AIR QUALITY MODELING AT SIGNALIZED INTERSECTIONS

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A good deal of effort has been focused in recent years on the problem of estimating the carbon monoxide ambient air quality impact of roadways. This effort has centered around the characterization of motor vehicle pollutant emissions and the dispersion of pollutants in the atmosphere. Emissions have been characterized as coming from vehicles traveling at an average route speed, and hence an average emission strength has been calculated as a function of average speed and VMT on traffic links. This is the approach presented in EPA Publication AP-42 (1), the FHWA program of model SAPOLLUT (2), and the user's manual for model APRAC-1A (3). The subsequent atmospheric dispersion of pollutants has been estimated by numerical integration along the roadway line source of a Gaussian point source plume, the method used in the EPA HIWAY model (4), or by application of the line source formulation of the Gaussian plume assumption, the technique used in a modified form in the FHWA line source model (5, 6) and in model APRAC-1A.

Increasing attention is now being paid, however, to the localized, microscale problem of hot spots of motor vehicle-related pollutants and, particularly, of carbon monoxide. Hot spots generally occur near locations where traffic congestion, slow speeds, and driving mode changes cause high emission densities and high concentrations. One such location is the signalized intersection. The average route speed assumption is inadequate to characterize either traffic movements or the concomitant emissions at signalized intersections.

This paper presents a validated method for handling the intersection problem. The analytical procedure considers both traffic flow parameters and the effects of driving mode changes on emissions, and it has been used to estimate emissions of carbon monoxide from observed traffic at a signalized intersection. The emission estimates have been applied as inputs to the HIWAY model, and the calculated concentrations show good mean agreement with those observed near the intersection.

METHODOLOGY

The main point of the following approach to describing vehicle movements at signalized intersections is the estimation of queue lengths and average idle times for each leg of the intersection. Other techniques are available, such as those of Webster (7) and Newell (8), and these may be more appropriate in some individual cases. The approach presented here, however, has been used as a component in the successful estimation of carbon monoxide concentrations near intersections, and the other techniques are as yet untried.

Emission factors that depend on driving mode as well as on speed are applied to an idealized model of the behavior of queuing vehicles to develop an emission profile for each intersection approach. All vehicles that stop are assumed to decelerate at a constant rate from a constant cruise speed. They queue up with each vehicle occupying an 8-m (26-ft) interval, and then they accelerate at a constant rate back to cruise speed.

The emission profile is calculated by adding the emissions from each vehicle in each interval according to the speed and mode of the vehicle in the interval.

Estimation of Traffic Parameters

Let the length of the red (plus amber) phase of a traffic signal be R, the vehicle arrival rate be q, the number of vehicles queued at the end of the red phase be N, and the number waiting at the beginning of the red phase be M. Then, based on the assumption of random arrivals and no service during R, the distribution of the quantity N - M is (9)

$$\frac{(qR)^k (e^{-qR})}{k!}, \quad k = 0, 1, \ldots \tag{1}$$

where k equals N - M.

This is a Poisson distribution with mean qR. Based on the assumption that M = 0, the mean queue length per cycle is

$$\overline{N} = q(\text{vehicles/sec})\, R(\text{sec/cycle}) \tag{2}$$

This formula neglects the possibility of additional queuing during the green phase before the initial queue clears the intersection. This can be accounted for as follows to provide a conservative estimate of the total queue length during a signal cycle. Given that N vehicles are queued at the beginning of the green phase, the distribution of the total number of vehicles N′ that will queue up during the red and green phases before the queue disappears is given by (9)

$$\frac{N}{N'} \frac{e^{-N'\rho}(N'\rho)^{N'-N}}{(N'-N)!}, \quad N' = N, N+1, \ldots \tag{3}$$

The mean of this distribution is

$$\overline{N}' = \frac{N}{1-\rho} \tag{4}$$

The parameter ρ is the traffic intensity, which equals the mean arrival rate q divided by the mean service rate s during the green phase. Since $\overline{N} = qR$, the mean total number of vehicles queued during a cycle is given by

$$\overline{N}' = \frac{qR}{1 - q/s} \tag{5}$$

To find the mean queue length on an approach to an intersection, q, R, and s or their equivalents must be known. This is accomplished by using the quantity G/C.

The quantity G/C may be used in 2 essentially equivalent ways. One is as the ratio of the volume of traffic on an intersection approach to the capacity of the approach if there were no competing traffic. The other is as the ratio of the length of the green phase of a signal cycle (seconds) to the cycle length (seconds). The volume of traffic

on an approach to an intersection is a known, an estimated, or a projected quantity. To compute the approach capacity assuming no competing traffic requires that a desired level of service plus other parameters that relate to turning movements, percentage of trucks, approach width, and location be known or assumed (10). The lengths of the green signal phase and the total cycle length can be readily measured for an existing signal or calculated for a planned signal installation, providing the signal is fixed time. For a demand-actuated signal, the phase lengths must be calculated based on the relative volume demand of opposing approaches to the intersection. The total cycle length must still be known. The following discussion describes this calculation as it was done for this study, and it shows the relationship of the 2 uses of G/C.

As an example of G/C calculations, suppose that all 4 approaches to an intersection with a demand-actuated signal have an unimpeded capacity of 1,600 vehicles/hour. That is, ignoring the signal and the conflicting traffic, each lane approaching the intersection can accommodate 1,600 vehicles/hour at the desired level of service. Suppose further that the signal at this intersection has 2 green phases, one for east-west movements and one for north-south movements. The assumed volumes and the calculated required G/C's are given below.

Phase	Approach	Volume (vehicles/hour)	G/C
1	East leg	400	400/1,600 = 0.25
	West leg	350	350/1,600 ≈ 0.22
2	North leg	800	800/1,600 = 0.50
	South leg	600	600/1,600 ≈ 0.38

The G/C for the intersection is the sum of the higher G/C for each green phase, or 0.25 + 0.50 = 0.75. The east and north legs are the critical approaches, and they carry the volumes that the signal must accommodate. Assuming that the amber or yellow phase is 0.10 signal cycle, then Y/C = 0.10, and G + Y/C = 0.85 required for the intersection. Since this is ≤1.00, the intersection will operate at the desired level of service.

Now, there is G/C = 1.00 - 0.85 = 0.15 left over to be divided between the 2 phases. When this has been apportioned, the result will be a G′/C′ for each phase, or what is actually provided for each of the phases. Phase 1 is given its proportion of the 0.15 according to its required G/C:

$$\left(\frac{0.25}{0.75}\right)(0.15) = 0.05$$

Hence, for phase 1, G′/C′ = 0.25 + 0.05 = 0.30. Similarly for phase 2,

$$G'/C' = 0.50 + \left(\frac{0.50}{0.75}\right)(0.15) = 0.60$$

Hence, if the signal cycle length C is 100 sec long, phase 1 will be (0.30)(100) or 30 sec, and phase 2 will be (0.60)(100) or 60 sec long. Note that G and C are now defined as the length of the green phase and the cycle length respectively. The previous meanings of demand volume and unimpeded capacity that were applied to G and C were used to determine how the demand-actuated signal would apportion the total cycle time to the 2 green phases.

The service rate s (vehicles/second) during green in equation 5 is nearly equivalent to the denominator used to compute the quantity G/C as described above. (Actually it will be slightly less, since there is some delay associated with getting the queue in motion. This leads to a tendency to underestimate $\overline{N}'$.) The volume parameter q (vehicles/second) is the actual volume using the roadway, and it is equivalent to the numerator used to calculate G/C. Hence at level of service E (capacity), 1 - G/C can be used for 1 - q/s.

For a demand-actuated signal, the length of the red (plus amber) phase, R, is given by R (seconds) = (1 - G′/C′) cycle length (seconds). The quantity G′/C′ is the actual green time to cycle length ratio provided at an approach to an intersection, as opposed to G/C, which is the green time to cycle length ratio required to accommodate traffic on an approach as discussed above. Thus, the mean total queue length can be computed by

$$\overline{N}' = \frac{(\text{V vehicles/hour})(1 - G'/C')(\text{cycle length})}{(3{,}600 \text{ s/hour})(1 - G/C)} \tag{6}$$

Including the amber time with the red time as 1 - G′/C′ is a conservative estimate that assumes nonaggressive driver behavior.

For a fixed-time signal, G/C will be constant for an approach, and this is used in place of G′/C′ used above to compute the length of the red (plus amber) phase. For this case,

$$\overline{N}' = \frac{(\text{V vehicles/hour})(1 - G/C)(\text{cycle length})}{(3{,}600 \text{ s/hour})\left(1 - \dfrac{\text{V vehicles/hour}}{\text{C vehicles/hour of green}}\right)} \tag{7}$$

Estimation of Emission Parameters

A signalized intersection resolves conflicts between opposing streams of traffic by alternately blocking and then allowing free passage of vehicles on intersecting approaches. This feature, plus the relatively fine detail in emission strength variations that must be known to assess nearby concentrations adequately, implies that the widely used average route speed method of computing emission strengths is not suitable in this case. A detailed knowledge must be provided of the emission variations from a vehicle undergoing mode changes from cruise through deceleration to idle and acceleration back to cruise. The recently developed Modal Analysis Model (11) supplies this emission detail.

The modal analysis model computes total emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen from a user-specified vehicle mix through 1971. Any desired driving sequence falling within the range of model applicability may be used. The model was modified for present purposes to calculate emissions at equal (8-m) length intervals for a given approach cruise speed, rate of deceleration, rate of acceleration, and departure speed for an average vehicle representing a 1974 low-altitude mix. A 1974 mix was obtained by calculating emissions for a 1971 mix based on Table 3.1.2.7 of Report AP-42 (1) and multiplying the results by the ratio of 1974 to 1971 test results. For carbon monoxide this ratio is 39/47. Figure 1 shows the carbon monoxide emission profile calculated by the modified modal analysis model for 1 vehicle decelerating from 56.3 km/h (35 mph) at 1.23 m/s^2 (2.75 mph/sec) and accelerating from 0 back to 56.3 km/h at 1.12 m/s^2 (2.50 mph/sec) with no idle time. These values of speed, deceleration, and acceleration are representative of the values observed at an intersection near a large regional shopping center in Oak Brook, Illinois (12).

The emissions from a single vehicle traveling at an average route speed of 32.2 km/h (20 mph) are also shown. The units on the abscissa are meters upstream (negative values) and downstream (positive values) from the intersection stop line, which,

Figure 1. CO emission profile calculated by modified modal analysis model.

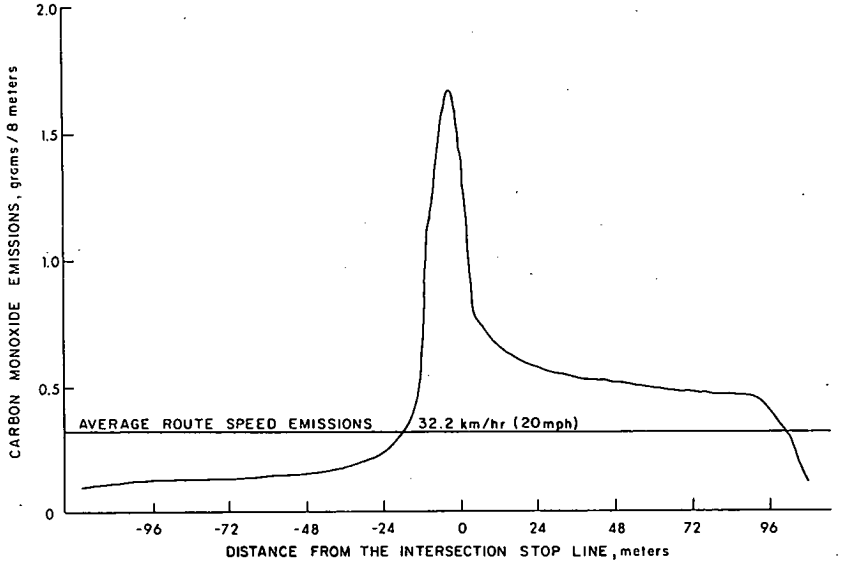
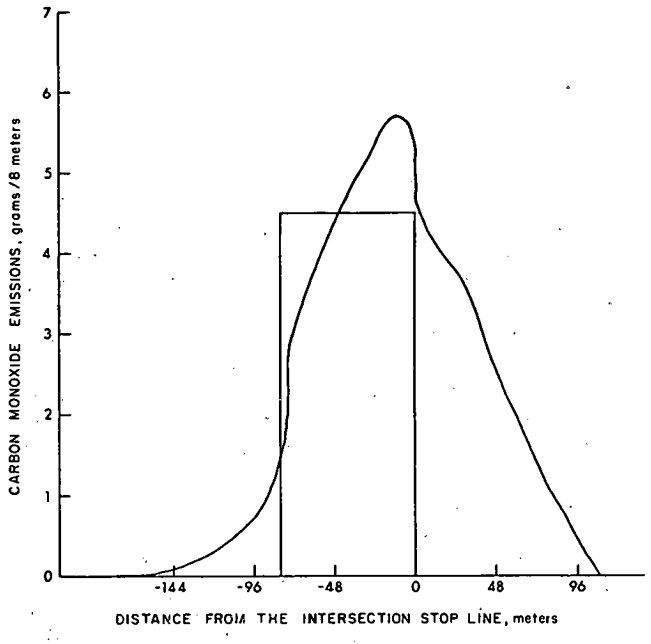


Figure 2. Profile and step function approximation of excess emissions for a queue of 10 vehicles.



for the single vehicle depicted here, is approximately the location of the front bumper when the vehicle is stopped. The vehicle moves from left to right. The ordinate units are g/8 m. Time is not included here, but it will be later in the discussion of applications of the procedures. All that is of interest at this point is the mass of CO emitted in each 8-m length interval by a stopping and starting (but not idling) vehicle.

The emission profile shown in Figure 1 for 1 vehicle is the starting point for developing the emission profile for a queue. It is convenient to consider the emission profile as being the sum of 3 components: excess emissions, idle emissions, and cruise emissions. The excess emissions are those that are attributable to deceleration and acceleration and that are in excess of those occurring at cruise speed.

As stated previously, all vehicles that stop are assumed to decelerate at a constant rate from a constant cruise speed. They queue up with each vehicle occupying an 8-m interval, and then they accelerate at a constant rate back to cruise speed. The emission profile for a queue is developed by adding the emissions from each vehicle in each interval according to the speed and mode of the vehicle in the interval. It consists essentially of adding up $\overline{N}'$ of the curves shown in Figure 1, with each successive curve displaced -8 m from the previous curve, i.e., 8 m upstream. Subtracting the cruise emission component gives the excess emission component for the queue for each length interval along the roadway.

Figure 2 shows the excess emission profile due to stopping and starting only for a queue of 10 vehicles having approach and departure speeds both equal to 56.3 km/h, deceleration of 1.23 m/s^2, and acceleration of 1.12 m/s^2. The scales on the ordinate and the abscissa are different from those in Figure 1. The emission profile shown in Figure 2 does not include idle or cruise emissions, but only the emissions in excess of cruise emissions occurring for stops and starts. The step function also shown in Figure 2 depicts an approximation to the profile of excess emissions. The amplitude equals the average emissions over the queue length of 10 vehicles, or 4.5 g. This average amplitude is 70 percent of the peak value of 5.7 g of carbon monoxide, and the area contained within the step function is 56 percent of the total excess emissions attributable to deceleration and acceleration. The step function approximation is introduced here because it can be conveniently presented and because it is an important aspect of the application to carbon monoxide concentration estimates discussed later.

The excess emissions described here are related to a spatial scale rather than to a temporal scale directly. They arise from 2 effects. This first is an increase in calculated emission rate during both deceleration and acceleration compared to the emission rate at cruise speed. The second is an increase in the time for a vehicle to travel 8 m during deceleration and acceleration compared to the time to travel 8 m at cruise speed. The emission profiles show the product of these 2 effects.

The method of constructing the emission profile for the 10 queuing vehicles and the calculation of the amplitude of the step function approximation are further explained by Table 1, which gives the emissions calculated by the modal analysis model from each of the 10 vehicles in each of the 8-m scale lengths through which the vehicles decelerate and accelerate. The distances from the intersection stop line represent the midpoints of the scale lengths, so that the first queuing vehicle occupies the scale length having its midpoint -4 m from the intersection stop line. Cruise emissions are 0.119 g/8 m.

Data for vehicle 1 show that it travels at cruise speed until it reaches the scale length with midpoint -108 m from the intersection stop line; then it begins to decelerate and the mass emissions/8 m increase. Acceleration emissions from vehicle 1 begin in the scale length with midpoint -4 m; cruising speed is attained again in the scale length having its midpoint at 108 m. Emissions from vehicle 2 are displaced 1 scale length upstream (negative direction) from the intersection compared to vehicle 1 because vehicle 2 must begin decelerating 1 scale length earlier to come to a stop in the scale length immediately behind vehicle 1. Likewise, vehicle 3 begins decelerating 1 scale length earlier than vehicle 2 and so on for the remaining vehicles.

Each row represents a scale length and each column gives the emissions from each vehicle in each row, or scale length. Adding across each row gives the total emissions of all vehicles in each scale length. Excess emissions are obtained by subtracting the cruise component from the total emissions; they thus represent the excess emissions

Table 1. Reference data for describing emission profile calculation.

Distance From Intersection Stop Line (m)	Emissions of Vehicles (g/8 m)										Total Emissions (g/8 m)	Cruise Component (g/8 m)	Excess Emissions (g/8 m)
	10	9	8	7	6	5	4	3	2	1			
-188	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	1.190	1.190	0.000
-180	0.126	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	1.197	1.190	0.007
-172	0.136	0.126	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	1.214	1.190	0.024
-164	0.139	0.136	0.126	0.119	0.119	0.119	0.119	0.119	0.119	0.119	1.234	1.190	0.044
-156	0.142	0.139	0.136	0.126	0.119	0.119	0.119	0.119	0.119	0.119	1.257	1.190	0.067
-148	0.146	0.142	0.139	0.136	0.126	0.119	0.119	0.119	0.119	0.119	1.284	1.190	0.094
-140	0.151	0.146	0.142	0.139	0.136	0.126	0.119	0.119	0.119	0.119	1.316	1.190	0.126
-132	0.157	0.151	0.146	0.142	0.139	0.136	0.126	0.119	0.119	0.119	1.354	1.190	0.164
-124	0.166	0.157	0.151	0.146	0.142	0.139	0.136	0.126	0.119	0.119	1.401	1.190	0.211
-116	0.177	0.166	0.157	0.151	0.146	0.142	0.139	0.136	0.126	0.119	1.459	1.190	0.269
-108	0.193	0.177	0.166	0.157	0.151	0.146	0.142	0.139	0.136	0.126	1.533	1.190	0.343
-100	0.219	0.193	0.177	0.166	0.157	0.151	0.146	0.142	0.139	0.136	1.626	1.190	0.436
-92	0.271	0.219	0.193	0.177	0.166	0.157	0.151	0.146	0.142	0.139	1.761	1.190	0.571
-84	0.600	0.271	0.219	0.193	0.177	0.166	0.157	0.151	0.146	0.142	2.222	1.190	1.032
-76	1.676	0.600	0.271	0.219	0.193	0.177	0.166	0.157	0.151	0.146	3.756	1.190	2.566*
-68	0.788	1.676	0.600	0.271	0.219	0.193	0.177	0.166	0.157	0.151	4.398	1.190	3.208*
-60	0.655	0.788	1.676	0.600	0.271	0.219	0.193	0.177	0.166	0.157	4.902	1.190	3.712*
-52	0.591	0.655	0.788	1.676	0.600	0.271	0.219	0.193	0.177	0.166	5.336	1.190	4.146*
-44	0.553	0.591	0.655	0.788	1.676	0.600	0.271	0.219	0.193	0.177	5.723	1.190	4.533*
-36	2.529	0.553	0.591	0.655	0.788	1.676	0.600	0.271	0.219	0.193	6.075	1.190	4.885*
-28	0.512	0.529	0.553	0.591	0.655	0.788	1.676	0.600	0.271	0.219	6.394	1.190	5.204*
-20	0.501	0.512	0.529	0.553	0.591	0.655	0.788	1.676	0.600	0.271	6.676	1.190	5.486*
-12	0.492	0.501	0.512	0.529	0.553	0.591	0.655	0.788	1.676	0.600	6.897	1.190	5.707*
-4	0.486	0.492	0.501	0.512	0.529	0.553	0.591	0.655	0.788	1.676	6.783	1.190	5.593*
4	0.481	0.486	0.492	0.501	0.512	0.529	0.553	0.591	0.655	0.788	5.588	1.190	4.398*
12	0.478	0.481	0.486	0.492	0.501	0.512	0.529	0.553	0.591	0.655	5.278	1.190	4.088
20	0.476	0.478	0.481	0.486	0.492	0.501	0.512	0.529	0.553	0.591	5.099	1.190	3.909
28	0.365	0.476	0.478	0.481	0.486	0.492	0.501	0.512	0.529	0.553	4.873	1.190	3.683
36	0.119	0.365	0.476	0.478	0.481	0.486	0.492	0.501	0.512	0.529	4.439	1.190	3.249
44	0.119	0.119	0.365	0.476	0.478	0.481	0.486	0.492	0.501	0.512	4.029	1.190	2.839
52	0.119	0.119	0.119	0.365	0.476	0.478	0.481	0.486	0.492	0.501	3.636	1.190	2.446
60	0.119	0.119	0.119	0.119	0.365	0.476	0.478	0.481	0.486	0.492	3.254	1.190	2.064
68	0.119	0.119	0.119	0.119	0.119	0.365	0.476	0.478	0.481	0.486	2.881	1.190	1.691
76	0.119	0.119	0.119	0.119	0.119	0.119	0.365	0.476	0.478	0.481	2.514	1.190	1.324
84	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.365	0.476	0.478	2.514	1.190	0.962
92	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.365	0.476	1.793	1.190	0.603
100	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.365	1.436	1.190	0.246
108	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	0.119	1.190	1.190	0.000

*Mean = 4.504 g/8 m.

due to deceleration and acceleration without idle emissions or the emissions that would have been obtained if all vehicles had remained at cruise speed. These are the emissions shown in Figure 2; this column of excess emissions shows the 10 emission values from the 10 queue positions that are used to calculate the average emissions for the step function approximation to the emission profile.

Table 2 gives the average excess emissions occurring over the distance occupied by various lengths and approach and departure cruising speeds. Also given are the standard deviation for each of the average excess emission values to indicate the range of emission values that are used to compute the average. For example, the brace on the right of Table 1 shows the emission values used to calculate the average value of 4.504 g/8 m. These can be compared with data in Table 2, which show, for a cruise speed of 56.3 km/h and a queue of 10 vehicles, an average excess emission value of 4.504 g/8 m with a standard deviation of 1.077 g/8 m. Table 2 also gives the total excess emissions (defined by the entire excess emission profile) contained within the step function approximation. The last column in Table 1, Excess Emissions, totals to 79.930 g. Of this, 45.040 g or 56 percent is accounted for over the 10 queue positions. This percentage is basically a function of the queue length and the distance required to stop and start. The greater the ratio of the queue length to the stop and start distance is, the greater will be the percentage of the total excess emissions contained within the step function.

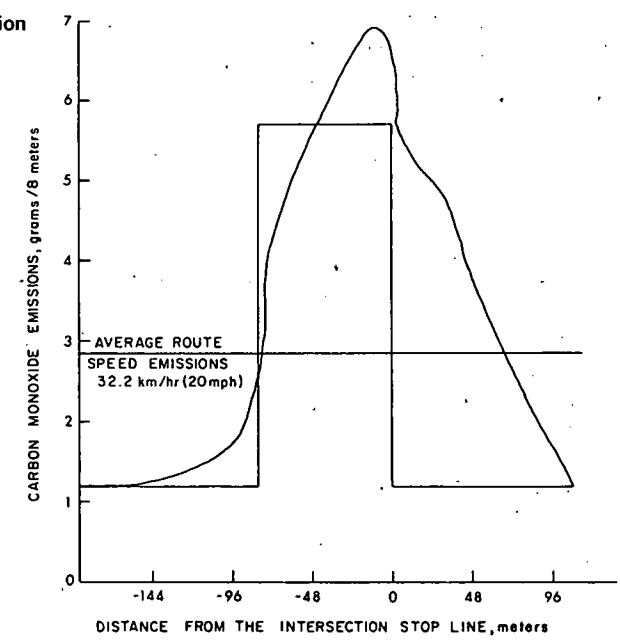
Emissions from cruise and idle modes must be added to those due to stopping and starting to develop the full emission profile. Cruise emissions are included simply by adding the cruise emissions from each vehicle in each 8-m interval. Figure 3 shows the result of adding cruise emissions to the emission profile and to the step function approximation for a queue of 10 vehicles. The profile approximation now contains 68 percent of the total emissions, and the approximated peak of 5.69 g is 83 percent of the

Table 2. Emission values for use in approximating emission profiles.

Speed (km/h)	Queue Length (vehicles)	Average Excess Emission (g/8 m)	Standard Deviation (g/8 m)	Percentage of Total Excess	Total Excess per Vehicle	Cruise Emission (g/8 m)
24.1	5	2.297	0.314	89.3	2.574	0.245
	10	2.436	0.255	94.6		
	15	2.482	0.216	96.4		
	20	2.505	0.190	97.3		
	25	2.519	0.171	97.9		
	30	2.528	0.157	98.2		
32.2	5	2.860	0.533	77.2	3.703	0.183
	10	3.282	0.577	88.6		
	15	3.422	0.492	92.4		
	20	3.492	0.440	94.3		
	25	3.535	0.401	95.5		
	30	3.563	0.370	96.2		
40.2	5	3.066	0.565	61.6	4.978	0.150
	10	3.984	0.866	80.0		
	15	4.315	0.857	86.7		
	20	4.481	0.792	90.0		
	25	4.581	0.734	92.0		
	30	4.647	0.684	93.3		
48.3	5	3.163	0.565	49.4	6.406	0.131
	10	4.389	1.077	68.5		
	15	5.061	1.237	79.0		
	20	5.397	1.215	84.3		
	25	5.599	1.157	87.4		
	30	5.733	1.096	89.5		
56.3	5	3.221	0.565	40.3	7.992	0.119
	10	4.504	1.077	56.4		
	15	5.541	1.521	69.3		
	20	6.154	1.643	77.0		
	25	6.522	1.637	81.6		
	30	6.767	1.590	84.7		
64.4	5	3.253	0.565	33.4	9.745	0.113
	10	4.569	1.077	46.9		
	15	5.679	1.561	58.3		
	20	6.645	1.983	68.2		
	25	7.265	2.114	74.6		
	30	7.678	2.128	78.8		
72.4	5	3.269	0.565	28.0	11.671	0.109
	10	4.601	1.077	39.4		
	15	5.727	1.561	49.1		
	20	6.773	2.051	58.0		
	25	7.719	2.484	66.1		
	30	8.378	2.647	71.8		
80.5	5	3.273	0.565	23.8	13.777	0.108
	10	4.610	1.077	33.5		
	15	5.740	1.561	41.7		
	20	6.790	2.051	49.3		
	25	7.806	2.556	56.7		
	30	8.764	3.029	63.6		

Note: Deceleration = 1.23 m/s² (2.75 mph/sec); and acceleration = 1.12 m/s² (2.50 mph/sec).

Figure 3. Emission profile and step function approximation for excess and cruise emissions for a queue of 10 vehicles.



peak of 6.90 g. When idle emissions are included in the full approximation, these percentages rise to about 95 percent.

Average route speed emissions for 32.2 km/h (20 mph) are also shown on Figure 3. The inclusion of idle emissions, like that of cruise emissions, is a simple calculation and is presented in the following discussion.

APPLICATION OF THE ANALYTICAL PROCEDURES

In this section, an example application of the traffic and emission estimation procedures is given, tying them together to derive inputs for a dispersion model. The results of the application of the procedures to estimating carbon monoxide concentrations at a signalized intersection are then presented.

Approximation of Emission Profiles for Queuing Vehicles

As an example (12), consider an approach to an intersection with a volume of 215 vehicles/hour, $\overline{G/C}$ equal to 0.18, a cycle length of 180 s, G + Y/C of 0.86, and G'/C' of 0.18/0.76 or 0.24. The mean total queue length per cycle is then

$$\overline{N}' = \frac{(215)(1 - 0.24)(180)}{(3600)(1 - 0.18)} = 10 \text{ vehicles/cycle}$$

The length of the red (plus amber) phase for this example is 138 s. On the average, a stopped vehicle waits one-half of the red phase, or 69 s for this case. The idle emission rate of carbon monoxide calculated by the modal analysis model is 0.234 g/s. This is assumed to occur in each of the queue positions an average of 69 out of every 180 s; that is, $(1 - G'/C')/2$, or 0.38 of the time. Hence, the idle emissions average 0.089 g/s for each queue position for this example. This representation tends to underestimate emissions in the lead queue positions, where vehicles wait longer than 1/2 R, and to overestimate emissions for the rear positions.

The HIWAY model calls for emissions in units of grams/meter-second; and now that volume and signal parameters have been specified, these will be calculated for approach and departure speeds of 56.3 km/h, deceleration of 1.23 m/s^2, and acceleration of 1.12 m/s^2. Since $\overline{N}' = 10$ vehicles/cycle, the excess emissions due only to stopping and starting are 4.504 g/8 m/cycle (Table 2), or 0.563 g/m/cycle. But the signal cycle is 180 s, so this becomes 0.563/180 = 0.00313 g/m·s because of stopping and starting. The volume of 215 vehicles/hour equals 10.75 vehicles/cycle for which cruise emissions must be added. The cruise emission rate is 0.119 g/8 m (Table 2), or cruise emissions of

$$\frac{(0.119 \text{ g})(10.75 \text{ vehicles/cycle})}{(8 \text{ m})(180 \text{ s/cycle})} = 0.00089 \text{ g/m·s}$$

The idle emissions were found earlier to be 0.092 g/s for each 8-m queue position, so the idle contribution is 0.01112 g/m·s. The approximation of the emission profile is then

1. 0.00313 g/m·s from stopping and starting,
2. 0.00089 g/m·s from cruise, and
3. 0.01112 g/m·s from idle.

or 0.01514 g/m·s over the 10 queue positions and 0.00089 g/m·s elsewhere. The

approximated peak is 95 percent of the peak calculated by using the modal analysis model, and the total approximated emissions are 94 percent of the total. This arises from the large contribution by idle emissions that are computed in the same manner for both cases. The step function approximation neglects excess emissions downstream from the queue. This becomes less important as queue lengths increase, since the high excess emissions during acceleration occur predominantly over the queue positions. This omission is accommodated by assuming that emissions in the center of the intersection equal the mean of the approximated peaks on each approach.

Comparison of Calculated and Observed Concentrations

The modal analysis model and the EPA HIWAY model are designed to estimate emissions and concentrations respectively. To test the compatibility of the 2 models in translating traffic and meteorological parameters into concentrations of carbon monoxide, a composite model was used to predict concentrations for comparison with values observed at a signalized intersection near a regional shopping center.

An exact analysis would include emission strengths calculated for each 8-m section of roadway, application of the HIWAY model to each 8-m section, and addition of the individual section contributions to find the calculated concentration at a receptor. An exact analysis, however, is quite consuming of both staff and computer time; the analysis and results presented here are from a study that determined how well the approximate emission profiles perform with the HIWAY model in estimating carbon monoxide concentrations so that a simple air quality assessment technique could be developed (13, 14). Hence, the approximation technique described earlier was used in obtaining these results.

During a 4-week monitoring program concurrent traffic, carbon monoxide, and meteorological data were collected at a major intersection near a regional shopping center. Figure 4 shows the locations of the carbon monoxide and meteorological monitors, and Figure 5 shows the physical characteristics of the intersection and the locations of the traffic counters. The intersection is controlled by a demand-actuated signal. During this same 4-week period, measurements were also taken of average cruise speeds and deceleration and acceleration rates at various times of the day.

As shown on Figure 4, Ecolyzer carbon monoxide monitors were located at stations 13, 14, 15, and 162. Stations 161 and 163 had NDIR instruments housed in a van, and along with station 162 were operated by the EPA Quality Assurance and Environmental Laboratory. The NDIR instruments were used for comparing and calibrating the Ecolyzer readings to the reference method. The Ecolyzer located at station 162 was changed during the program to ensure that it would not bias the calibration and correction of data taken at the other stations. The calculated and observed concentration comparisons to be presented were based on corrected Ecolyzer readings.

Twelve hours were chosen for analysis based on relatively low wind speed, a wind angle suitable for defining concentrations upwind and downwind of the intersection of Route 83 and Twenty-second Street, and completeness of the input data set for the hour under study. In 4 of these cases the wind was from the northeast quadrant, and concentrations were calculated for the monitor in the southwest quadrant (station 162). In the other 8 cases the wind direction was reversed, and concentrations were calculated for each of the 3 monitors in the northeast quadrant (stations 13, 14, and 15). Missing data occurred for 1 case at station 13 so that there are a total of 27 comparisons of observed and calculated values. Concentrations recorded by the Ecolyzer were used for the southwest location unless it was not operating for the particular hour under study. In these cases the average of the NDIR values (stations 161 and 163) was used. Complete data listings are given in another report (12).

Figure 6 shows a plot of the data pairs. Concentric circles indicate more than one point. Twenty-two calculated values are within a factor of 2 of those observed, and 5 vary by more than a factor of 2. Six of the calculated values agree exactly with the observed values. The average of all calculated concentrations is 3.5 ppm versus 3.8 ppm for the observed average. The correlation coefficient is $r = 0.34$, which indicates less

Figure 4. Continuous monitoring sites at Route 83 and Twenty-second Street.

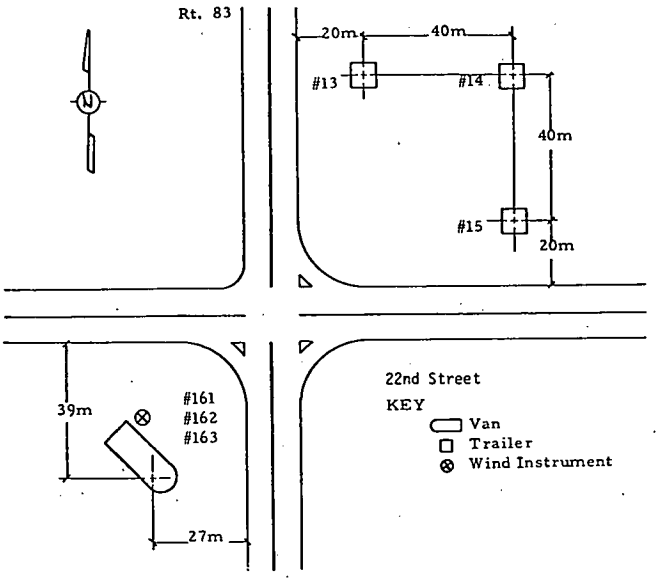


Figure 5. Location of traffic counters.

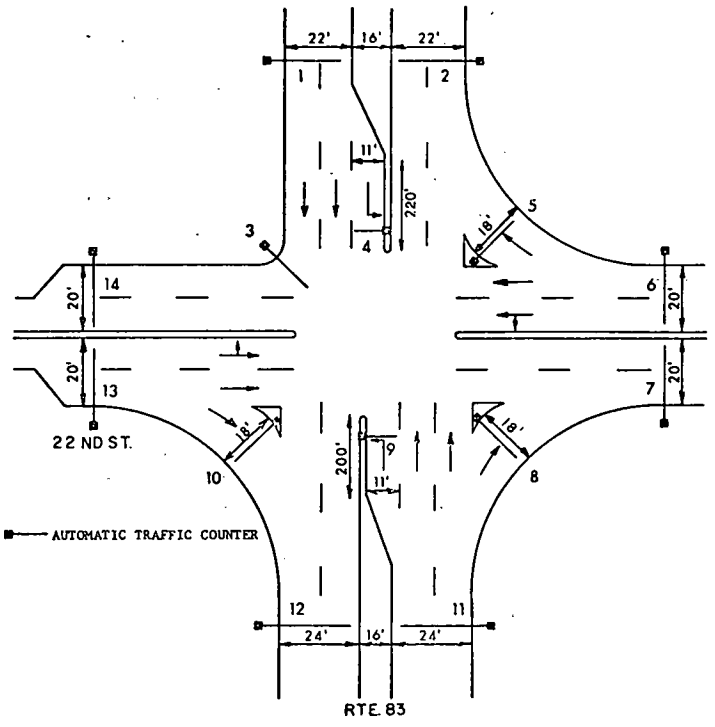
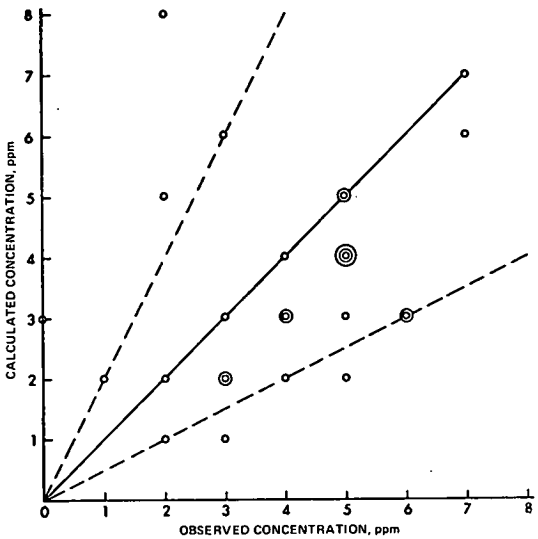


Figure 6. Calculated versus observed concentrations of CO.



than a 10 percent probability that the linear relation between calculated and observed values has occurred by chance.

When the values are normalized for wind speed, the mean calculated XU is 11.7 ppm-m/s compared to 13.7 ppp-m/s observed. The correlation coefficient is 0.44, significant at the 2 percent level. Predicted concentrations tend to be overestimated at low wind speeds and underestimated at higher wind speeds. The crossover occurs at wind speeds of approximately 3.5 m/s.

SUMMARY AND CONCLUSIONS

This paper describes an approach for relating the impact of traffic on ambient carbon monoxide concentrations near signalized intersections by (a) computing the emission profiles due to acceleration and deceleration of queuing vehicles for a range of queue lengths and approach and departure speeds, (b) approximating the profiles by simple step functions based on emissions on the portion of roadway occupied by the queues, (c) adding in emission components for cruise and idle modes of vehicle operation, and (d) using the derived emission profiles in a line source dispersion model to estimate ambient CO concentrations at selected receptor sites. The following steps for estimating emission profiles have been suggested and applied successfully.

1. Identify the parameters necessary for calculating the expected mean total queue length. These parameters are V = hourly demand volume, cycle length, G/C = required G/C ratio, G′/C′ = actual G/C ratio provided G/C = actual G/C ratio provided if the signal is fixed time, and capacity per hour of green.
2. Compute the expected mean total queue length using equation 6 for a demand-actuated signal or equation 7 for a fixed-time signal.
3. Round off the calculated queue length to a multiple of 5. If average emission factors are known for the exact queue length, these should be used and it would not be necessary to round off the queue length to a multiple of 5.
4. Identify the approach and departure speeds. If they are unequal, assume that both equal the departure speed. If the average emission factors are known for the given approach and departure speed combination, these should be used and it would not be necessary to make the assumption that both equal the departure speed.
5. Using the data presented in Table 2, find the mean emissions per 8 m due to stopping and starting for the queue length-speed combination.
6. Calculate the emission strength (grams/meter-second) over the distance occupied by the queue by adding the following:

$$\frac{(\text{mean stopping and starting emissions, g/8 m})}{(8\text{ m})(\text{cycle length, second})}$$

$$+\frac{(\text{cruise emissions, g/8 m})(\text{V vehicles/hour})}{(8\text{ m})(3600\text{ s/hour})}$$

$$+ \frac{(\text{idle emission rate, gram/second})(1/2 \text{ length of red phase, second})}{(8 \text{ m})(\text{cycle length, second})}$$

= emission strength over the queue length (grams/meter-second)

7. Assume that only the cruise speed emission strength exists upstream and downstream of the queue (excluding the center of the intersection).
8. After the emission strengths are found over the queue lengths for all approaches, average them, and assume this emission strength for lanes in the center of the intersection.

When the above approach was tested by using observed traffic data, it yielded a good estimate of the mean impact on nearby short-term carbon monoxide concentrations. Individual calculated and observed impacts on short-term CO concentrations were generally within a factor of 2 of one another.

This paper focuses heavily on presenting a detailed discussion of an analytical method for modeling the carbon monoxide air quality impact of signalized intersections. The intent is to describe the method fully, so that it may be easily applied by others. A number of comments can be made in conclusion on this topic in general.

1. The basic method is applicable to any vehicle-related pollutant, such as sulfates or lead, for which mode-dependent emission factors are available. In addition to carbon monoxide, the modal analysis model calculates emissions of total hydrocarbons and nitrogen oxides, and these pollutants could be readily modeled. The modal analysis model also calculates fuel consumption.
2. As alluded to earlier, the techniques presented here are not unique, except that they are the first to be applied and validated. They have been applied in the development of the EPA indirect source guidelines document (14).
3. Some of the assumptions used were made for the purpose of simplifying the method, and these can easily be accommodated if a more rigorous application seems warranted. An example is the assumption of constant deceleration and acceleration, which can readily be modified, and new emission estimates can be made based on varying deceleration and acceleration values.
4. The basic methods of simulating traffic, emissions, and dispersion can be applied to nonisolated intersections. Modeling studies that simulated traffic flow, mode-dependent emissions, and dispersion have been made to optimize signal progressions using air quality as the measure of effectiveness (15, 16). Along these same lines, these techniques could be used to include air quality as a measure of effectiveness in designing computer-controlled signal networks.
5. The methods presented in this paper supply the foundation for investigating the impact of traffic engineering practice on air quality. Perhaps contrary to intuition, there are situations in which the goals of the traffic engineer in promoting flow do not lead to good air quality and even cause hot spots (17). Much work remains to be done in the area of intersection modeling to identify these situations and to provide for alternative traffic management techniques that promote both traffic flow and air quality.

REFERENCES

1. Compilation of Air Pollutant Emission Factors, 2nd Ed. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C., Publ. AP-42, April 1973.
2. Special Area Analysis (SAPOLLUT Model). U.S. Department of Transportation, Aug. 1973.
3. R. L. Mancuso and F. L. Ludwig. User's Manual for the APRAC-1A Urban Diffusion Model Computer Program. Stanford Research Institute, Menlo Park, Calif.;

NTIS PB 213 091.
4. J. R. Zimmerman and R. S. Thompson. User's Guide for HIWAY: A Highway Air Pollution Model. U.S. Environmental Protection Agency, Rept. EPA-650/7-74-008, Feb. 1975.
5. J. L. Beaton, A. J. Ranzieri, E. C. Shirley, and J. B. Skog. Mathematical Approach to Estimating Highway Impact on Air Quality. Air Quality Manual CA-HWY-MR6570825(4)-72-08, Vol. 4.
6. Highway-Air Quality Computer Programs. Environmental Development Division, Federal Highway Administration, July 1973.
7. F. V. Webster. Traffic Signal Settings. Her Majesty's Stationery Office, London, Road Research Technical Paper 39, 1958.
8. G. Newell. Approximation Methods for Queues With Application to the Fixed-Cycle Traffic Light. SIAM Review, Vol. 7, 1965, pp. 223-240.
9. F. A. Haight. Mathematical Theories of Traffic Flow. Academic Press, New York, 1963.
10. Highway Capacity Manual. HRB Special Rept. 87, 1965.
11. P. Kunselman, H. T. McAdams, C. J. Domke, and M. Williams. Automobile Exhaust Emission Modal Analysis Model. U.S. Environmental Protection Agency, Publ. EPA-460/3-74-005, Jan. 1974.
12. R. M. Patterson and F. A. Record. Monitoring and Analysis of Carbon Monoxide and Traffic Characteristics at Oakbrook. U.S. Environmental Protection Agency, Rept. EPA-450/3-74-058, Nov. 1974.
13. R. M. Patterson and E. L. Meyer, Jr. An Approach for Relating Traffic to Ambient Carbon Monoxide Concentrations at Signalized Intersections. 68th Annual Meeting of Air Pollution Control Association, Boston, June 1975, Paper 75-44.4.
14. Guidelines for Air Quality Maintenance Planning and Analysis, Volume 9: Evaluating Indirect Sources. U.S. Environmental Protection Agency, Research Triangle Park, N.C., Rept. EPA-450/4-75-001, Jan. 1975.
15. J. R. Mahoney and R. M. Patterson. A Variable Emission Model for Air Pollutants in the Vicinity of Urban Roads. American Meteorological Society Conference on Urban Environment, Philadelphia, 1972.
16. R. M. Patterson and J. R. Mahoney. Traffic Motion Controls as an Emission Control Technique. 67th Annual Meeting of Air Pollution Control Association, Denver, June 1974, Paper 74-3.
17. R. M. Patterson. Traffic Flow and Air Quality. Traffic Engineering, Nov. 1975.