Dispersion Characteristics of Flows in Asymmetric Street Canyons and Sensitivity to Block Shape

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Flow visualization and tracer concentration measurements were made in rectangular and square (plan view) street canyon models in which the ratio of street width to the height of the upwind building was held constant at 0.83. The ratio of the heights of the upwind and downwind buildings was varied among 2.0, 1.0, and 0.67 for the rectangular block and was held constant at 1.0 for the square block. Tracer measurements were obtained across the faces of both the leeward and windward buildings for emissions in the local street canyon. Orientation of the canyon axis with respect to the free stream flow was varied from 0 to ±90 degrees in 10-degree increments. The structure of the dispersion patterns is strongly dependent on the canyon's asymmetry and is less dependent on the canyon's orientation to the prevailing flow. The patterns are also sensitive to the shape of the block: the rectangular block has a concentration maximum in midblock and the square block has maxima near the ends of the block. Concentrations are also significantly greater for the rectangular block than for the square block. Comparisons among vertical concentration profiles observed on the two canyon faces and among estimates from several commonly applied models for the rectangular block configuration are presented.

A fluid modeling and analytical study of flows in street canyons was made, using the Environmental Science and Services Corporation's atmospheric boundary layer wind tunnel (ABLWT) (Figure 1). Dispersion characteristics were investigated for three types of canyons: a step-up notch with the upwind building shorter than the downwind building, a step-down notch with the upwind building taller than the downwind building, and an even notch with upwind and downwind buildings of equal height. Normalized concentrations for various wind angles were determined at receptors mounted on the upwind and downwind building faces. Two shapes or configurations for the city block were studied, namely, rectangular and square (as observed in plan view). Vertical concentration profiles measured at midblock were compared with the predictions of several empirical and analytical models for those cases in which the free stream flow is normal to the axis of the rectangular street canyons.

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EXPERIMENTAL PROCEDURE

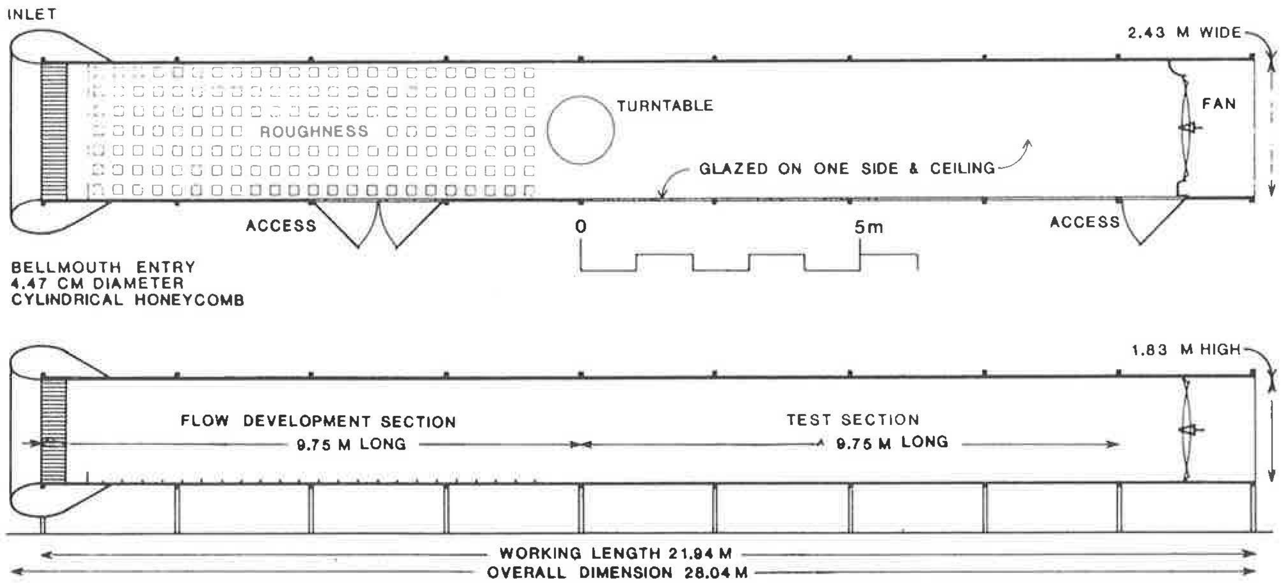
The boundary layer simulation was accomplished by using a 0.29-m-high castellated barrier and vortex generators placed at the test section entrance. The test section floor was covered with gravel roughness panels. Wind tunnel calibration and test procedures were in accordance with those outlined by the Environmental Protection Agency (*1, 2*).

Wind tunnel calibration consisted of an atmospheric dispersion comparability test (ADCT) to demonstrate that the fluid model dispersion was comparable to the predictions of the Gaussian plume distribution. Flow visualization and tracer concentration measurements were conducted with a scale model of an urban street grid mounted on a turntable that was inserted into the ABLWT test section. During these tests, the wind tunnel speed at a height of 1 m above the ABLWT floor was a constant 2 m/sec. Hoydysh et al. (*3*) have shown that for urban street grid models of the type studied here, the flow field and concentration patterns are independent of wind speed if the Reynolds number, based on building height and the free stream velocity, exceeds 3,400. For the present experiments, the Reynolds number was 10,000.

Two scale models of urban street grids were alternately tested in the ABLWT by mounting them on the turntable. The first model consisted of a central portion that had 12 city blocks, of which 10 had actual dimensions of 60 cm (length) × 20 cm (width) × 7.5 cm (height). The "street" width was 6.25 cm, and the "avenue" width was 10 cm. A second series of tests was conducted with a second urban model in which the city blocks were of the same height (7.5 cm) as in the first series, but their width and length were both set to 20 cm. In essence, the first series investigated rectangular city blocks, whereas the second series investigated square city blocks.

The street-level emission source used in both configurations consisted of two linear point source arrays separated by 2.5 cm. Adjacent point sources in the linear arrays were separated by 1.5 cm, and the source length was 90 cm. The emission source was nonbuoyant, zero exit momentum ethane trace gas with an emission rate of 200 cm^3/sec.

Tracer gas concentrations were measured at receptors mounted on the upwind (leeward) and downwind (windward) faces of the buildings that made up the street canyon. A maximum of 30 and 56 active receptors were used in rectangular and square block tests, respectively. In all tests, an additional receptor was located upwind of the model to monitor background concentrations in the wind tunnel approach flow.



PERFORMANCE & POTENTIAL

MEAN VELOCITY RANGE	0.3 - 4.6 M/SEC FOR DIFFUSION STUDIES. UP TO 18.2 M/SEC FOR WIND LOAD STUDIES
CONFIGURATION	HYBRID - OPEN OR CLOSED CIRCUIT
STRATIFICATION CONTROL	GROUND LEVEL SURFACE HEATING & COOLING NEUTRAL, STABLE, UNSTABLE, & INVERSION CONDITIONS
BOUNDARY LAYER THICKNESS	0.6 M TO 0.91 M IN TEST SECTION
MODEL SCALING	UP TO 1000:1

FIGURE 1 ESSCO Atmospheric Boundary Layer Wind Tunnel.

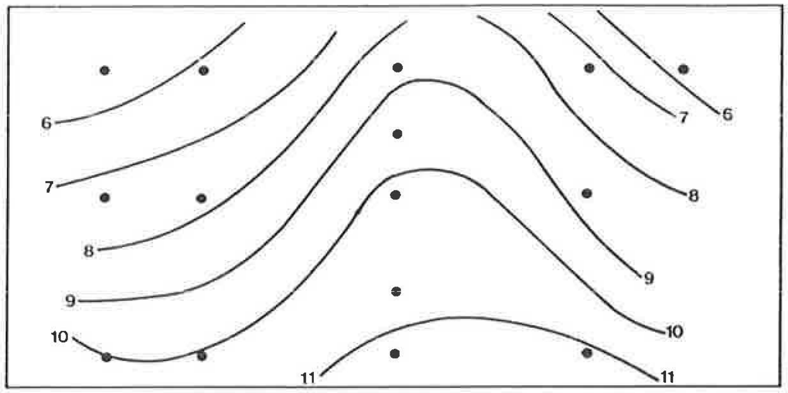
Concentrations were obtained by collecting simultaneous 1-liter samples over 5 minutes at each receptor. Samples were transferred to sample bags and analyzed off line by a Beckman Model 400 Hydrocarbon Analyzer (a flame ionization detector).

In the rectangular block tests, the height of the upwind block face was 7.5 cm. Receptors on the upwind face were arranged in five vertical arrays, three receptors were in each of the noncentral arrays, and the central array contained five receptors. The downwind block face was also equipped with five vertical receptor arrays. The number of receptors in each array varied with the height of the block: 3.75, 7.5, and 11.25 cm, respectively, for the step-down, even, and step-up notches. In the square block tests, receptors were mounted in vertical arrays on both block faces. Seven equally spaced arrays of four uniformly spaced receptors were arranged on each block face.

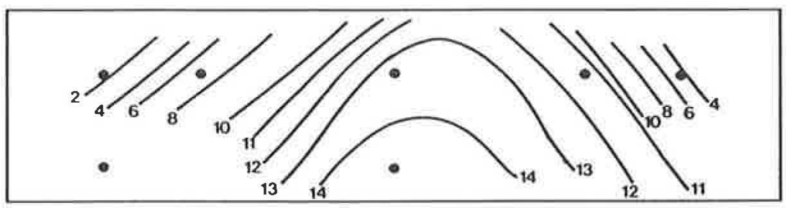
CONCENTRATION PATTERNS: RECTANGULAR BLOCK

Figure 2 illustrates contour patterns of the normalized concentration C^* (CU/Q) on the face of the upwind and downwind buildings for wind directions that are perpendicular to the notch axis (i.e., $\theta = 0$ degrees). The patterns for the step-down notch (upwind building twice the height of downwind building) are given in Figure 2. Several significant features can be observed. The contour pattern on the upwind building face displays a street-level gradient directed from the corners to midblock, and the vertical concentration gradient is similar at the corners and midblock. These patterns reflect horizontal transport into the notch from the corners (and their intersecting notches or streets) and significant upward transport along the entire face of the upwind building (i.e., the leeward face). Although there are few sampling points on the face of the downwind building (i.e., the windward face), a similar contour pattern is visible. One notable feature is the maximum concentration value on the short windward face, which exceeds the maximum on the taller leeward face by nearly 25 percent. This feature is present for wind angles through 30 degrees. For wind angles of 50–90 degrees, the more common situation of larger leeward face concentration is observed.

Concentration contours for the "even notch" (equal building heights) are similar on the upwind face and different on the downwind face. The pattern on the leeward face is virtually identical to that of the step-down configuration. The pattern on the windward (downwind) face is similar to the leeward face except that the concentrations and the gradients are less. The pattern of street-level concentrations on the leeward (upwind) face is very similar to the pattern on the windward face. However, the magnitude of the concentrations is about a factor of two larger than on the windward face. This is the more common cross-street gradient and has been observed in a large number of ambient observational studies (*4–8*) and fluid modeling studies (*9–15*). The mechanism for the advection from the building corners to midblock is presumably the intermittent vortices that are shed on the building corners. The



(a)



(b)

Street-Level Source, $\theta = 0^{\circ}$ and $H_{up} = 2H_{dn}$

FIGURE 2 Contours of normalized concentration ($C^* \times 10^{-3}$ CU/Q).

two vortices create a convergence zone in the midblock region, resulting in larger concentrations there, both at street level and aloft.

Concentration patterns for the "step-up notch" (upwind building height 0.67 of the downwind building height) exhibit both similarities and differences from those observed for the step-down and equal notches. Contours on the leeward face are nearly horizontal and do not show the upward midblock bulge characteristic of the step-down and even notches. The magnitude of the street-level concentrations on the leeward face is 50 percent that observed with the other two configurations, and the cross-street gradient is consistent with that of the even notch (i.e. about 2.5:1). The smaller concentrations indicate either more rapid flushing of the notch or enhanced entrainment of ambient air into the notch. However, the latter supposition is not supported by the concentrations associated with emissions from roof level (not shown), which are only slightly greater than for the other two notch configurations. If entrainment is a significant factor, it is probably the result of horizontal advection of clean air.

Figures 3 and 4 illustrate the dependence of the concentration due to street emissions on the angle of the wind relative to the notch. By convention, $\theta = 0$ degrees indicates a wind that is perpendicular to the notch axis, and $\theta = 90$ degrees is a wind parallel to the notch axis. The concentrations shown are those at midblock.

Figures 3 and 4 illustrate contour patterns as a function of height and wind angle for the equal notch for the leeward and windward faces, respectively. On the leeward face (Figure 3), street level concentrations vary only about ± 10 percent over the range of θ values. The pattern is more varied at roof level, where C^* decreases monotonically from a maximum at $\theta = 0$ degrees to a minimum at about 30 degrees; between 40 degrees and 90 degrees there is little variation. As a consequence, the vertical gradient is a minimum at 0 degrees and a maximum from 30 degrees through 90 degrees. On the windward side (Figure 4), the street-level concentration is a maximum at $\theta = 90$ degrees, with a secondary maximum at 0 degrees and a broad minimum between 20 degrees and 70 degrees. Near roof level, the concentration decreases steadily from its maximum value at 0 degrees to a minimum around 40 degrees and then varies little through 90 degrees. The variation with θ of both the leeward and windward patterns differs significantly from the common assumptions for street canyons (*4*) in that the pattern is invariant in each of two flow regimes, namely, the cross-street region (θ = 0–60 degrees) and the along-street region (θ = 60–90 degrees). Also, the concentration maxima near 90 degrees at street level and the cross-street gradient at 90 degrees are anomalies not described by earlier studies.

Concentrations on the leeward face of the step-down notch increase slightly at all heights between $\theta = 0$ and $\theta = 20$ and then fall off with increasing values of θ, decreasing slowly near street level and rapidly at roof level. At $\theta = 90$ degrees, the C^* value at street level is two-thirds that at $\theta = 0$ degrees, whereas near roof level the ratio is one-fifth.

The patterns for the step-up notch are again different from those of the other two configurations. Little horizontal (i.e., θ) structure is observed for the windward face for all θ values available (i.e., $\theta \leq 60$ degrees; no data were available for 60–90 degrees). The leeward face also shows little structure

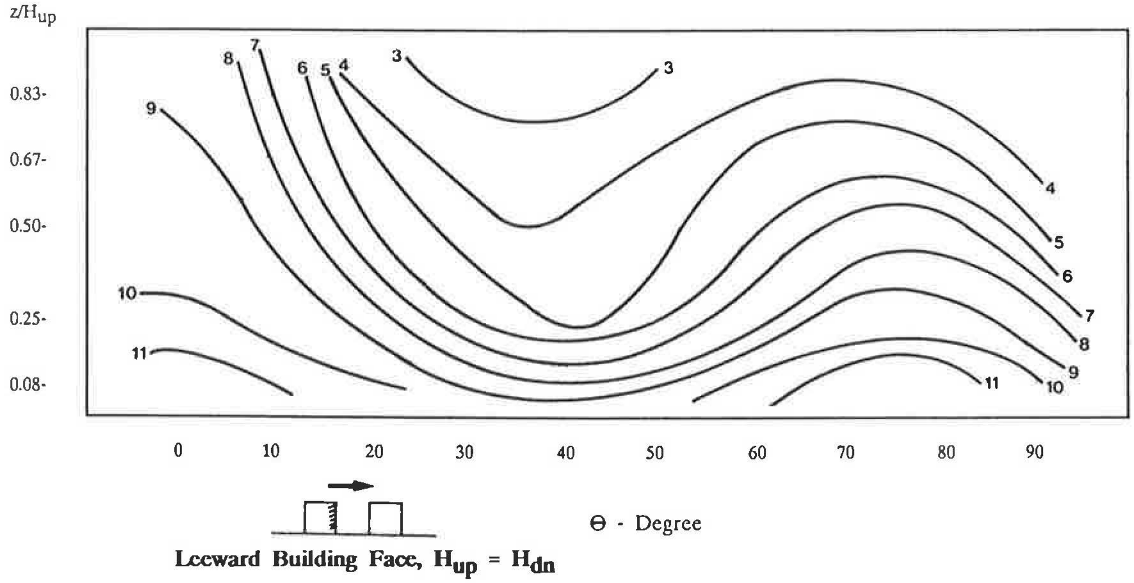


FIGURE 3 Midblock concentration ($C^* \times 10^{-3}$ CU/Q) contour diagram (height vs. wind angle), leeward.

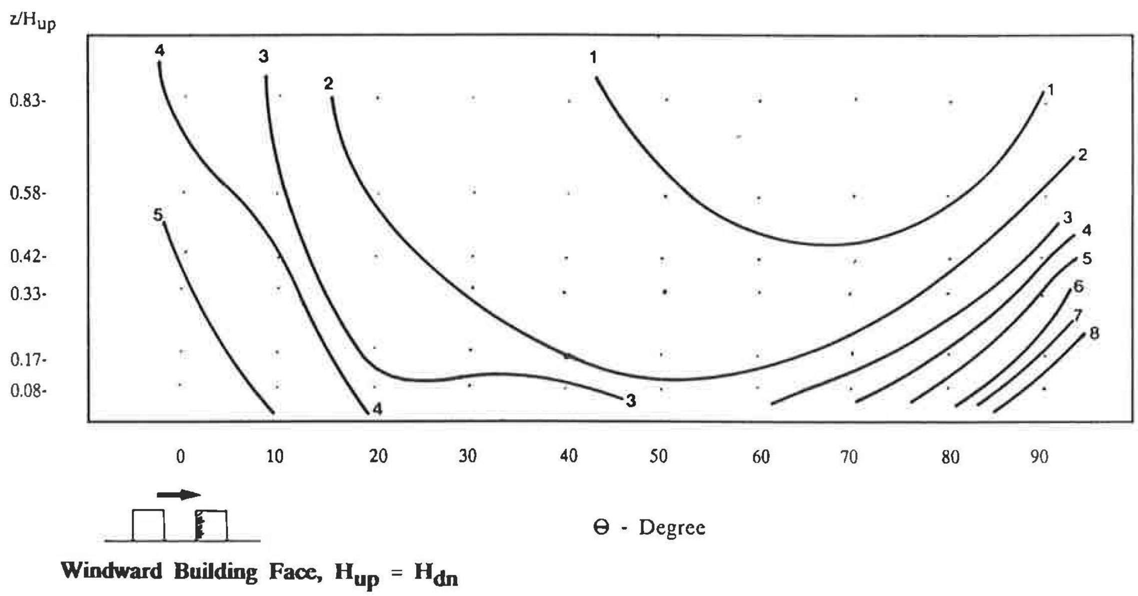


FIGURE 4 Midblock concentration ($C^* \times 10^{-3}$ CU/Q) contour diagram (height vs. wind angle), windward.

with θ through 40 degrees and then reflects a significant increase at all heights in concentration through θ = 50 degrees and 60 degrees.

CONCENTRATION PROFILES: RECTANGULAR BLOCK

The quantitative nature of the vertical profiles of concentration at the middle of the block were examined for all three notch configurations and then compared with empirical and analytical street canyon models for the even notch configuration. The observed vertical concentration profile on the leeward face of the step-down notch configuration is shown in Figure 5 for wind angles of 0, 30, 60, and 90 degrees. The street-level concentration first increases slightly with increasing θ (0–30 degrees) and then decreases markedly as θ increases further. Near-roof concentrations are a maximum at θ = 0 degrees, and they first decrease slightly, then sharply decrease with θ. As a consequence, the curvature of the vertical profile increases systematically as θ increases from 0 degrees to 90 degrees. The height variation of the concentration is seen to be well approximated by a simple exponential profile of the form

$$C^* = a \exp bz/H_{up} \qquad (1)$$

where a and b are regression coefficients, z is height, and H_{up} is the height of the upwind building. In Figure 5, the observed concentrations are indicated by different symbols and the regression curve is given by the solid line. Both a and b vary with θ in a complex manner: the value of a ranges from 8.55 to

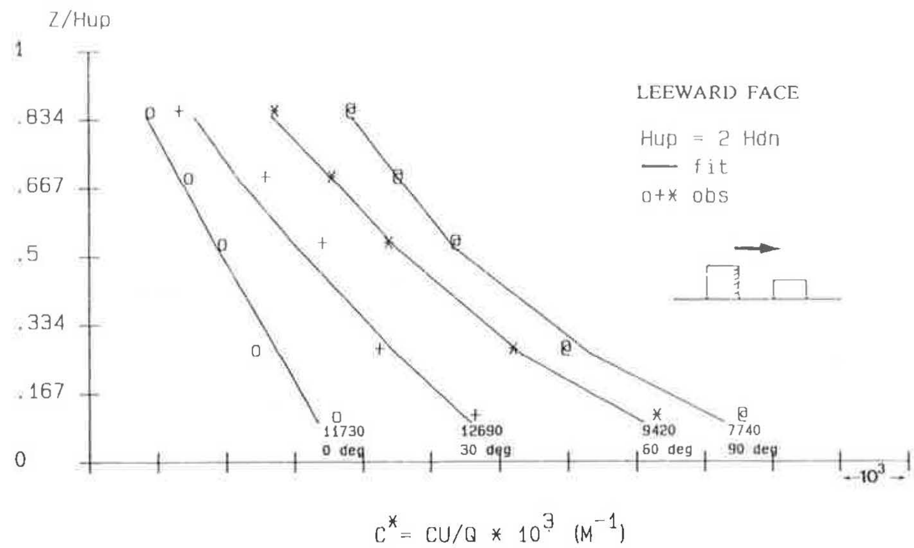


FIGURE 5 Midblock vertical concentration profiles for step-down notch configuration.

13.82×10^3, whereas b varies from a maximum of −0.33 to a minimum of −1.86. However, the exponential regression provides a consistently good fit to the data, with the explained variance (given by r^2) ranging from 0.95 to 1.00.

Street-level concentrations on the leeward face of the even-notch configuration are nearly invariant for θ values from 0 to 90 degrees. Near roof level, concentrations are a maximum at 0 degrees and decrease with increasing θ. The curvature of the vertical concentration profile again increases with θ. The pattern on the windward face reflects a fairly uniform slope from 0 degrees through 60 degrees. At larger values of θ, the curvature increases markedly, primarily in response to a large increase in the street-level concentration. The r^2 values range from 0.93 to 0.99 (with an average of 0.97 ±0.02) on the leeward face and from 0.81 to 0.99 (0.92 ±0.06) on the windward face. The empirical exponential curve again provides a consistently good fit to the observations. As before, both a and b vary widely with wind angle (θ).

The curvature of the profile for the step-up notch increases significantly with increasing θ on the leeward face, as did those of the other two configurations, but (unlike the case of the even notch) the curvature changes little on the windward face. The change in curvature on the leeward face is primarily due to an increase in the street-level concentration rather than the slope of the curve. The regression curves again fit the observations well: r^2 values range from 0.91 to 0.96 (average of 0.93 ±0.02) on the leeward face and from 0.87 to 0.99 (average of 0.93 ±0.05) on the windward face. The individual coefficients (a and b) vary less with θ, but the observed data are limited to a θ range of 0–60 degrees.

A number of empirical and analytical street canyon models have been developed over the past two decades for determining the height and cross-street variation of the pollutant mixing ratio (or concentration) from street-level vehicular emissions as a function of wind speed and direction, emission flux, and street canyon geometry. Two empirical models and one analytical diffusion model are evaluated here by using the concentration data from the even notch.

One of the earliest street canyon models was the empirical predecessor to the well-known APRAC model (named for the Air Pollution Research Advisory Committee) developed by Johnson et al. (*16*) from the observations of Georgii et al. (*4*) in Frankfurt am Main, West Germany. With street-perpendicular flow (θ = 0 degrees), Johnson and colleagues proposed that the streetside concentration on the windward (C_W) and leeward (C_L) sides is given by expressions of the form

$$C_W = C_b \exp [29\, Q(1 - z/z_r)] \quad (2)$$

$$C_L = C_b \exp [(45.6 + 4.68\, u)\, Q(1 - z/z_r)] \quad (3)$$

where Q is the emission flux, z/z_r is the ratio of the receptor height to building roof height, u is the wind speed, and C_b is the urban background concentration. Street-parallel flows were the average of the two equations. Although Georgii's data were all represented by Equations 2 and 3, other data were not well described. Subsequently, Johnson et al. identified several reasons:

- C_b should be an additive contribution rather than a determinant value;
- No separation of road and receptor was considered; and
- C at z_r did not necessarily equal C_b.

Some of these limitations are considered here by replacing the term C_b with the street-level concentration ($C_{W,0}$ or $C_{L,0}$), solving for the effective emission flux in Equation 3, and then evaluating the shape of the predicted windward concentration profile from Equation 2. If linearly extrapolated values of the leeward concentration at street and roof level for the even notch and a vortex radial velocity equal to 0.5 m s^{-1} (as determined from the flow visualization analysis) are used, the results presented in Table 1 are obtained for the observed and modeled concentrations on the leeward face. With both street-level and roof-level values of C_L^* prescribed, it is not surprising that the "model" (Equation 3) explains 94 percent of the variance of the intermediate five data points.

Next, the windward concentrations were determined from Equation 2 and the observed street-level windward concentration, yielding the results presented in Table 2. Clearly, the model (Equation 2) underpredicts the decrease in windward concentration with height; the corresponding value of r^2 is only 0.34. From the earlier analysis it was observed that the concentration decrease with height on both windward and leeward faces is well represented by a simple exponential function. The present analysis merely illustrates that the relative profile curvature on the two building faces is not described well by the modified form of the Johnson et al. model (*16*).

TABLE 1 OBSERVED AND MODELED (Equation 3) CONCENTRATIONS ON THE LEEWARD FACE

z/z_r	C_L^*(obs.)	C_L^*(3)	C_L^*(obs.)/C_L^*(3)
0.000	11,800	11,800	1.000
0.083	11,400	11,470	0.994
0.250	10,200	10,835	0.941
0.500	9,460	9,950	0.951
0.667	9,210	9,399	0.980
0.833	8,800	8,882	0.991
1.000	8,390	8,390	1.000

TABLE 2 OBSERVED AND MODELED (Equation 2) CONCENTRATIONS ON THE WINDWARD FACE

z/z_r	C_W^*(obs.)	C_W^*(2)	C_W^*(obs.)/C_L^*(2)
0.000	5,480	5,480	1.000
0.083	5,390	5,471	0.985
0.167	5,300	5,461	0.971
0.333	5,320	5,444	0.977
0.417	5,020	5,434	0.924
0.583	4,290	5,416	0.792
0.833	3,610	5,389	0.670
1.000	3,160	5,371	0.588

Johnson et al. (*4*) used new field data from San Jose, California, to develop a revised street canyon algorithm. If ΔC is the increment to the concentration that is attributable to street canyon emissions, then

$$\Delta C_L = Q/U_s Y \tag{4}$$

where Y is the vertical extent of the mixing volume and is assumed to be proportional to the sum of the diagonal traffic receptor separation plus a vehicle induced mixing length [$Y = k_1 (L + L_0)$]. The effective street-level wind U_s is taken to be proportional to the roof-level wind U_r and a vehicle drag flow (0.5 m s^{-1}), such that $U_s = k_2 (U_r + 0.5)$. When L_0 is assumed to be of the order of one vehicle dimension (about 2 m), then

$$\Delta C_L = Q/k_1 k_2 W (U_r + 0.5) (L + 2) \tag{5}$$

Johnson et al. (*5*) and Ludwig and Dabberdt (*17*) have determined experimentally that $k_1 k_2 = 1/7$ in independent field studies. The windward face concentration (ΔC_W) was first modified by Johnson et al., who reasoned that it should be height independent because of the thorough mixing and considerable transport from the emission source by the street canyon vortex:

$$\Delta C_W = Q/k_1 k_2 W (U_r + 0.5) \tag{6}$$

(where W is the street width). Ludwig and Dabberdt (*17*), however, reexamined Equation 6 and noted a decrease with height from entrainment. This observation resulted in the present form of the APRAC street canyon model, where

$$\Delta C_W = Q (H - z)/k_1 k_2 W (U_r + 0.5)H \tag{7}$$

Ludwig and Dabberdt stated that Equations 5 and 7 hold for values of θ from 0 to ±60 degrees.

In the absence of vehicle-induced turbulence in the notch, Equations 5 and 7 are revised slightly in the present application:

$$\Delta C_L = Q/k_1 k_2 LU_r \tag{8}$$

$$\Delta C_W = Q (H - z)/k_1 k_2 WHU_r \tag{9}$$

The distance L is taken to be the diagonal from the center of the street to the receptor; therefore Equation 8 can be rewritten for the even notch as

$$C_L^* = 7N^*/[(z/H)^2 + 1/4]^{1/2} \tag{10}$$

where $N^* = C_L^* (z = 0)/[7/0.4]$. If the observed C_L^* are used to normalize at street level, the values presented in Table 3 are the result. The corresponding value of $r^2 = 0.94$ indicates the observed profile is well represented by the APRAC model on the leeward face. However, it should be noted that the model systematically underpredicts at the upper receptor heights.

TABLE 3 OBSERVED AND MODELED (Equation 8) CONCENTRATIONS ON THE LEEWARD FACE

z/z_r	C_L^*(obs.)	C_L^*(8)	C_L^*(obs.)/C_L^*(8)
0.000	11,800	11,800	1.000
0.083	11,400	11,640	0.979
0.250	10,200	10,544	0.967
0.500	9,460	8,344	1.134
0.667	9,210	7,080	1.301
0.833	8,800	6,077	1.448
1.000	8,390	5,276	1.590

By using the normalizing factor for C_L^* and Equation 9, absolute values of C_W^* can be determined, as presented in Table 4. Again, the model systematically underpredicts at the upper levels: r^2 is very large at 0.93. Another measure of the performance of the APRAC street canyon model is its representation of the street-level cross-street concentration gradient.

The observed data indicate a ratio of C_L^* (observed)/C_W^* (observed) of 2.115 at the lowest measurement height (z/H = 0.083), while the APRAC model indicates a ratio of 1.794.

Hotchkiss and Harlowe (*18*) undertook both numerical and analytical solutions of the two-dimensional equations of motion and diffusion for unsteady flow in an open infinite notch. For the analytical solution evaluated here, the momentum equations were linearized and the diffusion equation was solved by a power series expansion of the velocity field. The geometry of the notch was very similar to the even notch reported here. The concentrations determined by Hotchkiss and Harlowe have been normalized as before, according to the observed value of C_L^* near street level, with the following results for both the leeward and windward faces. The ratio of observations to simulations varies on the leeward face from 1.0 at street level (by definition) to 1.832 near roof level and on the windward face from 0.667 at street level to 1.203 near roof level.

TABLE 4 OBSERVED AND MODELED (Equation 9) CONCENTRATION ON THE WINDWARD FACE

z/z_r	C_W^*(obs.)	C_W^*(9)	C_W^*(obs.)/C_W^*(9)
0.000	5,480	7,080	0.774
0.083	5,390	6,490	0.831
0.250	5,300	5,310	0.998
0.333	5,320	4,720	1.127
0.417	5,020	4,130	1.215
0.583	4,290	2,950	1.454
0.833	3,610	1,180	3,059
1.000	3,160	0	∞

These comparisons of observations with predictions by Hotchkiss and Harlow (H & H) indicate generally good agreement. On the leeward face, r^2 is 0.96, but the H & H model increasingly underpredicts with increasing height (as does the APRAC model). On the windward face, the model overpredicts substantially (by about 50 percent) near street level and underpredicts moderately near roof level. Overall, the modeled vertical gradients are significantly greater than the observed vertical gradients on both faces of the notch. At street level, the horizontal gradient from the H & H predictions is less than that observed. This was also the case with the APRAC model.

CONCENTRATION PATTERNS: SQUARE BLOCK

As summarized in the preceding sections, a major finding of the dispersion tests with the rectangular block configuration was the position of the concentration maxima in the middle of the street canyon with a perpendicular wind (i.e., θ = 0 degrees). Earlier fluid modeling tests in which Hoydysh and Ogawa (*12*) and Wedding et al. (*13*) used square blocks yielded different results: the concentration maxima were located at the ends of the street canyon near the intersections. Figure 6 illustrates representative concentration isopleth patterns from Hoydysh and Ogawa. To

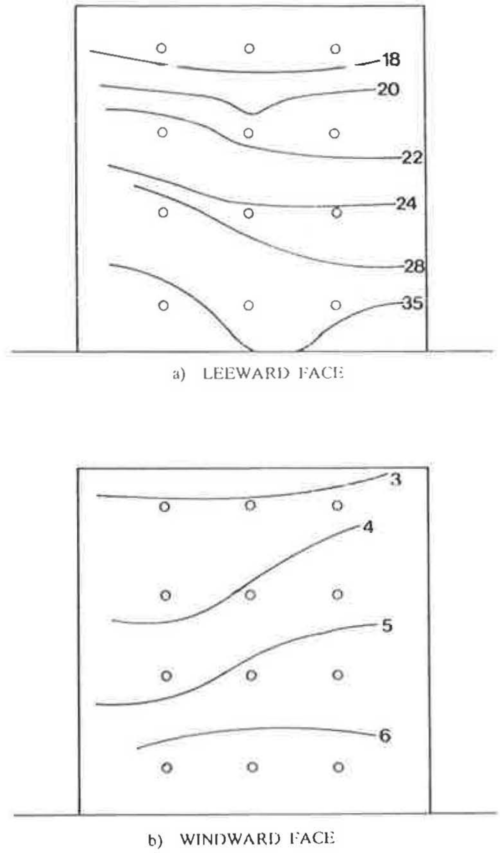


FIGURE 6 Concentration patterns in a square block grid (*12*).

establish the sensitivity of the concentration pattern to block configuration, additional tests were conducted in the ABLWT.

The urban street model was changed from a rectangular block configuration to a square block configuration, but the length and intensity of the line source remained unchanged. Similarly, the building height and street and avenue widths were also kept fixed. The resulting street canyon concentration pattern for the even notch is shown in Figures 7 and 8 for the upwind (a) and downwind (b) building faces. Figure 7 has an upwind fetch over a smooth surface, and Figure 8 corresponds to a rough upwind fetch. Upwind roughness has an insignificant effect on the magnitude or distribution of the concentration isopleths in the street canyon. This insensitivity is probably due to the very large roughness of the urban core, which dominates the roughness of the upwind fetch.

In a manner similar to that observed in the two earlier square block studies, the concentrations increased from the center of the street canyon outward to the edges or ends of the block. The leeward (i.e., upwind) concentrations continue to be significantly greater than the concentrations on the downwind (windward) building face. If the magnitude of the concentrations for the square (Figure 7) and rectangular blocks are compared, it can be observed that concentrations are more than a factor of two greater for the rectangular block. The reduction in the square block configuration is a consequence of the increased ventilation that corresponds to the shorter length of the street canyon. For the

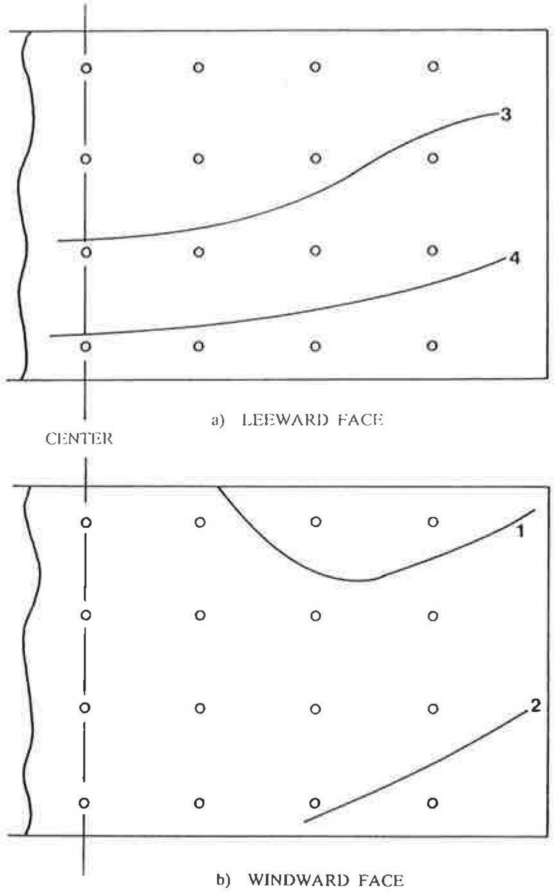


FIGURE 7 Concentration ($C^* \times 10^{-3}$) contours for square block and smooth upwind fetch; $\theta = 0$ degrees.

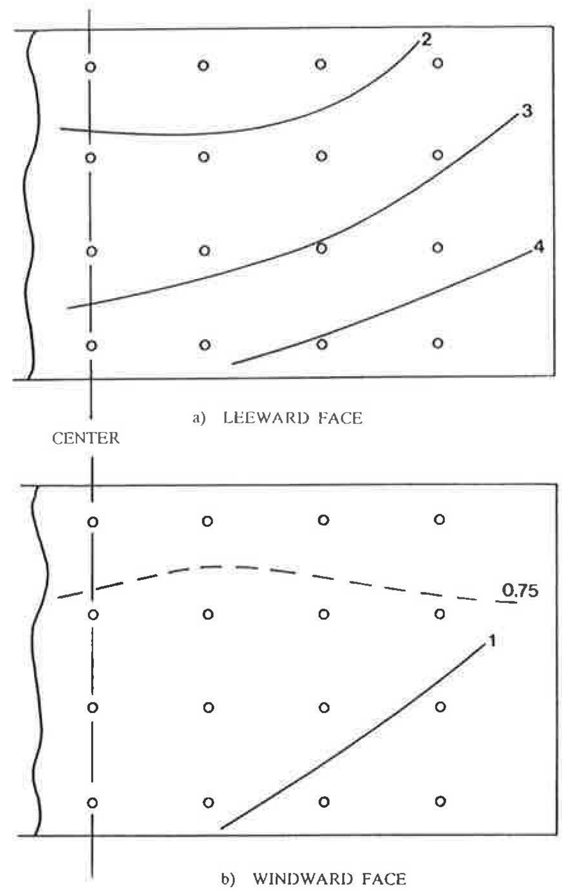


FIGURE 8 Concentration ($C^* \times 10^{-3}$) contours for square block and rough upwind fetch; $\theta = 0$ degrees.

rectangular configuration the ratio of street length (along the line source) to open space corresponding to the intervening avenues is 6:1, whereas for the square configuration the ratio is 2.0:1. A secondary effect may also be the result of the size of the corner vortices compared to the length of the block. For the shorter square block, it can be assumed that the turbulent mixing caused by the two corner vortices affects the entire length of the block.

CONCLUSIONS

The dispersion characteristics of flow in three notch configurations on a rectangular block were examined by using tracer gas techniques. The notches are representative of the broad types of street canyons found in urban areas. In addition, the differences between rectangular and square blocks for the street canyon distribution of concentrations were investigated. The results of these investigations have confirmed some previous research findings and provided several new insights as well.

From the rectangular block configuration, it can be concluded that

- Entrainment into the street canyon appears to be primarily the result of horizontal advection caused by vertical axis corner vortices.
- The distribution of trace gas concentration contours is nearly identical on the leeward faces of the even and step-down notch configurations and is characterized by higher concentrations at midblock. Leeward contours for the step-up notch are horizontally stratified throughout the notch, suggesting the absence of convergence (in comparison to the other configurations).
- Street-level cross-notch gradients indicate that concentrations are generally a factor of two or more greater for the leeward than for the windward face. The exception is for the step-down notch, where windward concentrations are slightly greater than those to leeward for free stream wind directions nearly perpendicular ($\theta \leq 30$ degrees) to the longitudinal notch axis.
- Concentrations are generally a factor of two lower in the step-up notch than in either the step-down or even notches.
- The vertical concentration profile is a simple exponential function for both notch faces and all three notch configurations in the case of the rectangular block, but the scale and shape coefficients vary widely.
- Evaluation of one analytical and two empirical models of concentration profile showed mixed results on the basis of data for the even notch and perpendicular flow in the rectangular block. The general features are represented, but the magnitude of the cross-street gradient is underestimated and the vertical gradient is both under- and overestimated by the various

models. None of the models is structured to represent the observed contour patterns as functions of wind angle and notch configuration.

When the concentration pattern in the even notch of the rectangular block is compared with that in the square block, it can be observed that

- Concentration maxima occur in the middle of the rectangular block but near the edges of the square block.
- With equivalent line source emission rates, concentration magnitudes are more than a factor of two greater for the rectangular block than for the square block.

The effect of block configuration on the shape and magnitude of the concentration field is a major new finding from this study.

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Publication of this paper sponsored by Committee on Transportation and Air Quality.