Air Quality Modeling for Predicting Traffic Pollution in Dhaka City

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Abstract

Many air pollution problems require simulation of the dispersion of pollutants from a given source or sources to estimate concentration of pollutants at a receptor site. A number of mathematical models (dispersion models) have been developed for this purpose. In Bangladesh applicability of available air quality models have rarely been assessed. This paper makes an endeavor to assess the applicability of an available model (Caline4 an USEPA model) and that of Gaussiun equations to predict air quality for a typical line source in Dhaka city. Predicted (by Caline4) Carbon Monoxide (CO) concentration at relatively short distance away from the road matched reasonably well with the measured values of CO. For predicting NOx and Sox concentrations Gaussian plume model for line sources can be used, provided its parameters are estimated with sufficient accuracy. Wide ranges of equations are available for estimating vertical dispersion coefficient σ_z*, one of the model parameters used in Gaussian plume equations. This paper assesses the applicability of the Gaussian plume mode in predicting air quality at short distance for line sources. A set of equations has been prepared to estimate* σ_z*, that can be used for reasonable prediction of short distance air quality using Gaussian equation.*

Keywords: Air quality model; Gaussian plume model; Emission factor; Vertical dispersion coefficient

Introduction

Dhaka has over the years grown into a mega city. Air pollution in Dhaka city is reported to be serious and damaging to public health. Uncontrolled emission from motor vehicle has been identified as one of its major causes of air pollution.

Available air quality monitoring data suggests that the ambient concentrations of some pollutants especially suspended particulate matter (PM-10, PM-2.5), NOx and SOx in air of Dhaka are much higher than their acceptable limits set for Bangladesh.

To keep the pollutant concentration within the acceptable limit the government has taken a number of initiatives including banning of leaded fuel and banning of two-stroke three-wheeler from Dhaka. It is also planning to formulate a comprehensive strategy for improving urban air quality. Before taking any specific action it is important to identify the potential impacts and to predict the effect of the actions. Air modeling software can be used for the prediction of change in air quality for a proposed action. Computer models have been developed to predict air quality under different scenarios and such models could be very useful in predicting the consequences of actions that may have an impact on air quality. For example the possible impact of banning two-stroke engines on Dhaka air quality can be assessed with the help of air quality models.

A number of mathematical models (dispersion models) have been developed to predict air quality in a particular region or at a receptor. Among them, despite its limitations, the Gaussian plume model has enjoyed a degree of popularity mainly due to its simplicity and the fact that it gives reasonable results. However use of air quality models is very limited in Bangladesh. In this study two models – the Gaussian plume model and Caline4, an USEPA (U. S. Environmental Protection Agency) model for predicting CO concentration have been used for predicting air quality at short distance away from road. Carbon monoxide concentrations predicted by Caline4 have been compared with available data. Applicability of the Gaussian plume model in predicting air quality has also been assessed in this study.

Study Area

In this study the air quality models have been used to predict concentration of air pollutant near the Sonargaon Roundabout, the busy intersection of Panthapath and the Kazi Nazrul Islam Avenue. During July-September 2001 a 24-hr continuous air monitoring study was conducted near Hotel Sonargaon (Paul 2002). The Environmental Monitoring Unit (EMU) was placed at the south east corner of Panthapath crossing. Location of the monitoring spot has been presented in Fig. 1.

Observed data show that CO, NOx and SO_2 concentrations reach their peak values between 8 to 10 a.m. Table 1 presents air monitoring data of 26th August, 2001, at the Sonargaon Hotel site at 8 a.m. and 9 a.m., obtained from the monitoring study. In this study these data have been compared with model predictions.

Air Quality Modeling

Traffic and Road Geometry Data

Air quality modeling needs a comprehensive set of input information on traffic volume and composition, road geometry and emission factors for different vehicular fleets. Information on emission factor of different vehicular fleet has been collected from a previous study (Kabir 2002) and is presented in Table 2.

Data on traffic composition was collected from a survey conducted by the Department of Civil Engineering of BUET. Table 3 presents the Traffic Count Survey data for 8 to 10 a.m. at Sonargaon Roundabout. The lane widths of different approach roads are presented in Table 4.

Caline4: USEPA Air Quality Model

In this study, Caline4, a widely used USEPA public domain model was used to analyze impacts of motor vehicle emissions at the Sonargaon Roundabout. The model (version 1.31) is available at www.dot.ca.gov/hq/env/air/Software.

The 'Caline4' model demands extensive data on roadway

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geometry, traffic queue, vehicle count, vehicle speed, etc. In this study the Sonargaon Roundabout was selected for model simulation primarily because roadside air quality data as well as traffic and road geometry data for this busy intersection were available. The available roadside air quality data for this site has been summarized in Table 1 and the data on traffic volume and road geometry have been presented in Tables 3 and 4 respectively.

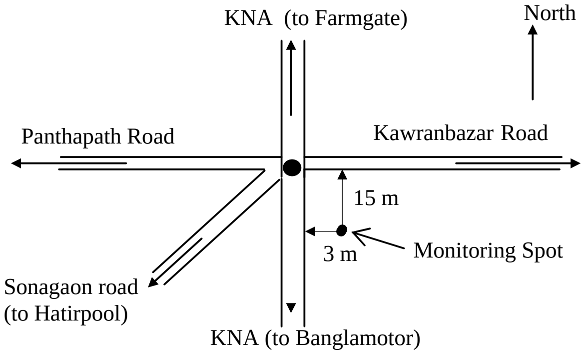

Fig. 1 Location of air monitoring sampling spot

Table 1 Air monitoring data of CO, NOx, and SO_2 on August 26, 2001 at Sonargaon

Hour	**CO (ppm)**		**NOx (ppm)**		**SO_2 (ppm)**	
	Hourly Highest	Hourly Lowest	Hourly Highest	Hourly Lowest	Hourly Highest	Hourly Lowest
8	7.08	2.10	0.173	0.0344	0.3615	0.0820
9	7.19	3.45	0.234	0.0687	0.4297	0.1855

Source: Paul (2002)

Table 2 Selected Emission Factors for the vehicular fleet in Dhaka (in gm/km)

Category of Vehicles	**CO**	**NOx**	**SOx**
Bus/Minibus	25.92	20.47	3.14
Truck	31.79	6.48	4.27
Light Vehicle	42.67	1.48	0.41
Three Wheeler	28.10	0.03	0.25
Motor Cycle	26.00	0.02	0.22

Source: Kabir (2000)

Table 3 Traffic Count Survey at Sonargaon Roundabout on August 26, 2001

Approach	**North (KNA)**		**South (KNA)**		**East (Panth)**		**West (Panth)**		**Other (Son)**	
Time (a.m.) Vehicle Category	8:00 – 9:00	9:00-10:00	8:00 – 9:00	9:00-10:00	8:00 – 9:00	9:00-10:00	8:00 – 9:00	9:00-10:00	8:00 – 9:00	9:00-10:00
Bus	509	411	400	380	37	54	11	7	4	8
Truck	31	31	13	17	22	30	4	11	10	7
L. Veh	1461	1120	1376	1214	845	776	817	719	318	329
T. Wheel	1225	1269	957	1161	677	756	414	495	469	449
M. Cycle	251	206	106	96	85	47	148	87	70	73
Rick	--	--	--	--	--	--	--	--	394	560
Total	3477	3037	2852	2868	1666	1663	1394	1319	1261	1418

Source: Haq (2002)

L. Veh (Light Vehicle) = Car, Jeep, Taxi, Pajero, Microbus, Ambulance, Pickup, Maxi, Duranta etc.;
Bus = All type of buses; Truck = All type of trucks; T. Wheel (Three Wheeler) = Tempo, Babytaxi, Mishuk;
Rick = Rickshaw, Van; M. Cycle = Motor Cycle;
KNA = Kazi Nazrul Islam Avenue; Panth = Panthapath road; Son = Sonargaon road

Table 4 Roadway width of different approach roads at Sonargaon Roundabout

Approach Road	**Lane Width, feet (m)**
North (Kazi Nazrul Islam Avenue)	125.60 (38.3)
South (Kazi Nazrul Islam Avenue)	96.80 (29.5)
East (Panthapath road)	104.00 (31.7)
West (Panthapath road)	109.25 (33.3)
Other (Sonargaon road)	86.60 (26.4)

Source: Hassan (2002)

Receptor position has been selected at monitoring spot (Fig. 1) to compare the results with observed data. The height (Z) for receptor position is taken as 1.8 m (average human height).

Parameters assumed in predicting CO concentration using Caline4 are as follows:

- Wind speed: 1 m/s (Coe 1998)
- Wind direction: Worst case wind angle. For this option model selects the wind angles that produce the highest CO concentrations at each of the receptors (Coe 1998).
- Mixing Height: 1000m (Coe 1998)
- Ambient Temperature: 20 ^{o}C

Gaussian Plume Model

Caline4 is a user interface designed to work with CO protocol and can only be used for CO concentration analysis. So for the prediction of other pollutants (e.g. NOx, SOx) concentration the basic equation of Gaussian plume model for line source have been used in this study.

Gaussian plume model considers the assumption that the time averaged pollutant concentration downwind from a source can be modeled using a normal or Gaussian distribution curve. The basic Gaussian dispersion model applies to a single point source such as smokestack, but it can be modified to account for line sources (such as emission from motor vehicle) or area sources. To begin, let us consider a single point source as shown in Fig. 2. The co-ordinate system has been set up to show a cross section of the plume, with z representing the vertical direction and X being the distance directly downwind from the source. Since stack emission have some initial upward velocity and buoyancy, it might be some distance downwind before the plume envelope might begin to look symmetrical about a centerline. The centerline would be somewhat above the stack height. The highest concentration of pollutant would be along this centerline, with values getting lower as we get further away.

The Gaussian plume model assumes that pollutant concentration follows a normal distribution in both the vertical planes and in the horizontal direction as shown in Fig. 3. It also treats emission as if coming from a virtual point source along the plume centerline, at an effective stack height H.

The equations used in Gaussian plume model for estimating pollutant concentration in air are as follows (Masters 1991):

i) Point source:

(a) No ground reflection (particles, Nitric acid, Vapor):

$$C(x,y,z)=\frac{Q}{(2\pi\sigma_y\sigma_z u)}\times e^{\left[\frac{-y^2}{2\sigma_y^2}\right]}\times e^{\left[-\left(\frac{(z-H)^2}{2\sigma_z^2}\right)\right]}$$

(b) Ground reflection (CO, SO_2, NO_2):

$$C(x,y,z)=\frac{Q}{(2\pi\sigma_y\sigma_z u)}\times e^{\left[\frac{-y^2}{2\sigma_y^2}\right]}\times\left\{e^{\left[-\left(\frac{(z-H)^2}{2\sigma_z^2}\right)\right]}+e^{\left[-\left(\frac{(z+H)^2}{2\sigma_z^2}\right)\right]}\right\}$$

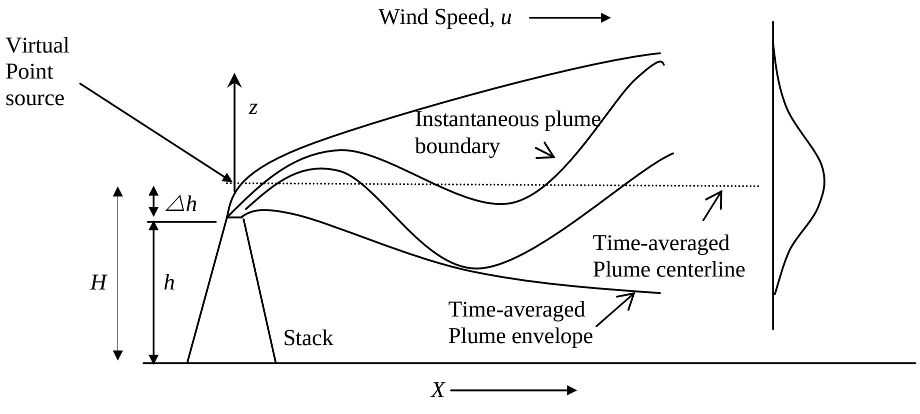

Fig. 2 The instantaneous plume boundary and a time-averaged plume envelope

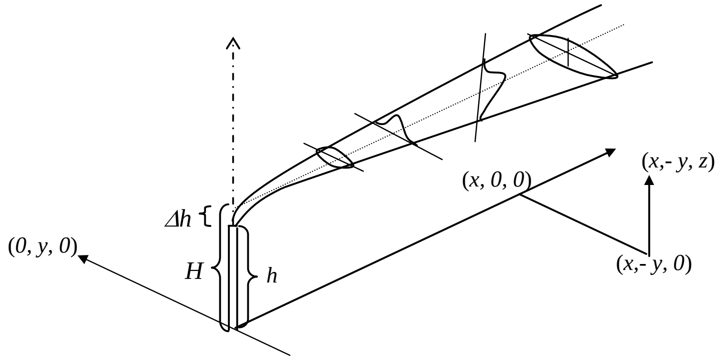

Fig. 3 Plume dispersion coordinate system, showing Gaussian distributions in the horizontal and vertical directions

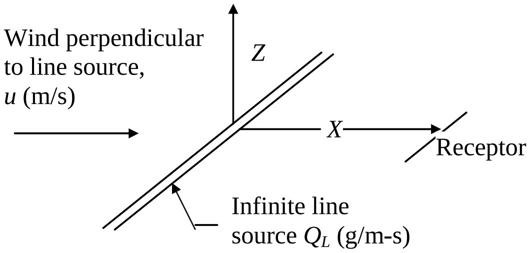

Fig. 4 Line diagram showing a typical line source

where,
C = pollutant concentration (g/m^3, μg/m^3)
Q = uniform continuous emission rate (g/s, μg/s)
u = mean wind speed at plume height (m/s)
σ_y = cross wind dispersion parameter (m)
σ_z = vertical dispersion parameter (m)
x, y, z = location of receptor
H = effective stack height
(= stack height + plume rise = $h + \Delta h$)

ii) Line source (e.g., roadway):

For line source, for example motor vehicle traveling along a straight section of a highway, cross wind dispersion along y direction is neglected and stack height H = 0. Therefore the equations for line sources take the following forms (Masters 1991):

(a) For no ground reflection (particles, Nitric acid, Vapor):

$$C(x,0,z) = \frac{Q_L}{(\sqrt{2\pi}\sigma_z u)} \times e^{\left[-\left(\frac{(z-H)^2}{2\sigma_z^2}\right)\right]} \tag{1}$$

(b) For ground reflection (CO, SO$_2$, NO$_2$):

$$C(x,0,z) = \frac{Q_L}{(\sqrt{2\pi}\sigma_z u)} \times \left\{ e^{\left[-\left(\frac{(z-H)^2}{2\sigma_z^2}\right)\right]} + e^{\left[-\left(\frac{(z+H)^2}{2\sigma_z^2}\right)\right]} \right\} \tag{2}$$

Eqs. (1) and (2) represent the line source equations for Gaussian plume model. Since for CO, NOx and SOx ground reflection must be considered, Eq. (2) has been used here. Input variables used for simulation are as follows:

- Effective stack height, H = 0 m (for line source)
- Receptor position in vertical direction, z = 0 m
- Wind speed, u = 1m/s (assumed according to USEPA recommendation, as field data for wind speed is not available)
- Source emission rate per unit length of road (g/m-s), Q_L is determined using information on traffic volume and emission factor.
- Vertical dispersion coefficient (m), σ_z is determined using information on atmospheric stability condition (A-B) and receptor position (distance perpendicular to the road centerline), x. CO concentrations from the equation are obtained in g/m^3.

Estimation of Vertical Dispersion Coefficient, σ_z and Source Emission Rate

This coefficient (σ_z) is not only a function of downwind distance, but also depends on atmospheric stability, release height, surface roughness, height of the mixing layer, as well as other factors. The most common procedure for estimating the vertical dispersion coefficient was introduced by Pasquill and modified by Gifford and adopted by the U.S. Public Health Service. It is presented here as Fig. 5 (Masters 1991), where the parameters A-F represent stability classifications based on qualitative descriptions of prevailing environmental conditions, where A represents extremely unstable atmosphere and F represents stable atmosphere.

It is often easier to use computer to work with Eqs. (1) and (2), in which case the graphical representation of dispersion coefficient is inconvenient. There are several equations available to estimate the value of vertical dispersion coefficient, σ_z to fit the well-known curve of Pasquill-Gifford shown in Fig. 4. The equations available to determine the value of vertical dispersion coefficient σ_z are listed below:

1. Martin's Equation (Masters 1991):

$$\sigma_z = C x^d + f$$

2. Rao (1989):

$$\sigma_z = B x^p$$

3. American Meteorological Society (Jennings 2002):

$$\sigma_z = a x^b$$

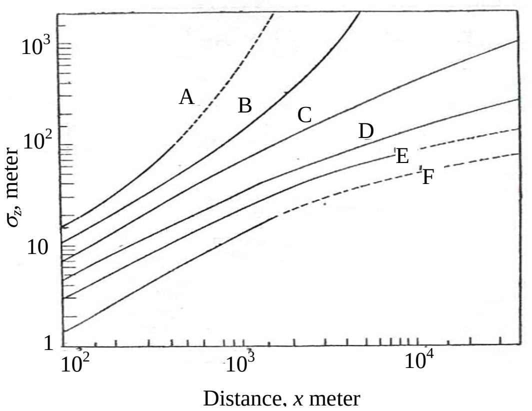

Fig. 5 Vertical dispersion coefficient σ_z as a function of distance downwind

4. Turner's Equation (Jennings 2002):

$$\sigma_z = a\, x^b$$

More detailed description of the equation including values of the constants *a, b, c, d, f, B* and *p* have been presented in Ferdous (2003).

3. Briggs' Formula (Lyons & Scott 1990):

Table 5 presents the equation for Gaussian dispersion coefficients for different stability condition given by Briggs.

For determining the most suitable values of σ_z to be used in the Gaussian model, CO concentration at the Sonargaon Roundabout, was estimated using all available equations and the results (CO concentration) were compared with those obtained by Caline4. For his purpose, only a single link (Kazi Nazrul Islam Avenue South approach) was defined in link geometry screen of Caline4.

Source emission rate per unit length of road (g/m-s), Q_L for Kazi Nazrul Islam Avenue north approach during 8 to 9 a.m. was determined as presented in Table 6.

Results and Discussion

Prediction of CO Concentration using Caline4

Table 7 presents a comparison of CO concentration values obtained by Caline4 with those observed during field survey. The simulation was made for the traffic condition prevailing in August 26, 2001 and compared with CO concentration measured at the same day. In order to compare the predictions made by Caline4, CO concentration at monitoring spot (Fig. 1) was determined for both stable and unstable conditions. The results show that the predicted values are in between the observed highest and lowest hourly average values.

Prediction of CO Concentration using Gaussian Plume Model

CO concentrations for different stability classes (A-E) were calculated from the Gaussian equation (Eq. 2) using different equations for estimating σ_z value. The CO concentration as a function of horizontal distance for different stability classes was calculated; Fig. 6 shows the result for stability class E.

Table 5 Formula recommended by Briggs for σ_z, where 100<x<10000m

Stability Class	σ_z (m)
	Open Country Condition
A	$0.20x$
B	$0.12x$
C	$0.08x(1+0.0002x)^{-0.5}$
D	$0.06x(1+0.0015x)^{-0.5}$
E	$0.03x(1+0.0003x)^{-1}$
F	$0.016x(1+.0.0003x)^{-1}$
Urban condition	
A-B	$0.24x(1+0.001x)^{0.5}$
C	$0.20x$
D	$0.14x(1+0.0003x)^{-0.5}$
E-F	$0.08x(1+0.0015x)^{-0.5}$

Table 6 Estimation of Source emission rate per unit length of road (g/m-s), Q_L

Vehicle Category	Volume, Veh/hr (X_i)	Emission Factor, gm/km (E_i)
Bus	400	25.92
Truck	13	31.79
L. Veh	1376	42.67
T. Wheel	957	28.1
M. Cycle	106	26
Source emission rate per unit length of road, $Q_L = \Sigma\left(\frac{X_i}{3600} \times \frac{E_i}{1000}\right) =$		0.02754g/m-s

Table 7 Comparison of CO concentrations predicted using Caline4 with observed data

DATE: 26th August 2001 (Day of traffic count survey)			CO Conc. (ppm) at Monitoring Spot
Prediction at monitoring spot using Caline4 (at 8 to 9 a.m.)	Stability	(Most Unstable	3.5
		(Most Stable)	3.7
Observed data on 26th August 2001 (Day of traffic count survey)	Hourly Highest	8 a.m.	7.08
		9 a.m.	7.19
	Hourly Lowest	8 a.m.	2.1
		9 a.m.	3.45

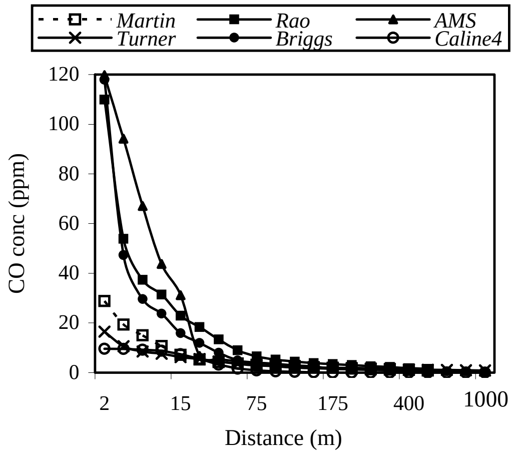

Fig. 6 Comparison of CO concentration prediction using different approaches for stability class E

Fig. 6 shows that for stability class E, analytic solution (Gaussian equation), using σ_z value obtained from Turner's equation very closely matched the CO concentrations obtained by Caline4 for a distance above 8 m.

Selection of Equation for Estimating σ_z

In this study, results of analytic solution (Gaussian equation) for CO concentration using different equations for estimating σ_z have been compared with the results of Caline4 at different locations. From detailed analysis of the results obtained from the Gaussian model (using different methods for estimating σ_z) and then comparing with the Caline4 model results, the most suitable equations for estimating σ_z for different stability classes are determined.

Table 8 shows the selected equations for estimating vertical dispersion coefficient for different stability conditions. Fig. 6 shows a comparison of CO concentrations obtained by the Gaussian plume Eq. (2) using selected σ_z values estimated according to Table 8, with those obtained by Caline4. Fig. 7 shows reasonable match between the different model results.

Prediction of NOx and SOx Concentration using Gaussian Equation

NOx and SOx concentration at the monitoring spot (Fig. 1), 3m from KNA (South) and 15m from Panthapath (East), was calculated by the Gaussian equation for stability class E, using the selected vertical dispersion coefficient.

Source emission rate per unit length of road (g/m-s) Q_L was determined for KNA (South) and Panthapath (East) during 8 to 9 a.m. using source emission factors and traffic volume presented in Table 2 and Table 3. NOx emission rates at KNA (South) and Panthapath Road are 0.002872g/m-s and 0.000603 g/m-s respectively; and SOx emission rates at KNA (South) and Panthapath Road are 0.000594 g/m-s and 0.000207 g/m-s respectively.

The results of NOx and SOx predictions are presented in Table 9. Observed data at monitoring spot on the day of traffic count survey are presented in Table 10. Observed SO_2 concentrations at the monitoring spot are more or less close to the predicted value, whereas for NOx, observed values appeared to be significantly lower than the predicted value.

Table 8 Selected equations for vertical dispersion coefficient

Stability Class	Equation for σ_z	Source	Range	Description			
A	$\sigma_z = 0.24x(1+0.001x)^{0.5}$	Briggs	8m-1000m	x in m, σ_z in m			
B	$\sigma_z = C x^d + f$	Martin	x <8m	x in km, σ_z in m	*C*	*D*	*f*
					106.6	1.149	3.3
	$\sigma_z = 0.24x(1+0.001x)^{0.5}$	Briggs	8m-1000m	x in m, σ_z in m			
C	$0.20x$	Briggs	10m-1000m	x in m, σ_z in m			
D	$\sigma_z = a x^b$	Turner	5m-1000m	x in km, σ_z in m	*a*	*b*	
					0.73	0.55	
E	$\sigma_z = a x^b$	Turner	5m-1000m	x in km, σ_z in m	0.82	0.48	

Table 9 NOx and SO_2 concentration for stability class E at monitoring spot predicted analytically

Position	NOx Concentration (ppm)	SO_2 Concentration (ppm)
Contribution from KNA (south) –3m	1.415	0.293
Contribution Panthapath (east) –15m	0.137	0.047
At monitoring spot (Total)	1.552	0.340

Table 10 Observed values of NOx and SOx at monitoring spot near Sonargaon Roundabout

Observed Data on 26th August 2001 (Day of Traffic Count Survey)		NOx Conc. (ppm) at Monitoring Spot	SOx Conc. (ppm) at Monitoring Spot
Hourly Highest	8 a.m.	0.173	0.3615
	9 a.m.	0.234	0.4297
Hourly Lowest	8 a.m.	0.0687	0.082
	9 a.m.	0.0591	0.1855

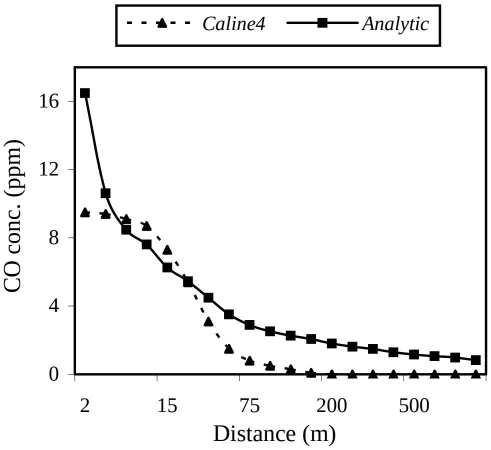

Fig. 7 Comparison of the CO concentration obtained by analytic solution (Gaussian equation) using selected σ_z values with those obtained by Caline4 for stability class E

Conclusion

Predicted CO concentration using Caline4, at short distances away from road matched the observed data quiet well. It appears that the USEPA preferred highway pollution model Caline4 could be conveniently used for predicting CO concentration provided the input data are estimated correctly. Gaussian plume model provides a simple method by which useful results can be obtained provided its limitations are properly understood. Different models are available for estimating the vertical dispersion coefficient (σ_z) in the Gaussian equation and these different methods yield significantly different results especially at short distances. From comparison of results obtained by using the Gaussian equation and Caline4, suitable equations for estimating σ_z values have been proposed for different stability condition.

Gaussian model neglects the turning of wind due to frictional effects. This tends to spread plume in cross sectional direction. Also the consideration of absorption or deposition of pollutants when the plume reaches the ground is neglected. If the plume is reactive the model gives inaccurate results. Hence care is required in using the equation.

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