Model predictions of mean carbon monoxide concentration for Delhi*

(MRS.) NIRUPAMA RAGHAVAN
Centre for Atmospheric Sciences, IIT, New Delhi
and
B. PADMANABHAMURTY
India Meteorological Department, New Delhi

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सार — दिल्ली के शहरी क्षेत्रों के लिए शीत ऋतु के एक महीने के दौरान कार्बन मोनोआक्साइड सघनता की मॉडल गणना कर ली गई है । इस मॉडल में मिश्रण ऊंचाइयों और स्थिरताओं का भी उपयोग किया गया है । आकाश के स्वरूप से नगर केन्द्र की उच्च सघनता अनुवात के समूह नजर आते हैं । इस अध्ययन से वायु की गति तथा दिशा के प्रति कार्बन मोनोआक्साइड सघनता की संवेदनशीलता और विकिरण तथा दिन के समयानुसार संयमित संवेदनशीलता की पुष्टि होती है ।

ABSTRACT. Model calculations of carbon monoxide (CO) concentrations for urban Delhi for a winter month have been made. In this model mixing heights and stabilities also are used. The spatial pattern showed pockets of high concentration downwind of city centre. The study confirmed the sensitivity of CO concentrations to wind speed and direction and moderate sensitivity to emissions and hour of day.

1. Introduction

Carbon monoxide is a common pollutant particularly in the urban atmosphere. It is a dangerous asphysiant because it combines strongly with the haemoglobin of blood reducing its ability to carry oxygen. Though inert it can build-up to levels that constitute a human health hazard under certain meteorological conditions. The most important source of carbon monoxide in urban areas is vehicular traffic which is very high in Delhi. It is, therefore, appropriate to make model calculations of carbon monoxide concentrations for urban Delhi. The present work predicts the mean concentrations of carbon monoxide for the month of December. In this month, mixing heights are low for a sizeable fraction of the day and under stable atmospheric conditions, build-up of ground level pollutant concentrations is likely.

2. Choice of dispersion model

Several models have been used to predict carbon monoxide concentrations due to traffic in urban areas (Johnson *et al.* 1972, Ott *et al.* 1967, Remsberg *et al.* 1979). The first two are based on a receptor oriented model, for a Gaussian type of diffusion; the model is used to predict current and future carbon monoxide concentrations, on the basis of quasi steady state diffusion equation :

$$\bar{u}(z)\frac{\partial \bar{c}}{\partial x} = \frac{\partial}{\partial z}\left[K(z)\frac{\partial \bar{c}}{\partial z} \right] \tag{1}$$

$\bar{u}(z)$ is the mean velocity in the x-direction, $K(z)$ is the coefficient of eddy diffusivity. Here, along wind diffusion is assumed to be negligible in comparision with the vertical diffusion term. A similar equation can be written for dispersion in the crosswind direction. Remsberg *et al.* (1979) use a time dependent box type of model, to examine the effect of nocturnal inversion on hourly carbon monoxide concentration:

$$C_{n+1} = C_n\left(1 - \frac{V_n \triangle t}{L}\right) + \frac{V_n \triangle t}{L}.b_n + \frac{q_n \triangle t}{h} \tag{2}$$

L is the horizontal dimension of the box, b_n is the concentration at the lateral boundary, V_n is the local horizontal wind velocity, q_n is the CO source strength.

Here C_{n+1} is the predicted concentration at time $(n+1)\triangle t$; CO is taken as some threshold value of .2 ppm.

Since the present work uses climatological values for wind and mixing heights, it is more appropriate to use a steady state model to predict monthly mean concentrations. Hence a receptor oriented model using a Gaussian plume for dispersion is constructed.

3. Model characteristics

Eqn. (1) can be solved exactly for simple power law forms of $K(z)$ and $\bar{u}(z)$ like

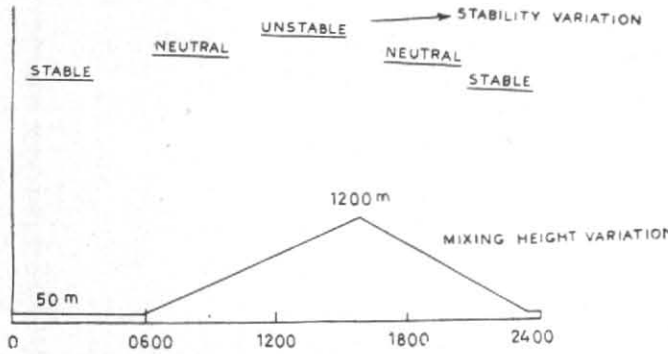$$K(z)=K_1 (Z/Z_1)^n \text{ and } \bar{u}(z) = \bar{u}_1 (Z/Z_1)^m$$

Fig. 1. Diurnal variation of mixing heights and stability. Mixing heights are typical for the month of December)
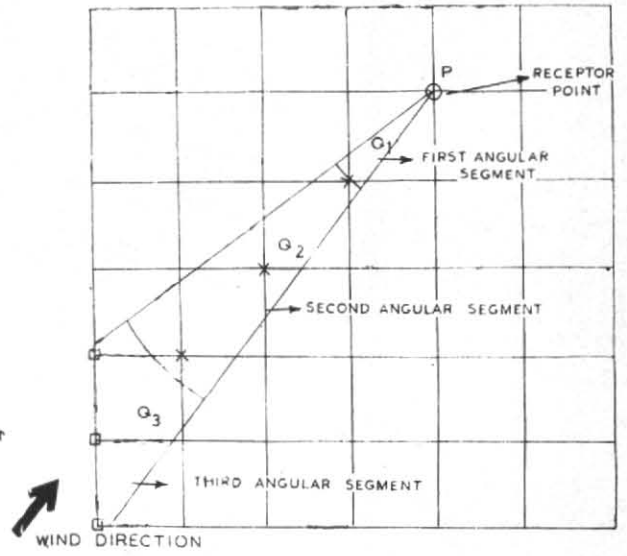
Fig. 3. A typical 22-5° upwind sector for receptor point P. Q_1, Q_2, Q_3, are source strenghts in the angular segments 1, 2 and 3
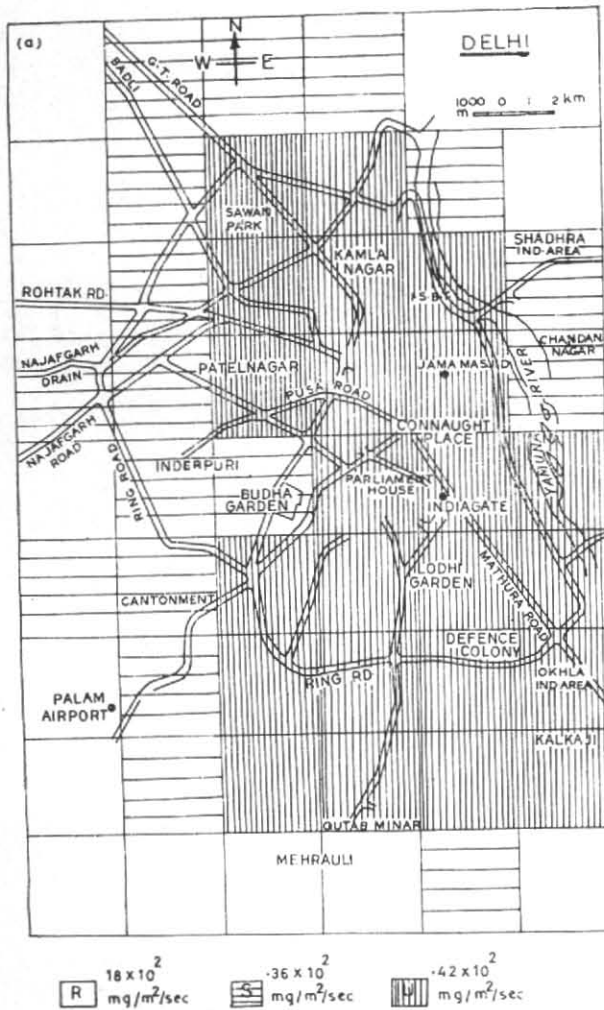
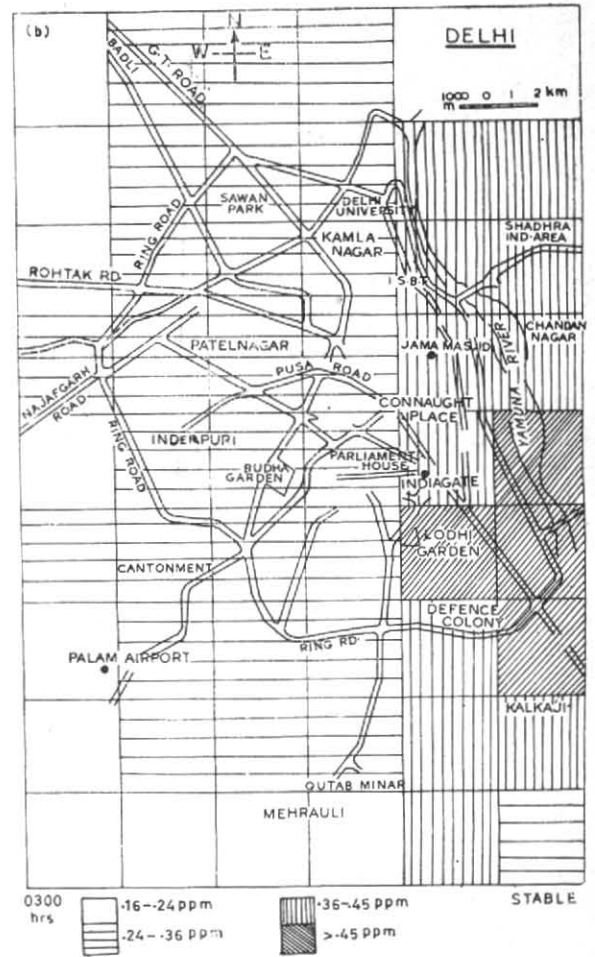Fig. 2. Emission inventory over the urban grid for Delhi

Fig. 4. Concentration pattern for carbon monoxide over the urban grid for 0300 hr for stable condition

where K_1 and $\bar{u}_1$ refer to a fixed reference height Z_1.

It has been shown by Pasquill (1974), that the concentration variations with distance and the vertical spread variation with distance are mutually reciprocal only when $m=0$, *i.e.*, in the idealised case when wind is constant with height, making the use of reciprocal plume hypothesis possible. The solution of Eqn. (1) for the case where $m=n=0$, for a ground level point source is given by :

$$\bar{c} = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp(-y^2/2\sigma_y^2) \qquad (3)$$

$\bar{c}$ is the ground level concentration, Q is the source strength; σ_y and σ_z in units of length are the standard deviations of the cloud distribution in the y and z directions and are a function of distance x. The pollution resulting from many small sources like exhausts from vehicles, however, form an *area source*. The ground level concentration due to an area source can be obtained by integration over area, of the point source plume formula.

Following Hanna (1971) the concentration at a receptor point due to all area sources in the upwind half plane can be written as :

$$\bar{c} = \int_0^\infty \int_{-\infty}^\infty (Q/\pi u \sigma_y \sigma_z) \, e^{-y^2/2\sigma_y^2} dy dx \qquad (4)$$

Since most plumes include only an angle of approximately $20°$, sources outside this sector in the upwind direction of the receptor do not contribute to the ground level concentrations at the receptor. Thus Eqn. (4) becomes

$$\bar{c} = \int_0^\infty \sqrt{2} \, Q/(\pi \, \sigma_z \, \bar{u}) \, dx$$

The pollutant is assumed to be well mixed up to a height of σ_z given by

$$\sigma_z = ax^b$$

Here a and b are parameters dependent on the stability of the atmosphere. If Q can be specified on a grid pattern in the upwind direction then piecewise integration gives :

$$\bar{c} = \frac{\sqrt{2/\pi}}{\bar{u}(1-a)^b} \, \Sigma_i \, Q_i \, (x_{i+1}^{1-b} - x_i^{1-b}) \qquad (5)$$

where the summation over i goes up to the upwind edge of the city.

For all grid distances of x_i from the receptor for which

$\sigma_z >$ mixing height

the contribution to the cncentration to the receptor is given by

$$c_i = \frac{\sqrt{2/\pi}}{\bar{u} \, h_{mix}} \, Q_i (x_{i+1} - x_i)$$

h_{mix} being the mixing height.

Time (IST)	Stability	a	b
0000-0600	Stable	0.06	0.71
0700-1000	neutral	0.22	0.80
1100-1600	unstable	0.33	0.86
1700-1900	neutral	0.22	0.80
1900-2400	stable	0.06	0.71

Thus, for a given wind direction and emission pattern, the concentration at every receptor point can be calculated.

4. Meteorological data

The meteorological data required for obtaining monthly mean concentrations are (1) wind frequency tables for the chosen month, (2) typical stability parameters for the city, as a function of time of the day and (3) mixing heights also as a function of time of the day for the chosen month.

Hourly wind data for the month of December over the years of 1967 to 1976 collected at Safdarjung, New Delhi, have been used. Wind speeds are classified into five classes with mean velocities of $3.0, 8.5, 15.5, 24.5$ and 33.5 m/sec. Wind directions are grouped into 16 directions each encompassing an angular sector of $22.5°$.

Stability parameters as suggested by Smith (1968) are used (Table 1). Also given in Table 1 are average stability categories considered for a particular time of day. These variations are consistent with those found by Hanna (1978) for many U.S. cities. The variation of mixing height with time of the day and the maximum and minimum mixing heights at Delhi in the month of December were obtained from the Climatological studies made by Padmanabhamurty and Mandal (1979).

5. Emission inventory

Mathur (1979) has estimated that the total emission of carbon monoxide in the urban Delhi area is 240 tonnes/day, through sample survey measurements in December 1977. A 6×9 grid 4 km on the side was imposed on the Greater Delhi area. Each grid was designated as rural (R), sub-urban (S) or Urban (U) (Fig. 1). The respective fractions of the total emission that is released in rural, suburban and urban parts was determined as follows. EPA specifications (1971) give the relative number of sampling stations in rural, sub-urban and urban areas, for various cities as a function of population. As a first approximation the emission fractions in the three types of areas were considered to be in the same ratio as
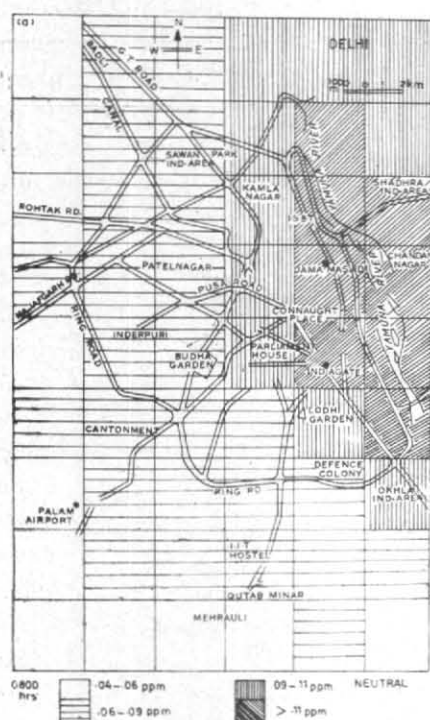
Fig. 5.   Same is as in Fig. 4, but for 0800 hr
          for neutral condition

Fig. 6.   Same as in Fig. 4, but for 1600
          hr for unstable condition
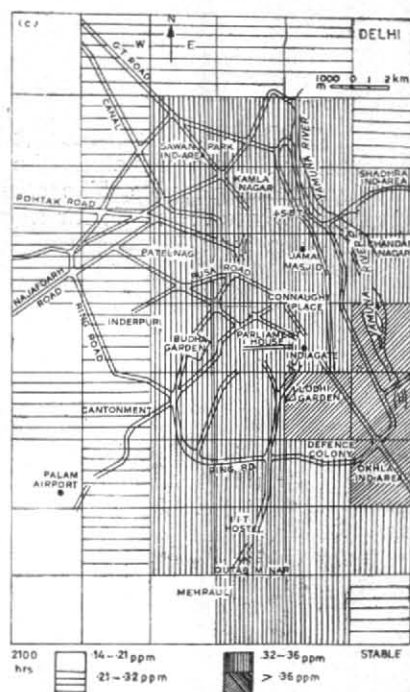
Fig. 7.   Same as in Fig., 4, but for 2100
          hr for stable condition

the sampling stations for a city of the size and population of Delhi. Accordingly the strength of each grid area source was obtained in milligram/m²/sec (Fig. 2).

6. Wind sector geometry

Eqn. (5) is solved for each wind direction segment of 22.5 deg., *i.e.*, the grid pattern of emission is aligned with each wind direction for each receptor point. Fig. 3 shows the assumed geometry. For a fixed receptor point each upwind sector is divided into radial segments up to the edge of the city. The width of each successive segment is twice that of the previous segment. The source strength Qi in the ith upwind segment is obtained by finding the average strength due to all the grid square area sources that lie within this segment. Such a logarithmically increasing segment width has the advantage that at the receptor point the relative concentration contribution due to successive segments is in proportion to the relative source strengths. Thus contributions from all grids up to the edge of the city are taken into account. Again when a detailed inventory based on traffic information is incorporated the effect of nearby emissions can be considered precisely. Since the emission pattern assumed in this work has a resolution

limited by the grid size (4 km) the size of the first segment is taken equal to the grid size.

7. Computation procedure

The input for computing the mean concentrations are :

(a) Wind frequency tables % (frequency of wind in metres/sec),

(b) Mixing heights,

(c) Stability parameter, and

(d) Emission strengths (milligram/m²/sec).

A program AIRQUALITY has been developed for ICL 2960. It inputs meteorological information and emission inventory through subprograms WEATHER and EMIT while UPWIND solves the wind sector geometry for each receptor point, DISPER calculates the appropriate source strength within each angular segment and then computes the concentration contribution due to each upwind segment, with appropriate a and b parameters. In its current form the program uses hourly wind frequency and emission prescribed in the grid squares as mentioned earlier. Modification to include other patterns could be introduced easily.

The output of the program are the monthly mean CO concentration in ppm as a function of time of day for each receptor point. In addition an 8 hr and 24 hr averages can be derived from this using the known relationships between concentrations measured for different averaging times (Urone 1977).

8. Predicted concentration pattern

Fig. 4 gives the expected carbon monoxide pattern at 0300 hr over the area of Delhi. At this time the atmosphere is stable and has a mixing height of 50 m the concentration pattern shows that a pocket of maximum concentration of greater than 0.45 ppm is located southeast of the centre of city. This is consistent with the winds at that time which are predominently from northnorthwest and west (see figure). This pocket of peak concentration is surrounded by a slightly lower concentration covering almost all of the eastern one third part of the city. On moving westwards the concentration decreases, dropping to 0.16 ppm at the western edge of the city. Figs. 5, 6 and 7 give the concentration patterns at 0800, 1600 and 2100 hr for neutral, unstable and stable conditions of atmosphere. In each case the zone of high concentration is found in the direction with respect to city centre, that is downwind from the prevailing wind direction for that hour. This clearly demonstrates the effect of wind direction in the dispersal of carbon monoxide.

The four patterns presented also show the combined effect of the three meteorological variables for a given emission. The stability of the atmosphere controls the vertical spread of the pollutant through parameters a and b. If the mixing height is less than this spread, then the vertical dilution is restricted by this height. The third parameter is the combined frequency of wind direction and speed typical of that hour, which influences the horizontal dilution. One of the effects of wind has already been seen to be, to decide the location of pockets of maximum concentration. At 0300 hr a low mixing height coupled with low wind speeds restricts the next lower level of concerntration to about one third of the city. At 2100 hr similar wind speed but much larger mixing height (730 m) reduces the peak predicted concentration by 20% for the same conditions of stability. Further, the area of the next lower level concentration is twice as large, occupying nearly two-thirds of the city.

As expected, at 0800 hr (neutral stability) the peak concentration is considerably less. With a mixing height of around 200 m, relatively high concentrations occur in one third of the city in the northeastern sector, downwind of the prevailing wind direction The pattern at 1600 hr (Fig. 6) shows the least peak concentration with lower concentrations prevailing over more than three fourths of the city, relatively high concentrations occur in the southeast sector.

It is seen that the concentration levels even for the highly stable, low mixing height case is less than 0.5 ppm, a satisfactorily low level. It must, however, be pointed out that the present investigation calculates monthly mean concentrations. The values averaged over an hour are typically higher by a factor of 4.4, giving an hourly concentration of 2.2 ppm. It must be emphasised that we use an inventory which is a twentyfour hour average and also assume zero background concentration, the hourly peak emission can be up to 2.5 times the average. In addition local effects like street canyon phenomena may further increase local concentrations, leading to situations when the EPA standard for maximum 8 hour concentration of 9 ppm (EPA, 1972) may be exceeded. Work is in progress including these aspects. Roth (1974) has shown that CO concentrations are most sensitive to wind speed and direction and moderately sensitive to emissions and hour of day. These conclusions are also confirmed in the present work.

Acknowledgements

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