART,WAIT,ACCEL,TBUP
COMMON /H4/TP1,T12
COMMON /H6/SUM1,SUM2,SUM3,GAMMA(501,5,3)
COMMON /H7/QCU,GND,QHC,NY
CALL LUCATE(K,I2,XSP)
WR1=0.
WR2=0.
WF1=0.
ARG1=0.
ARG2=0.
ARG3=0.
ARG4=0.
ARG5=0.
ARG6=0.
CALL SPEED(K,I2,UK)
XVINT2=XINTRP(NIAB,VINT,T,T2)
XVINT1=XINTRP(NIAB,VINT,T,T1)
WR1=XVINT2-XVINT1
IF(XSP.LI.0.) GO TO 14
IF(K.LT.KSTALL) GO TO 12
CALL EXCEED(K,I1,IF1,XPAS)
IF(X(I).LE.XPAS) GO TO 12
XVINTP1=XINTRP(NIAB,VINT,T,TP1)-XPAS
IF(T2.LE.TSTART) GO TO 1
IF(T2.LE.TBUP) GO TO 1
CALL LUCATE(K,TBUP,XBUP)
TACL=TBUP
IF(T1.GE.TBUP) TACL=11
IF(XBUP.LE.0.) XBUP=0.
WR2=XVINT2-XINTRP(NIAB,VINT,T,TACL)+XBUP
IF(XBUP.EQ.0.) GO TO 12
GO TO 2
WR2=XSPP
CONTINUE
WF1=XVINT2-XVINTP1
ARG1 = X(I)-WR2
ARG2 = X(I)-WF1
H12=ABS(H(ARG1)-H(ARG2))
IF(H12.EQ.0.) GO TO 11
ARG=XINTRP(NIAB,VINT,T,T2)-X(I)

```

1
2

```

NCUN=2
CALL TARG(K,ARG,1,T1,T2,TT3,NCUN)
VV2=XINTRP(NTAB,V,T,TT3)
CALL SPEED(K,TT3,UK2)
CALL SOURCE(K,UK2)
DUV=ABS(UK2-VV2)
IF(DUV.LE.0.5) DUV=0.5
F=1/DUV
SUM1=SUM1+(QCU/A)*F*H12
SUM2=SUM2+(QNU/A)*F*H12
SUM3=SUM3+(QHC/A)*F*H12
CONTINUE
11 IF(TP1.LE.T1) GO TO 10
ARG3=WF1-X(I)
ARG4=WR1-X(I)
H34=ABS(H(ARG3)-H(ARG4))
IF(H34.EQ.0.) GO TO 10
CONTINUE
13 ARG=XINTRP(NTAB,VINT,T,T2)-X(I)
NCUN=1
CALL TARG(K,ARG,1,T1,T2,TT3,NCUN)
CALL SPEED(K,TT3,UK1)
CALL SOURCE(K,UK1)
VV1=XINTRP(NTAB,V,T,TT3)
DUV=ABS(UK1-VV1)
IF(DUV.LE.0.5) DUV=0.5
F=1/DUV
SUM1=SUM1+(QCU/A)*F*H34
SUM2=SUM2+(QNU/A)*F*H34
SUM3=SUM3+(QHC/A)*F*H34
GO TO 10
12 ARG5=XSP-X(I)
ARG6=WK1-X(I)
H56=ABS(H(ARG5)-H(ARG6))
IF(H56.EQ.0.) GO TO 14
ARG=XINTRP(NTAB,VINT,T,T2)-X(I)
NCUN=3
CALL TARG(K,ARG,1,T1,T2,TT3,NCUN)
VV2=XINTRP(NTAB,V,T,TT3)
CALL SPEED(K,TT3,UK2)
CALL SOURCE(K,UK2)
DUV=ABS(UK2-VV2)
IF(DUV.LE.0.5) DUV=0.5
F=1/DUV
CONTINUE
17

```

```

SUM1=SUM1+(QCU/A)*F*H56
SUM2=SUM2+(QNU/A)*F*H56
SUM3=SUM3+(QHC/A)*F*H56
GO TO 14
CONTINUE
IF(I2.LE.ISTART) GO TO 14
IF(I2.LE.TBUP) GO TO 14
ARG7=XSP-X(I)
ARG8=WR2-X(I)
H78=ABS(H(ARG7)-H(ARG8))
IF(H78.EQ.0.) GO TO 14
ARG=XINTRP(NTAB,VINT,T,T2)-X(I)
NCUN=4
CALL TARG(K,ARG,I,I1,I2,TT3,NCUN)
VV4=XINTRP(NTAB,V,T,TT3)
CALL SPEED(K,TT3,UK4)
CALL SOURCE(K,UK4)
DUV=ABS(UK4-VV4)
IF(DUV.LE.0.5) DUV=0.5
F=1/DUV
SUM1=SUM1+(QCU/A)*F*H78
SUM2=SUM2+(QNU/A)*F*H78
SUM3=SUM3+(QHC/A)*F*H78
CONTINUE
RETURN
END

```

10

14

```

SUBROUTINE EXCEED(K,T1,TP1,XPAS)
COMMON /H1/1(1000),V(1000),VINI(1000),TN(1000),TIME(10),X(501)
COMMON /H2/XL,A,TREF,DELT,NTAB,NT,SPACE,UF,N,NX,S,U
COMMON /H3/ISTALL,XSTALL,KSTALL,ISTARI,WAIT,ACCEL,IBUP
TAI=11
IF(T1.GT.FSTART) GO TO 2
ITER=0
CONTINUE
ITER=ITER+1
CALL SPEED(K,TAI,UA1)
VAL=XINTRP(NIAB,V,1,TAI)
IF(VAL-GE-UA1) GO TO 3
IF(ITER-GE-200) GO TO 2
TAI=TAI+0.3
GO TO 1
TP1=TAI+50
XPAS=XL
GO TO 4
CONTINUE
TP1=TAI
CALL LOCATE(K,TP1,XPAS)
RETURN
END

```

CC

```

FUNCTION H(ARG)
H=0.0
IF(ARG.GT.0.) H = 1.0
RETURN
END

```

CC

```

FUNCTION XINTRP(N,A,B,C)
DIMENSION A(1000),B(1000)
IF(C.GT.B(1)) GO TO 1
XINTRP = A(1)
GO TO 4
CONTINUE
IF(C.LE.B(N)) GO TO 2
XINTRP = A(N)
GO TO 4
CONTINUE
DO 3 I=1,N
IF(B(I).LE.C) GO TO 3
XINTRP = A(I-1)+(A(I)-A(I-1))/(B(I)-B(I-1))*(C-B(I-1))
GO TO 4
CONTINUE
RETURN
END

```

```

SUBROUTINE FTIME(KT)
COMMON /H1/T(1000),V(1000),VINT(1000),TN(1000),TIME(10),X(501)
COMMON /H2/XL,A,TREF,DELT,NTAB,NF,SPACE,UF,N,NX,S,U
COMMON /H3/TSTALL,XSTALL,KSTALL,TSTART,WAIT,ACCEL,TRUP
T1 = 0.0
DT = .1
C**** USE NEWTON'S METHOD TO FIND TIME CORRESPONDING TO VEHICLE ENTRY
TMAX=TREF+(N1-1)*DELT+1.
DO 3 I=1,N
CALL LOCATE(I,TMAX,P)
IF(P.LT.0.) GO TO 4
IF(1.GE.KSTALL) GO TO 1
ITER = 0
T1=(I-1)*S/U
CALL LOCATE(I,I1,P)
GO TO 2
1 CONTINUE
ITER=ITER+1
T1=T1+.03
CALL LOCATE(I,I1,P)
IF(P.GE.0.) GO TO 2
GO TO 1
TN(I)=T1
KT=1
2 CONTINUE
3 RETURN
4 END

```



```

SUBROUTINE LOCATE(K, IH, P)
COMMON /H1/T(1000), V(1000), VINT(1000), TN(1000), TIME(10), X(501)
COMMON /H2/XL, A, TRKF, DELT, NIAB, NI, SPACE, UF, N, NX, S, U
COMMON /H3/ISTALL, XSTALL, DELT, KSTALL, TSTALL, WAIT, ACCEL, IBUP
COMMON /H5/TKF(1000), XAC, US, KNEW
IF (IH.GT.TSTALL) GO TO 21
-----CASE 1-----
UNIFORM TRAFFIC FLOW AT SPEED U
UNIFORM SPACING, S
P = U*IH-(K-1)*S
GO TO 100
CONTINUE
-----CASE 2-----
TRAFFIC STALL BEGINNING AT TSTALL AND XSTALL FROM
AN INITIALLY UNIFORM TRAFFIC FLOW AT U & S.
NSTALL IS THE LAST CAR TO PASS XSTALL AT TSTALL
-----STALL HAS OCCURRED-----
DRI = 20.
IF (K.GE.KSTALL) GO TO 22
P = U*IH-(K-1)*S
GO TO 100
CL = 20.
T5=IH
TAC=TSTALL+(K-KSTALL)*WAIT
TBUP=IAC
TR = .3
TSAFE = (S-CL)/U
IF (TK.GT.TSAFE) TR=TSAFE
IF (K.GT.KSTALL) GO TO 50
TKF(K)=TSTALL+(U-UF)/DRI
IF (T5.GT.TKF(K)) T5=TKF(K)
P=U*ISTALL+U*(T5-TSTALL)-.5*DRI*(T5-TSTALL)**2-(K-1)*S
US=U-DRI*(T5-TSTALL)
PSI=P
GO TO 60

```

```

50      TKB=TSSTALL+(K-KSTALL)*TK
      IF(TH.LE.TKB) GO TO 51
      DW=2*(KSTALL-K)*DK1*(SPACE-S+(U-UF)*TK)
      DRK=DR1/(1+DW/((U-UF)*(U-UF)))
      TKF(K)=TKB+(U-UF)/DRK
      IF(T5.GT.TKF(K)) T5=TKF(K)
      P=J*TKB+U*(T5-TKB)-.5*DRK*(T5-TKB)**2-(K-1)*S
      USE=U-DRK*(T5-TKB)
      PS1=P
      GO TO 60
51      P=U*T5-(K-1)*S
      GO TO 100
60      CONTINUE
      IF(CUF.EQ.U..AND.TH.GT.TAC) GO TO 61
      IF(CUF.EQ.U.) GO TO 100
      CALL SUBLOC(K,TH,PS1,DRK,P)
      GO TO 100
61      CONTINUE
C----- TRAFIC RESTART NOW -----
      CALL ACCLUC(K,TH,TAC,PS1,P,DRK)
      RETURN
      END
100

SUBROUTINE NEWKST(TSSTALL,TSTART,KSTALL)
COMMON /H5/TKF(1000),XAC,US,KNEW
TS=TSSTALL
K=KSTALL
1  TS=TS+1.
   CALL LOCATE(K,PS,PS)
   IF(PS.LT.XAC) GO TO 1
   IF(TS.GE.TSTART) GO TO 10
   K=K+1
   GO TO 1
10  KNEW=K
   RETURN
   END

```

```

SUBROUTINE ACCLOC(K, FH, TAC, PSI, P, DRK)
COMMON /H1/T(1000), V(1000), VINT(1000), TN(1000), TIME(10), X(501)
COMMON /H2/XL, A, TREF, DELT, NTAB, NI, SPACE, UF, N, NX, S, U
COMMON /H3/TSALL, XSTALL, KSTALL, ISSTART, WAIT, ACCEL, THUP
COMMON /H5/TRF(1000), XAC, US, KNEW
TK=0.3
TKB=TSALL+(K-KSTALL)*TR
T6=TH-IAC
T7=T6
U1=0.
IF(TAC.LT.TKF(K)) GO TO 60
P=PS1+(TAC-TRF(K))*UF
TMAX=(U-UF)/ACCEL
IF(T6.GT.TMAX) T6=TMAX
P=P+.5*ACCEL*T6*UF*UF
THUP=IAC
IF(T6.EQ.TMAX) P=P+U*(T7-T6)
GO TO 101
CONTINUE
IF(TAC.LE.TKB) GO TO 51
CALL SPEED(K, IAC, U1)
T1=TKF(K)
IF(TH.LT.TKF(K)) T1=TH
P1=UF*(T1-IAC)+.5*DRK*(T1-TAC)**2
TMAX=(U-U1)/ACCEL
IF(T6.GT.TMAX) T6=TMAX
P=PS1-P1+.5*ACCEL*T6*T6+U1*T6
THUP=IAC
IF(T6.EQ.TMAX) P=P+U*(T7-T6)
GO TO 100
P=U*TH-(K-1)*S
51 CONTINUE
101 CONTINUE
100 RETURN
END

```

```

SUBROUTINE SUBLOC(K,TH,PS1,DRK,P)
COMMON /H1/T(1000),V(1000),VINT(1000),TN(1000),TIME(10),X(501)
COMMON /H2/XL,A,TRF,DELT,NTAB,NT,SPACE,UF,N,NX,S,U
COMMON /H3/TSFALL,XSTALL,KSTALL,TSTART,WAIT,ACCEL,TBUP
COMMON /H5/TKF(1000),XAC,US,KNEW
IF(PS1.GT.XAC) GO TO 1
IF(K.LT.KNEW.AND.TH.LT.TKF(K)) GO TO 100
IF(K.LT.KNEW) GO TO 2
TAC=TSTART+(K-KNEW)*WAIT
TBUP=TAC
IF(TH.GT.TAC) GO TO 20
IF(TH.LE.TKF(K)) GO TO 100
GO TO 2
1 CONTINUE
IF(K.GT.KNEW) GO TO 30
TEX=(-UF+SQRT(UF*UF+2*DRK*(PS1-XAC)))/DRK
TS1=TKF(K)-TEX
UP1=UF+DRK*TEX
IF((TH-TS1).LT.0.) GO TO 100
GO TO 3
2 TS1=TKF(K)+(XAC-PS1)/UF
UP1=UF
3 TS2=TH-TS1
IF(TS2.LT.0.) GO TO 10
TS3=TS2
TMAX=(U-UF)/ACCEL
IF(TS2.GT.TMAX) TS2=TMAX
P=XAC+.5*ACCEL*TS2*TS2+UP1*TS2
US=UP1+ACCEL*TS2
IF(TS2.EQ.TMAX) P=P+U*(TS3-TS2)
GO TO 100
10 P=PS1+UF*(TH-TKF(K))
US=UF
GO TO 100
20 CONTINUE
IF(TH.LT.TAC.AND.TH.GT.TKF(K)) GO TO 10
CALL ACCLUC(K,TH,TAC,PS1,P,DRK)
US=UF+ACCEL*(TH-TAC)
IF(US.LT.UF) US=UF
IF(US.GT.U) US=U
100 RETURN
END

```

```

SUBROUTINE VELOZ
COMMON /H1/I(1000),V(1000),VINT(1000),TM(1000),TIME(10),X(501)
COMMON /H2/XL,A,TREF,DELT,NTAB,NT,SPACE,UF,N,NX,S,U
DIMENSION F(1000),UH(1000)
INPUT SECTION OF PROGRAM
N,NUMBER OF VEHICLES      K,NUMBER OF TIME STEPS
NL,TUNNEL LENGTH          TA,TUNNEL AREA
D,HYDRAULIC DIAMETER      VA,VEHICLE AREA
U,VEHICLE VELOCITY        CD,VEHICLE DRAG COEFFICIENT
H,TIME STEP SIZE          CF,TUNNEL DRAG COEFFICIENT
V,INDUCED VELOCITY        VI,INITIAL INDUCED VELOCITY
V1=0.                      INITIAL INDUCED VELOCITY INPUT
C.....
D = 20.
TSTEP=1.0
H=TSTEP
NH=(TREF+DELT*NT)/TSTEP+3
CF=.03
CD=.05
VA=20.
NHOLD1 = 1
NHOLD2 = 0
NHOLD3 = 1
JHOLD = 0
DU 50 KK=1,NH
C.....
NHOLD2 = JHOLD + NHOLD2
TI = TSTEP*(KK-1)
T(KK) = TI
DU 60 IG=NHOLD3,N
CALL LUCAIE(IG,TI,PL)
CALL SPEED(IG,TI,SC)
P(IG)=PL
UH(IG)=SC
C.....
IF(PL.GT.XL) NHOLD1 = NHOLD1 + 1
IF(PL.GT.0.) NHOLD2 = NHOLD2 + 1
IF(PL.LE.0.) GO TO 70
CONTINUE
60

```

70	IF (NHOLD1.LE.1) GO TO 75
	NHOLD3 = NHOLD1
75	JHOLD = NHOLD1-1
	HOLD = 0.
	IF ((NHOLD2-NHOLD1).LT.0) GO TO 90
	DO 80 II=NHOLD1,NHOLD2
	YY = UH(II)-V1
	CB = 1.
	IF (YY.LT.0.) CB=-1.
	HOLD = HOLD + CB*(VA*CD*(UH(II)-V1)*(UH(II)-V1)
	/(A*XL*2.))
	CONTINUE
80	NHOLD2 = 0
90	F = HOLD - (CF*V1*V1/(2.*D)) - (V1*V1/(2.*XL))
	V1 = V1 + H*F
	V(KK) = V1
	CONTINUE
50	NIAB = NH
	RETURN
	END

```

SUBROUTINE SPEED(K,14,SC)
COMMON /H1/1(1000),V(1000),VINT(1000),TW(1000),TIME(10),X(501)
COMMON /H2/XL,A,IREF,DELT,NTAB,NT,SPACE,UF,N,NX,S,U
COMMON /H3/ISIALB,XSTALL,KSTALL,ISTART,WALL,ACCEL,TBUP
COMMON /H5/INF(1000),XAC,US,KNEW
IF(14.GT.TSTALL) GO TO 21
C-----
C-----CASE 1-----
C-----UNIFORM TRAFFIC FLOW AT SPEED U UNIFORM SPACING S-----
SC = U
GO TO 100
21 CONTINUE
C-----
C-----CASE 2-----
C-----TRAFFIC STALL-----
IS=14
IF(N.GE.KSTALL) GO TO 22
SC = U
GO TO 100
22 CONTINUE
IREV=3
IKB=ISTALL+(N-KSTALL)*IK
IAC=ISTART+(K-KSTALL)*WAIT
DK1 = 20.
C-----COMPUTE DECELERATION RATE-----
CL=20.
IF(14.GT.IKB) GO TO 50
SC=U
GO TO 100
50 CONTINUE
DK=2*(KSTALL-K)*DK1*(SPACE-S+(U-UF)*TR)
DKK=DK1/(1+DK/(U-UF)*(U-UF))
IF(UF.NE.U.) GO TO 40
IF(14.GT.IAC.AND.IAC.GT.IKB) GO TO 60
SC=U-(T4-IKB)*DKK
IF(SC.LT.UF) SC=UF
IF(TAC.LE.IKB) SC=U
GO TO 100
40 CONTINUE
60

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IF(T4.GT.TKF(K)) GO TO 70
IF(K.LE.KNEW) GO TO 70
TAC=TSTART+(K-KNEW)*WALT
IF(T4.GT.TAC) GO TO 60
SC=U-(T4-TK)*DRK
IF(SC.LT.UF) SC=UF
GO TO 100
CALL LOCATE(K,T4,P4)
SC=US
GO TO 100
C-----CASE 3-----
C----- TRAFFIC RESTART -----
60  U1=U-(TAC-TK)*DRK
    IF(U1.LT.UF) U1=UF
    SC=U1+(T4-TAC)*ACCEL
    IF(SC.GT.U) SC=U
    CONTINUE
    VEL=SC
    RETURN
    END
100

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SUBROUTINE TARG(K,ARG,I,T1,T2,TT3,NCUN)
COMMON /H1/I(1000),V(1000),VINI(1000),TW(1000),TIME(10),X(501)
COMMON /H2/XL,A,TREF,DELT,NTAB,NT,SPACE,UF,N,NX,S,U
COMMON /H3/TSALL,XSTALL,KSTALL,TSTART,WAIT,ACCEL,TRUP
COMMON /H4/TP1,TT2
ITER=0
D1=0.
D2=0.
IF(K.GE.KSTALL) GO TO 15
TX1=0.
10 CONTINUE
CALL LOCATE(K,TX1,P1)
D1=XINTRP(NTAB,VINI,T,TX1)-P1
TX2=TX1+.01
CALL LOCATE(K,TX2,P2)
D2=XINTRP(NTAB,VINI,T,TX2)-P2
T3=TX1+.01/(D2-D1)*(ARG-D1)
TEST=ABS(T3-TX1)
ITER=ITER+1
IF(ITER.GE.50) GO TO 55
IF(TEST.LT..05) GO TO 55
TX1=T3
GO TO 10
15 CONTINUE
NITER=1000
IF(NCUN.NE.2.AND.NCUN.NE.4) GO TO 25
IF(NCUN.EQ.4) GO TO 20
TT3=TP1
GO TO 30
TT3=TRUP
GO TO 30
20 TT3=T1
25 CONTINUE
CALL LOCATE(K,TT3,P1)
IF(P1.LT.0.) GO TO 50
ITER=ITER+1
D1=ARG+P1
D2=XINTRP(NTAB,VINI,T,TT3)

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114=113+0.1
CALL LOCATE(K,114,P2)
E=ABS(D1-D2)
IF(MCUN.EQ.2) GO TO 35
VLES1=X1*IRP(NTAB,V71,113)
IF(E.GE.00.) 113=113+E/VLES1
IF(P1.EQ.P2) GO TO 40
CONTINUE
IF(E.GT.400) 113=113+3.
IF(E.GT.200) 113=113+2.
IF(E.GT.50.) 113=113+.05
IF(E.LE.2.) GO TO 60
GO TO 45
40 IF(D1.LE.D2) GO TO 60
45 CONTINUE
IF(11E8.GE.NITER) GO TO 60
50 CONTINUE
IF(MCUN.EQ.2) 113=113+.05
IF(MCUN.EQ.2) 113=113+.02
GO TO 30
55 CONTINUE
113=13
60 CONTINUE
IF(MCUN.EQ.2) 112=113
RETURN
END

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SUBROUTINE SOURCE(K,U2)
DIMENSION CU75(20),HC75(20),CO80(20),HC80(20),ST(20)
REAL NOX75(20),NOX80(20)
COMMON /H1/T(1000),V(1000),VINT(1000),TN(1000),TIME(10),X(501)
COMMON /H2/XL,A,TREF,DELT,NTAB,NT,SPACE,UF,N,NX,S,U
COMMON /H7/QCO,QNU,QHC,NYEAR
DATA CU75/984.,1282.,1324.,1488.,1579.,1580.,1552.,
$1588.,1608.,1668.,1685.,1699.,1644.,1703.,1697.,
$1660.,1609.,1694.,1738.,1688.,1975.,1059.,1012.,975.,942.,954.,
$1024.,1003.,950.,901.,914.,925.,903.,935.,895.,772.,821.,
$73.,59.,83.,88.,95.,76.,110.,13.,123.,59.,144.,40.,161.,63.,
$181.,18.,195.,96.,219.,80.,233.,60.,254.,00.,287.,00.,
$DATA NOX80/5.,49.,10.,70.,20.,00.,29.,16.,37.,49.,43.,47.,49.,30.,
$55.,57.,64.,77.,73.,10.,82.,76.,93.,00.,109.,05.,120.,56.,
$135.,22.,146.,83.,164.,92.,176.,14.,191.,77.,218.,43.,
$DATA HC75/94.,0.,112.,0.,111.,2.,117.,0.,130.,6.,142.,2.,156.,0.,
$166.,2.,178.,3.,189.,7.,204.,6.,209.,1.,206.,3.,217.,5.,235.,0.,
$245.,0.,241.,7.,245.,8.,268.,2.,266.,8.,9.,90.,8.,96.,98.,111.,119.,
$126.,130.,130.,130.,135.,1.,148.,1.,150.,150.,149.,144.,5.,170.,8.,
$DATA ST/1.,31.,3.,00.,6.,00.,8.,86.,11.,90.,14.,81.,17.,50.,20.,34.,
$23.,15.,26.,13.,29.,55.,32.,50.,37.,13.,40.,30.,44.,19.,
$47.,20.,51.,76.,54.,76.,58.,86.,64.,82./
U1=U2
IF(CU1.EQ.0.) U1=1.47
THIS SUBROUTINE CALCULATES THE POLLUTANT SOURCE STRENGTH AS
A FUNCTION OF VEHICLE TYPE (BASED ON K) AND SPEED (U).
IF(CNYEAR.EQ.1980) GO TO 10
U1=XINTRP(20,CO75,ST,U1)
QCO=U1/3600.
U2=XINTRP(20,NOX75,ST,U1)
QNU=U2/3600.
U3=XINTRP(20,HC75,ST,U1)
QHC=U3/3600.
GO TO 20
10
U1=XINTRP(20,CO80,ST,U1)
QCO=U1/3600.
U2=XINTRP(20,NOX80,ST,U1)
QNU=U2/3600.
U3=XINTRP(20,HC80,ST,U1)
QHC=U3/3600.
20 RETURN
END

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VITA

Kao-Huah Huang was born in Kaohsiung, Taiwan, The Republic of China, on March 1, 1953. He received his elementary and high school education in Kaohsiung. In June 1976 he graduated from The National Cheng Kung University, Tainan, Taiwan, where he received his Bachelor of Science degree with a major in Aeronautical Engineering. In the following two years, from October 1976 to August 1978, he served in the China Air Force as a second lieutenant. From September 1978 to July 1979 he was employed by The National Cheng Kung University as a teaching assistant.

He began his graduate studies at The University of Tennessee Space Institute in September 1979 as a graduate research assistant for the Atmospheric Science Division. He received his Master of Science degree in December 1980.