PREDICTING MOTOR VEHICLE AIR POLLUTION CONCENTRATIONS FROM HIGHWAY NETWORK ANALYSIS

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An urban diffusion model has been developed that uses urban transportation planning variables, such as speeds, volumes, and distances on network links, together with readily available meteorological data to forecast concentrations of carbon monoxide in an urban area. The model includes a submodel that computes carbon monoxide concentrations in urban street canyons, taking account of carbon monoxide produced within the canyon as well as background carbon monoxide. The model is particularly well suited to evaluation of the relative air pollution potential of alternative urban highway networks. It can also be used to evaluate alternative strategies for meeting air quality standards and to indicate sites for air quality monitoring stations. The model has been validated in a 2-year program that has included comparison of historical data from continuous air-monitoring stations and instrumented sites in St. Louis and San Jose. The model will be expanded to take account of other pollutants such as oxides of nitrogen.

•THE growing severity of review of new highway construction at the corridor and route location levels requires analysis of environmental factors at the time alternative networks are studied. This is particularly important for urban network study, where the choice of paths through the network may be greatly influenced by traffic and construction requirements that make certain paths more attractive than others. No matter how attractive the proposed network changes may be to the traffic engineer or city planner, they cannot be implemented if there are environmental effects that are unacceptable to the local community.

Methods for evaluating the effect of network changes on community values have been proposed (1) including the effects of air pollution. The study of air pollution effects at the network level will help to avoid future problems. Also, air pollution effects occur on a scale similar to that of the network, and they should be analyzed throughout the network, not just in the vicinity of the new construction.

A model, designated APRAC-1A, for analyzing air pollution concentrations that result from urban highway networks has been developed at the Stanford Research Institute. This model is programmed for a large-scale electronic computer to accept highway network descriptions and meteorological parameters that are commonly available and will produce concentration values at designated coordinates in the area. Further, the model is sensitive to changes in network configuration and traffic volumes.

Figure 1 shows one output of the model—concentration isopleths for the St. Louis area based on the historical network file of the IBM 360 urban planning program battery. The concentrations shown in Figure 1 are those that would result for a specified set of meteorological conditions if the traffic grew at the rate forecast and if no improvements were made in vehicular emissions. Figure 2 shows how the concentrations would change with improved emission control devices on the vehicles.

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The APRAC-1A diffusion model can be used to derive a number of different kinds of indexes for various uses. For example, the community-values analysis has suggested that "population dose" might be a meaningful community-effects parameter. Population dose can be computed from 8-hour average concentration values at the traffic zone centroids, multiplied by the zone population. Other pollution-related indexes could also be developed.

MODEL FORMULATION

The APRAC-1A model has several components: an emissions model that converts the traffic input data into spatially distributed emissions, a diffusion model that describes the mixing and transport of the pollutant as it moves downwind, submodels that convert conventional meteorological data to atmospheric mixing parameters, and a submodel that describes phenomena in downtown street canyons (streets lined by tall buildings). The model is discussed in detail elsewhere (2, 3, 4); however, the following brief description is included to illustrate its capabilities.

Emissions Submodel

The emissions submodel is organized to accept highway data that describe each link in the network. The link data required are node coordinates, distance along link between nodes, average daily traffic volume, and average speed. These parameters are commonly available from historical record files in traffic planning programs or can be derived from other commonly available materials such as maps.

Emissions from each link are computed according to a composite route model that was developed (5) by measuring emissions from a large number of vehicles over a composite urban route and then fitting the following exponential relation between the resultant average emissions, E (grams/vehicle-mile) and average route speed, S (mph):

$$E = \alpha S^{\beta} \qquad (1)$$

The original values of the constants α and β were derived from tests performed on vehicles that were not equipped with exhaust emission control devices. Parameters for vehicles with various degrees of emission control have been estimated (1). These estimated values of α and β for various model years are as follows:

Model Year	α	β
1972 to 1974	160	0.48
1975 to 1979	16	0.48
After 1980	8	0.48

The emission model somewhat underestimates emissions for congested streets and overestimates them for freely flowing traffic streams because idling and low-speed emissions have been averaged over a composite route that includes both types of travel. The validation program indicated that this effect is noticeable, but not serious, in larger scale studies with numerous links because the emissions from a variety of streets tend to be grouped and treated together. An alternative emissions model has been developed (6) for use in detailed investigations of small areas. This alternative model, however, requires knowledge of fine details such as number of signals per mile and ratio of volume to capacity.

Because hourly values are usually desired from the model, the average daily traffic must be allocated to the individual hours. The model contains provision for describing diurnal traffic patterns (Fig. 3). These patterns are usually available from local traffic departments or from a regional transportation study.

For purposes of calculating the concentration at a point receptor, the total emissions within logarithmically spaced annular segments are determined. These segments are aligned with the mean transport wind as shown in Figure 4. The innermost sector extends 125 m from the receptor—roughly comparable to the size of a city block. The outer sectors are 22.5 deg wide, which corresponds to the plume width predicted by Gifford (7) for slightly unstable conditions; the broader 45-deg sectors near the receptor allow for large initial dispersion. Emissions are assumed to be uniformly distributed within each sector. The smaller sectors near the receptor provide the higher resolution required for nearby sources. Emissions in each segment are calculated as the sum of the emissions on all the links and parts of links that lie within the segment.

Diffusion Model

The "Gaussian plume" diffusion formulation used by this model assumes that the vertical concentration profile from a crosswind line source (such as a road) is Gaussian in shape (Fig. 5). The spread of this vertical concentration distribution is characterized by its parameter, σ_z, which has been found experimentally to be reasonably well approximated by an equation of the form

$$\sigma_z = ax^b \tag{2}$$

The parameters a and b depend on the atmospheric stability; x is the downwind travel distance.

A simple box model is applied for distant segments when there is a limiting mixing depth, h, determined by the vertical temperature stratification. Under these conditions, pollutants tend to be distributed uniformly in the vertical after sufficient travel has taken place, and the concentration, C_i, from the ith segment is proportional to the source strength, Q_i, in that segment and the distance subtended by it $(x_{i+1} - x_i)$. the concentration is inversely proportional to wind speed, u, and mixing depth, h:

$$C_i = \frac{x_{i+1} - x_i}{uh} Q_i \tag{3}$$

A change from the Gaussian model to the box model is made at the distance where the two would give equal values of concentration if applied to a line source.

Mixing Height Submodel

Mixing height is determined from the morning lapse rate at the nearest National Weather Service Radiosonde station using the physical characteristic that a mixed layer of the atmosphere has an adiabatic lapse rate. The observed lapse rate and the surface temperature at a given hour during the day determine the height at which a parcel of air lifted adiabatically would reach the temperature observed at that height by the radiosonde. This is the mixing height. During daylight hours, observed airport surface temperatures are used to determine mixing height. During predawn hours, airport temperatures are augmented to account for urban heat island effects. Interpolated values are used during post-sunset hours.

Stability Submodel

Atmospheric stability is categorized to determine the proper function to use for σ_z. The stability submodel has employed a method that makes use of observed wind speed and cloud cover and the intensity of isolation. The last factor is not measured but can be estimated by using available cloud cover measurements. In general, daytime stability increases with wind speed and decreases with increased solar heating. At night, the stability increases with the increased surface cooling. Increased wind reduces the stability. The model reflects these effects.

Street Submodel

In evaluating the performance of the model after the first-stage development, extensive comparisons (including regression analyses) were made of calculated concentrations with those observed at the Community Air Monitoring Program stations in Chicago, St. Louis, Denver, Cincinnati, and Washington, D.C. The agreement was generally

Figure 1. Calculated concentration patterns based on forecast of 1990 traffic without emission controls.

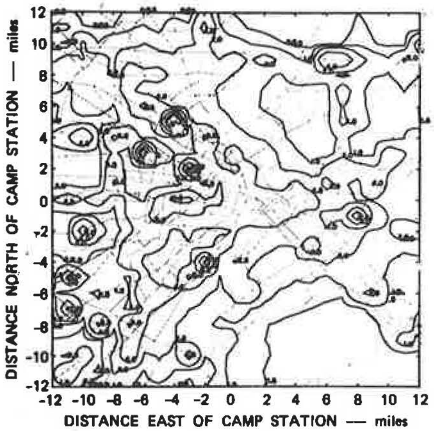


Figure 2. Calculated concentration patterns based on forecast of 1990 traffic with emission controls.

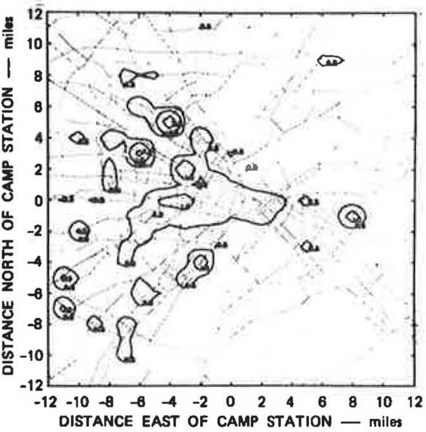


Figure 3. Hourly distribution of traffic.

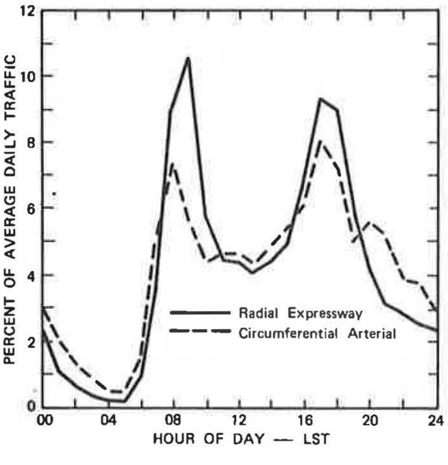


Figure 4. Segments used for spatial partitioning of emissions.

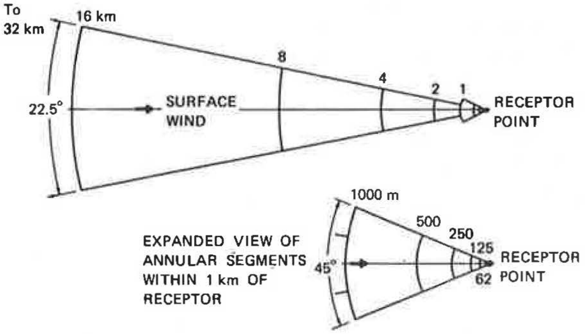
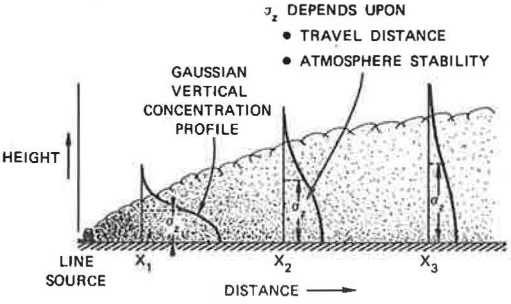


Figure 5. Vertical diffusion according to Gaussian formulation.



fair to good, at least in terms of trends, although there were some instances of poor agreement. Field experiments conducted since the model was initially formulated have revealed several reasons for the observed disagreements. Foremost is the fact that local effects in street canyons and around buildings can sometimes cause carbon monoxide (CO) concentrations to vary by as much as a factor of 3, or 10 ppm from one side of the street to the other. It is obvious that any model that did not account for these effects could be expected to have large errors. A submodel has been developed to take account of these street canyon effects.

Observed distributions of CO imply a helical air circulation in street canyons like that shown in Figure 6. Locations on the leeward side of the building (Fig. 6) are exposed to substantially higher concentrations than on the windward (left) side because of the reverse-flow component across the street near the surface. Thus, the concentration, C, at a point is the sum of two contributions. One is the concentration, C_b, of the air entering the street canyon from above. It is assumed that the concentration computed by the basic diffusion model represents C_b. The second component, ΔC, arises from the CO emissions generated within the street canyon.

Equations for calculating the ΔC components on both the leeward and the windward sides were empirically derived by Johnson et al. (3) and modified by Ludwig and Dabberdt (4). These equations predict that the additive concentrations from the local street traffic are proportional to the local street emissions, Q_L (in grams/meter-second), and inversely proportional to the roof-level wind speed, u (in meters/second), as augmented by a small amount (0.5 m/sec has been found to work well) to account for the air movement induced by traffic. In front of the downwind buildings the air begins its downward flow at roof-level concentration. Pollutants are gradually entrained as the air sinks toward street level, so that CO concentrations on this side of the street increase slightly in the downward direction. The concentrations of the added CO should be inversely proportional to the width of the street, W, which governs the volume of air available for dilution of the emissions from the vehicles in the street. Entrainment has been assumed to vary linearly with height, z, through the depth, H, of the street canyon. Thus, the added CO concentration is given by the following equation for the side of the street on which the buildings face the wind:

$$\Delta C = K \frac{Q_L}{w(u + 0.5)} \frac{H - z}{H} \tag{4}$$

For the other side of the stree, box-model reasoning is used. The volume into which the emissions are mixed is limited by the air circulation toward the buildings and upward. As the air moves from the street-level source, the volume into which the pollutants are mixed increases; the concentration is taken to be inversely proportional to the slant direction, r, between the receptor and the nearest traffic lane. For concentrations in front of the upwind buildings, the equation is

$$\Delta C = K \frac{Q_L}{r(u + 0.5)} \tag{5}$$

The constant, K, is the same for both equations. When the wind blows nearly parallel (within ±30 deg) to the street, the additive concentration, ΔC, is described by the average of the values from Eqs. 4 and 5 and is the same on both sides of the street.

EVALUATION OF MODEL PERFORMANCE

Extensive measurement programs have been conducted in San Jose (3) and St. Louis (4) to test the performance of the various submodels and of the composite model itself. The program and its results as they apply to each of the submodels and the overall performance are described briefly.

Emissions Submodel

San Jose has an extensive computer-based traffic monitoring system that provides detailed information on the traffic in the central business district. This detailed traffic information allowed the emissions submodel to be applied in this area with good confidence. The traffic flow is known from the monitoring network; the average speed was determined from the movements of a project van around the downtown perimeter.

Emissions calculated from the submodel were compared to independent estimates made from a CO mass budget analysis that was based on upper-level wind measurements and CO concentrations measured around the central business district with helicopter- and van-borne instruments. Similar studies were undertaken in St. Louis, where the traffic information was not quite so detailed. The difficulties with the method include uncertainties in the wind field and possible significant changes of CO emission rate during the measurement periods, but the results were sufficiently reliable that serious inaccuracies in the emissions submodel would have been noted if they had been present. The averages of the cases studied show that the two types of CO emission estimates agree within a factor of about 1.5. There seems to be no justification for changing the submodel for most urban applications at this time. Better measurements and recent studies of vehicular accelerations and decelerations on freeways would allow refinements for future applications to these roadways.

Mixing Height Submodel Evaluation

Vertical profile measurements of temperature up to 1,000 m were obtained from helicopter flights and from balloon soundings. These were used to determine mixing depths, which were compared with submodel calculations. Decreases in lapse rate usually marked the top of mixing layer. On several days, the mixing depth was also estimated from measurements made with a laser radar (lidar) that can detect a sharp reduction in aerosol concentration at the top of the mixing layer. The submodel mixing depth was within 50 percent of the mixing depth obtained from temperature soundings and lidar observations in about two-thirds of the cases studied. The submodel used to determine the mixing depth is adequate if representative low-level morning temperature soundings are available.

Stability Submodel Evaluation

The algorithm used to determine stability category was checked against measurements of wind direction variability, and it was found that the two were very consistent. The dependence of σ_z on downwind distance and stability has been revised to reflect the vertical diffusion reported by others for urban fluorescent particle tracer tests in St. Louis, Minneapolis, and Winnipeg.

Street Canyon Submodel Evaluation

Streets in downtown San Jose and St. Louis were instrumented to obtain the data necessary to describe and model the street effects. CO concentrations were measured in detail in the street canyon; winds (in three dimensions) were also measured at numerous locations. Data were automatically collected and recorded on magnetic tape and subsequently used to determine the air circulations and the distributions of CO in the street. Use of this submodel has substantially improved the performance of the model in highly urbanized downtown areas.

Overall Performance of the Model

Performance of the total model, including all its subunits, has been checked against the data obtained at the CO-measuring sites in downtown St. Louis street canyons. Figure 7 shows comparisons of measured and calculated CO concentrations in these two street canyons. The measurements were made at a height of about 4 m, 3 m from the buildings. The street canyon labeled Broadway had a height-to-width ratio of about 1.5 and the other (Locust) had a ratio of about 2. Observations in San Jose indicated good model performance in canyons wider than they were high.

About 650 hours of data were used to test the model performance. The calculated and observed values of CO concentration had root-mean-square differences of 3 to 4 ppm in the street canyon and about 2.5 ppm at roof level. This agreement was achieved by

Figure 6. Cross-street circulation between buildings.

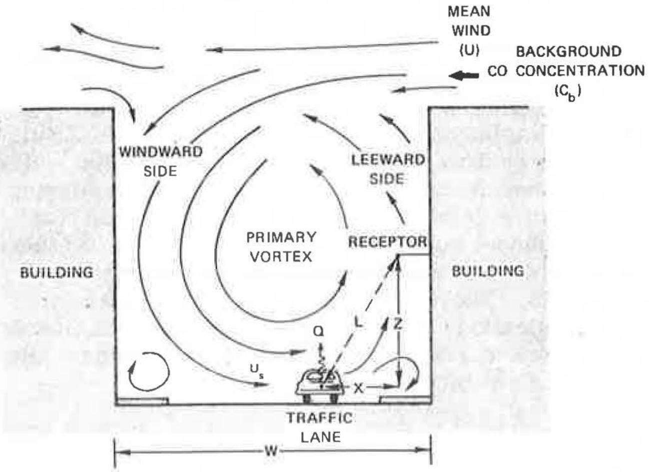
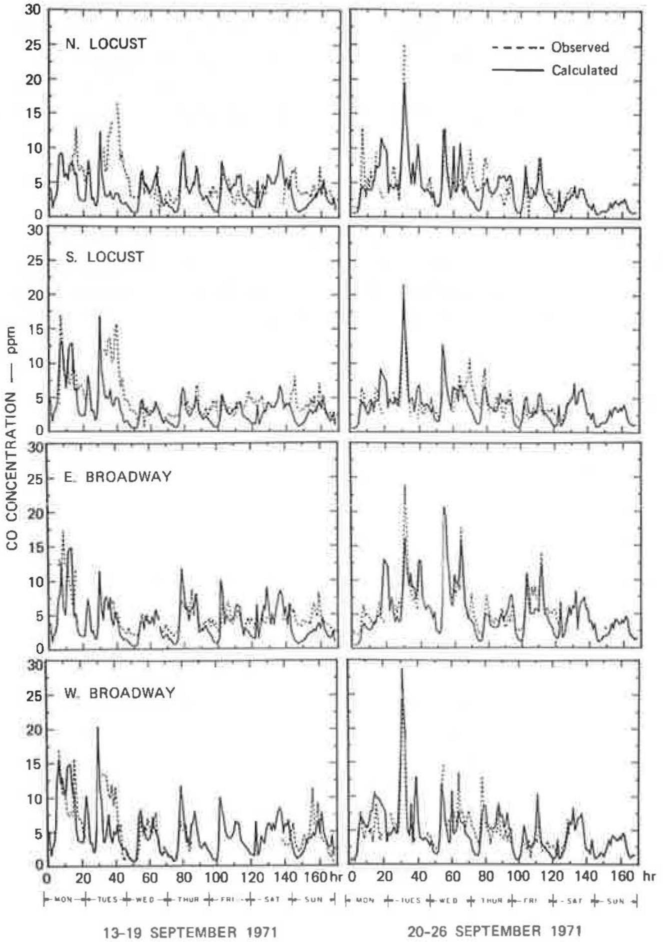


Figure 7. Comparisons of observed and calculated CO concentrations.



using readily available meteorological and traffic data and without any special calibrations. The model was able to predict median and 98th-percentile concentrations for the period within about 2.5 ppm.

APPLICATIONS

Ultimately, it is hoped that urban planners will incorporate diffusion models and their capabilities for forecasting air pollution into the planning process. In addition to its use for comparing the air pollution from alternative network configurations, the model could be used to study the effects of various land use practices and to provide a rational approach to identifying which mixes and configurations of industrial, commercial, and residential areas will reduce air pollutant concentrations. The effects of transporting a part of the commuting population in other than private vehicles are also amenable to investigation with diffusion models.

Various air pollution control strategies can be evaluated by using diffusion models. In the broad sense, the topics discussed in the preceding paragraph—land use practices, alternative transportation systems, and highway network configurations—all represent control strategies. The simplest control strategy appears to be emission reduction, which is readily treated by the APRAC-1A diffusion model (Figs. 1 and 2). On a relatively small scale, improving traffic flow in highly congested areas will reduce air pollution. For the study of these effects, more detailed traffic and emissions models are required to provide better input to the diffusion model and its street canyon submodel. Recently, the feasibility of this type of application has been demonstrated (8). It should be quite feasible to evaluate the effects of actions such as better signal progression, one-way street patterns, and left-turn lanes.

In addition to its use as a tool for evaluating air pollution control strategies, the APRAC-1A diffusion model will provide guidance for locating monitoring stations and estimating the conditions that prevail between existing, widely spaced monitoring sites. For example, in Figure 1, pollution concentrations show peaks in certain areas for the meteorological conditions indicated. Monitoring in such areas will indicate the peak levels to be expected in the area, and the fact that these are the maximum points can be verified by a small number of measurements in adjacent areas. Further, once the levels forecast by the model are verified by measurement, running the model with current traffic and meteorological conditions will provide a continuing picture of what is going on between the stations.

At the present time, the APRAC-1A model provides a way of forecasting CO concentrations that have been verified by an extensive field test program. It is clear that the model formulation will be applicable to other nonreactive gaseous pollutants, and perhaps lead aerosols, if appropriate emissions models are developed. In addition, the model may provide useful information on some reactive pollutants.

By demonstrating the ability to trace a nonreactive gas like CO, the model also shows that it can describe the concentration of the sum of the products of some reactive pollutants produced by vehicles. For example, some data obtained during the model verification indicate that it will be possible to forecast NO_x concentrations resulting from vehicular emissions. Such a forecast would not distinguish between NO and NO_2, and no emission model is available that describes NO_x emissions adequately. We hope to be able to address these problems in the near future because the usefulness of the model in certain areas will be greatly enhanced by the addition of that capability.

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