ADVANCED STREET CANYON SPECIFICATION

CERC

In this document 'ADMS' refers to ADMS-Roads 5.1, ADMS-Urban 5.1 and ADMS-Airport 5.1. Where information refers to a subset of the listed models, the model name is given in full.

1. Introduction

This paper contains the technical specification for the advanced street canyon dispersion module in ADMS. This module takes into account the effects of a street canyon on the dispersion of pollution from a road source.

The principal effects of a street canyon on the dispersion of pollution from a road source are: pollution is channelled along the canyon; pollution is dispersed across the canyon by circulating flow at road height; pollutants are trapped in recirculation regions; pollutants leave the canyon through gaps between buildings; pollutants leave the canyon from the canyon top; and pollutants leave the canyon from the downstream end of the canyon. In the ADMS advanced street canyon module, each of these effects is modelled using a separate component source, with differing source geometry, source dispersion type, wind direction, region of influence and source strength. The final concentration is the weighted sum of contributions from the component sources. The magnitudes of the weightings depend on the canyon properties and the wind direction relative to the canyon orientation.

The general effects of an urban area on wind velocity and turbulence are included in the urban canopy flow module in ADMS, as described in the Urban Canopy Flow Specification document (P34/01). The flow within an individual street canyon is controlled by the orientation of the canyon relative to the wind direction and the properties of the canyon, such as width and height. Such flow within a canyon is calculated within the advanced canyon module, as described in Section 3.

ADMS includes a basic street canyon model, based on the Danish model OSPM [1], which is described in the Street Canyon Model specification (P28/01). The advanced street canyon model differs from the basic street canyon model by including consideration of the effects of canyon asymmetry, the porosity of canyon walls and canyons with heights substantially greater than their widths, as well as affecting concentrations both inside and outside the canyon.

There are two modes for the advanced street canyon calculations; standard mode and network mode. Network mode analyses the road network geometry to account for the flow of pollutants between and out of street canyons. Standard mode takes a simpler approach and assumes that all canyons are part of a large network of similar canyons. Network mode requires a more detailed and accurate road geometry than standard mode and is also computationally more expensive, but provides greater detail near the start and end of isolated street canyons by including the effects of the presence of any upstream canyons on the canyon being considered and considering the destination of material which leaves through the end of the canyon. Standard mode is likely to be most appropriate when modelling a large and relatively uniform urban area, whereas when modelling small areas of roads in detail then network mode should be used.

Within this document, Section 2 lists the data used in the advanced canyon module to characterise the properties of a street canyon. Section 3 defines the flow conditions within the canyon, which drive the in-canyon dispersion. Section 4 describes the methodology used to characterise the street canyon network in network mode. Section 5 describes the formulation of each of the component sources used in the module and Section 6 the procedure for calculating the weighting between the sources. Additional considerations for complex canyon geometries, such as asymmetric canyons and elevated road sources, are described in Section 7. Some additional calculations required to take into account chemical reactions of pollutants dispersing from road sources within street canyons are described in Section 8.

2. Data used in the advanced canyon module

2.1 User inputs

The input data for each canyon in the advanced canyon module are listed below. Each variable except name, vertex coordinates and fraction covered is defined for each side i of the canyon. The orientation of the canyon is defined by the first two vertices of the road source, with properties defined for right and left sides of the canyon when looking from the first towards the second vertex.

Name	Road source name
x_1, y_1	Coordinates of the first vertex
x_2, y_2	Coordinates of the second vertex
H_{avg_i}	Average building height
H_{max_i}	Maximum building height
H_{min_i}	Minimum building height
g_i	Width from road centreline to canyon wall
b_i or α_i	Length of road with adjacent buildings, or porosity (see §2.2)
F_c	Fraction of canyon area covered by overhanging features

A side of the canyon is considered to have a canyon wall if H_{avg_i} and total road length are greater than user-defined minima, with default values of 2 m and 1 m respectively. For physical reasons, g_i must be greater than half the road width w.

2.2 Characterisation of a street canyon

The user input data values are used to calculate derived variables used to characterise the street canyon, as follows:

$H = (H_{avg_L} + H_{avg_R})/2$	Overall average canyon height (m)
$H_{min} = \min(H_{avg_L}, H_{avg_R})$	Overall minimum canyon height (m)
$H_{max} = \max(H_{avg_L}, H_{avg_R})$	Overall maximum canyon height (m)
$H_{\Delta_i} = 2(H_{avg_i} - H_{min_i})$	Range of building heights for each side (m)
$g = g_L + g_R$	Total canyon width (m)
$\alpha_i = 1 - b_i/L_R$	(If b_i input) Porosity for each side, where L_R is the road length
H/g	Ratio between canyon height and width
ϕ_c	Angle of the canyon segment relative to north (degrees)

The porosity of a canyon wall is defined as the proportion of the road length which does not have adjacent buildings.

For a specific road source segment and hour of meteorological data, the upstream and downstream canyon sides are identified, and associated properties indicated with subscripts u and d. For wind directions very close to parallel with the canyon orientation, definitions of upstream and downstream sides are not relevant and average properties, or a convention that the left side is upstream, may be used instead.

3. In-canyon flow

The in-canyon flow has components parallel to and perpendicular to the canyon axis. The component of the wind parallel to the canyon, U_x, is given by:

$$U_x(z) = U_c(z)\cos(\phi_c - \phi_w) \quad (1)$$

where z is the height above the ground, U_c is the magnitude of the wind speed, ϕ_c is the canyon orientation and ϕ_w is the angle of the upstream wind, both relative to north. The angles and vectors are illustrated in **Figure 1**.

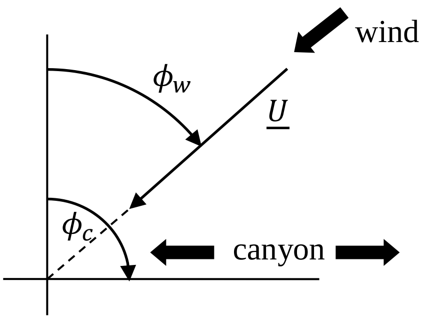

Figure 1 - Orientation of flow vector (U_x, U_y) with respect to the canyon.

The component of the wind perpendicular to the canyon is given by:

$$U_y(y,z) = U_c(z)\hat{h}(z)\,\eta\,\sin(\phi_c - \phi_w) \quad (2)$$

Here, the flow within the canyon is proportional to the resultant prevailing wind speed at the top of the canyon. By assuming circular flow relative to the origin at $\left(y = \frac{g}{2}, z = \frac{H}{2}\right)$, as illustrated in **Figure 2**, we find the function $\hat{h}(z)$ to be in the range $[-1,1]$, with $\hat{h}(H) = 1$ and $\hat{h}(0) = -1$, specifically:

$$\hat{h}(z) = \begin{cases} 2\frac{z}{H_R} - 1 & z \le H_R \\ 1 & z > H_R \end{cases} \quad (3)$$

where H_R is defined as one canyon width above the source height plus twice the initial mixing height. η is a factor which is used to reduce the velocity across the canyon, to account for obstruction by traffic, which is set to 0.5.

Note that this flow field is only used for dispersion along and across the canyon at the source height in the dispersion model, expected to be near the surface. For the purposes of the dispersion calculations, a minimum value of 0.3 m/s is applied to U_y.

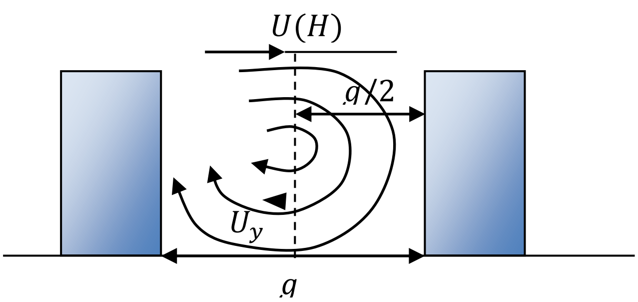

Figure 2 - Flow perpendicular to the canyon.

The vertical profile of velocity within a street canyon is also modified according to expressions similar to those used for the urban canopy flow, but substituting canyon height for displacement height, to create a more locally representative flow field. An effective value of the proportion of the local area occupied by buildings, λ_P, is calculated based on porosity and fraction covered by assuming that the buildings extend for one canyon width on each side of the road, as illustrated in **Figure 3**.

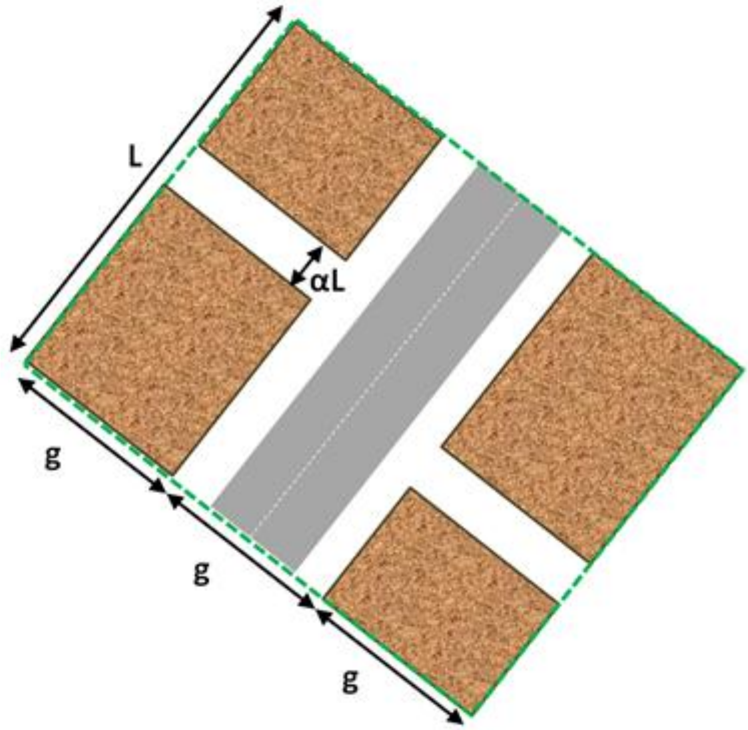

Figure 3 Diagram of an individual canyon, assuming that buildings extend one canyon width beyond each of the canyon walls.

The local area occupied by buildings, A_B, is calculated as follows:

$$A_B = 2(1-\alpha)Lg + 0.75F_cLg \tag{4}$$

The value of 0.75 in the second term on the right is used to account for potential height variation in overhanging features that cover part of the canyon. λ_P is then calculated as $A_B/3Lg$, which leads to the following expression:

$$\lambda_P = \frac{2(1-\alpha) + 0.75F_c}{3} \tag{5}$$

This leads to a vertical profile of velocity given by:

$$U_C = \frac{u_{*S}}{\kappa}\ln\left(\frac{z}{z_{0S}}\right) \tag{6}$$

where κ is von Karman's constant (0.4); z_{0S} is the within-canopy roughness (0.1 m); and u_{*S} is calculated by defining velocities at half the canyon height:

$$u_{*S} = \frac{\kappa(1-\lambda_P)^2U(H)}{\ln\left(\frac{H}{2z_{0S}}\right)} \tag{7}$$

where U is the upstream velocity profile.

For $z > H/2$ the velocity is interpolated between the within-canyon and outside-canyon solutions in order to ensure a smooth vertical profile of velocity.

Similarly, the lateral and vertical turbulence velocity profiles are altered near the ground according to

$$\sigma_{v,w}(z) = \sigma_{v,w}(H)\exp\left(-\frac{(H-z)}{2g}\right) \tag{8}$$

with variables as before.

4. Street network

When running in network mode the geometry of the network of roads is analysed for each wind direction. This analysis is used to determine the length of canyons upstream of each street canyon, in order to determine the material entering the canyon from upstream canyons. Similarly, the number of downstream roads and canyons for each canyon must be found in order to determine the destination of material leaving the canyon from the end.

At the start of each run the road network is analysed to determine how the roads are connected. Two roads are connected if they share an end vertex, i.e. road junctions are only considered at the end of roads and not at intermediate vertices. Then during the dispersion calculations for each wind direction and for each canyon segment two properties are calculated: the length of upstream canyons, L_u; and the fraction of material leaving the end of the canyon, γ.

As part of these calculations the number of downstream roads (non-canyon and canyon) needs to be calculated. For segments of a canyon which are not the most downstream segment then there is exactly one downstream canyon and no downstream non-canyons. For the most downstream segment of a canyon the numbers are calculated by looking at all of the roads which connect to the most downstream vertex, checking their orientation relative to the wind direction and whether they are a canyon.

Then for each canyon segment the total length of canyon upstream to this segment is calculated using an iterative process, as follows:

- If this is not the most upstream segment for this canyon then add the projected length of the next upstream segment of the canyon along with the upstream length of that segment.
- If this is the most upstream segment then for each connecting canyon add the projected length of the connecting segment from that canyon along with its upstream length. If the connecting canyon has multiple downstream roads (non-canyon or canyon) then partition this length (and therefore the emissions) equally between the downstream roads.

When calculating the upstream canyon length a cut-off is applied to limit the length of upstream canyon considered, since material dispersed from the top of the canyon limits the amount of material from 'far' upstream which is able to reach a canyon.

The fraction of material leaving through the end of the canyon is calculated as the number of non-canyon downstream connecting roads divided by the total number of downstream connecting roads, thus accounting for the material which has not gone into any other canyons. If there are no connecting downstream roads then the fraction leaving the end of the canyon is set to 1. Note that this fraction is applied to the amount of material reaching the end of the canyon and so even with a value of 1 material is still able to leave the canyon via the top or the porous sides.

5. Component sources

Seven separate component sources are used to model a single road source segment within the advanced canyon module. Three component sources represent the dispersion within the canyon:

- a source representing the dispersion along the street, including channelling effects;

whose influence is only considered within the canyon, and

- a source representing the dispersion across the street, including the effects of circulating flow at road height; and
- a source representing the recirculation region;

whose influence is only considered within the recirculation region.

Four further component sources represent the dispersion out of the canyon. The first of these:

- a source representing the dispersion between the buildings;

influences concentrations throughout the modelling domain, the second:

- a source representing direct dispersion from the top of the canyon;

is considered everywhere in the modelling domain outside the street canyon, the third:

- a source representing escape of recirculating material from the top of the canyon;

is considered everywhere in the modelling domain outside the recirculation region, and the fourth:

- a source representing the dispersion out of the end of the canyon;

is considered downwind of the end of the canyon. These sources are illustrated in a schematic manner in **Figure 4**. Sections 5.1 to 5.7 describe each of these component sources in further detail. The emissions from the road source are divided between the component sources by a weighting which is described in Section 6.

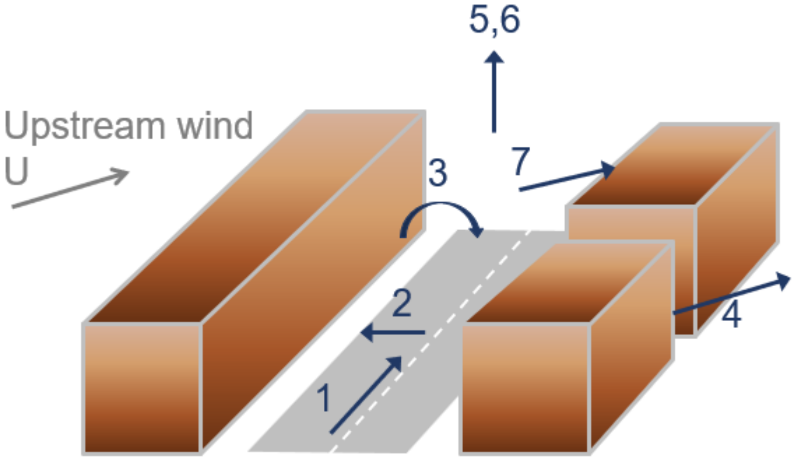

Figure 4 Illustration of the seven component sources used in the advanced canyon module

5.1 Dispersion along the street

The dispersion along the street is represented by a ground level road source with the flow parallel to the street. The road source may be narrower than the canyon and there may be more than one road source to represent different lanes of the road.

The plume spread from the along-canyon source is determined by the transverse turbulence velocity, σ_v, until the plume impacts on the canyon sides. The plume can reach each canyon side at a different distance along the street if the road source centreline is not in the centre of the canyon. A reflected plume is considered from each canyon side with a height greater than zero. Only one reflection from each canyon wall is explicitly included in the modelling; once the plume reflected from one canyon wall reaches the opposite canyon wall the concentration is considered to be well-mixed across the canyon. The vertical diffusion for the road line source is the same as for an ordinary road source. The source strength for this component source is denoted by q_1. In network mode the road source may be extended in the upstream direction to account for material flowing into the canyon from other parts of the road network. In standard mode the concentration from source 1 is constant along the length of the canyon based on an effective segment length set by the user, with a default value of 300 m.

In the initial phase of dispersion, the concentration from a single element of the source, C_i, is given by:

$$C_i = \frac{Q_i}{2\sqrt{2\pi}U_x w\sigma_z}\left(\exp\left(-\frac{\left(z_{op} - z_s - H_0\right)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{\left(z_{op} + z_s + H_0\right)^2}{2\sigma_z^2}\right)\right)(LateralProfile) \tag{9}$$

where Q_i (g/s) is the emission rate from this element, U_x is the velocity along the canyon axis at the mean plume height, w is the width of the road source, σ_z is the plume depth, z_{op} is the output point height, z_s is the source height, H_0 is the initial road mixing height and the lateral profile is given by the standard ADMS expression with additional reflection terms:

$$\begin{aligned} LateralProfile &= \left[\operatorname{erf}\left(\frac{y_{op} + \frac{L_S}{2}}{\sqrt{2}\sigma_y}\right) - \operatorname{erf}\left(\frac{y_{op} - \frac{L_S}{2}}{\sqrt{2}\sigma_y}\right)\right] \\ &+ \left[\operatorname{erf}\left(\frac{2g_+ - y_{op} + \frac{L_S}{2}}{\sqrt{2}\sigma_y}\right) - \operatorname{erf}\left(\frac{2g_+ - y_{op} - \frac{L_S}{2}}{\sqrt{2}\sigma_y}\right)\right] \\ &+ \left[\operatorname{erf}\left(\frac{-y_{op} - 2g_- + \frac{L_S}{2}}{\sqrt{2}\sigma_y}\right) - \operatorname{erf}\left(\frac{-y_{op} - 2g_- - \frac{L_S}{2}}{\sqrt{2}\sigma_y}\right)\right] \end{aligned} \tag{10}$$

In this equation the first square bracket contains the standard ADMS lateral profile, the second gives the reflection term from the canyon wall in the positive y direction, and the third gives the reflection term from the canyon wall in the negative y direction. The individual variables are as follows: y_{op} is the lateral position of the output point relative to the source centreline; L_S is the element length; σ_y is the plume width; g_+ is the distance from the source centreline to the canyon wall in the positive y direction and g_- is the distance from the source centreline to the canyon wall in the negative y direction. The method for dividing the source into elements and further information about the lateral profile is given in the ADMS Technical Specification paper P31/01 (Road Sources).

Once the plume becomes well-mixed across the canyon, the concentration from a single element of the source, C_i, is given by:

$$C_i = \frac{Q_i}{\sqrt{2\pi}U\sigma_y\sigma_z}\left(\exp\left(-\frac{(z_{op}-z_s-H_0)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z_{op}+z_s+H_0)^2}{2\sigma_z^2}\right)\right) \quad (11)$$

where σ_y is now the plume width limited by the canyon width on one or both sides.

5.2 Dispersion across the street

The direction in which emissions are dispersed at street level is influenced by the height of the canyon, H, in relation to the canyon width, g, as illustrated in **Figure 5**. The formulation for shallow canyons, $H/g < 1$, is given in Section 5.2.1 while additional aspects for deeper canyons, $H/g > 1$, are covered in Section 5.2.2.

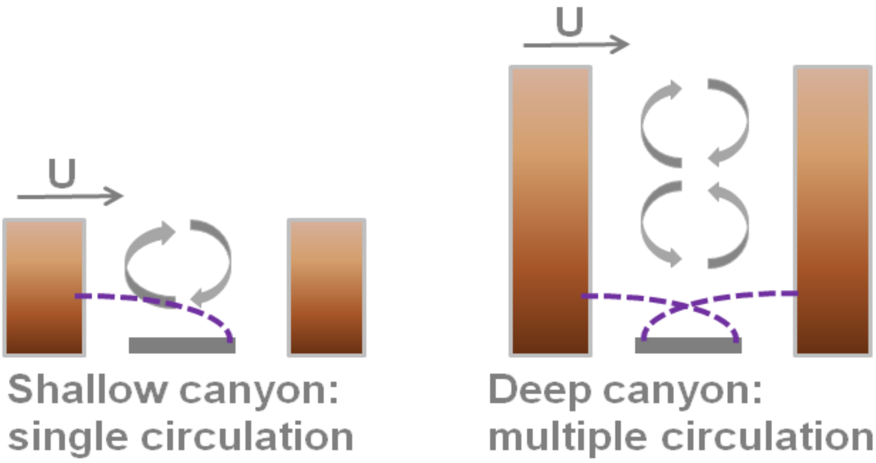

Figure 5 Diagrams of across-canyon source for shallow and deep canyons

5.2.1 Shallow canyons H/g < 1

The dispersion across the street is represented by a ground level road source with the flow taken to be perpendicular to the street. Note that for this source the flow across the street is in an upstream direction relative to the background flow. As the plume is advected to the edge of the canyon it spreads due to flow divergence and vertical diffusion (σ_w). An analytical integrated solution is used for this source due to the short distance over which its dispersion is considered.

For this source the ground-level concentration, C_0, at distance y from the centre of the road (or from the centre of the part of the road within the recirculation region if there is a partial recirculation region, see §5.3.2) is given by

$$C_0 = \frac{Q}{\sigma_W w}\ln\frac{2U_yH_0+\sigma_W\left(y+\frac{wF_r}{2}\right)}{2U_yH_0+\sigma_W(y-w_{incl})} \quad (12)$$

where Q (g/m/s) is the emission rate, σ_W is the atmospheric vertical diffusion at height $z_s + H_0$, w is the road width, F_r is one or the fraction of the road within the recirculation region if there is a partial recirculation region (see §5.3.2), U_y is as defined in Section 3, H_0 is the initial mixing height for road sources (1 m) and w_{incl} is the width of the road from which emissions affect the output height, given by

$$w_{incl} = \min(\frac{wF_r}{2}, y, y - \Delta y_{Zop}) \quad (13)$$

where

$$\Delta y_{Zop} = \frac{\left(z_{op} - z_s - 2H_0\right) U_y (z_s + H_0)}{2\sigma_W} \quad (14)$$

which is an estimate of the horizontal distance required for the plume to spread from its initial depth $z_s + H_0$ to the height of the output point, z_{op}. The ground-level concentration, C_0, is applied to output points within the recirculation region that are at or less than the source height, z_S, plus $2H_0$. For higher output points within the recirculation region, a vertical profile is applied as follows:

$$C = C_0 \frac{\left(z_{op} - z_S + 2H_0\right)}{4H_0} + \frac{Q}{\sigma_W w} \frac{z_{op} - z_S - 2H_0}{4H_0} \ln\left(\frac{y - w_{incl}}{y + \frac{wF_r}{2}}\right) \quad (15)$$

5.2.2 Deep canyons H/g > 1

In idealised flow situations, the flow field generated within a deep canyon, driven by crosswind flow at the top of the canyon, is a sequence of alternating eddies; each of these occupies a depth of approximately g within the canyon. In real flow field situations however, it is unlikely that such well-defined flow structures will exist due to the irregular nature of the canyon walls i.e. gaps between buildings and obstructions into the canyon. These irregularities lead to an unstructured flow field in the canyon, and the wind vector at the road will be variable in strength and unpredictable in direction.

In order to represent the uncertainty relating to the direction of wind flow at the road, when the canyons are relatively deep (H/g >1) the dispersion across the street is represented by a weighted sum of concentrations calculated assuming the ground level flow is in the opposite and same directions as the background flow:

$$C = \begin{cases} C_1 & \frac{H}{g} < 1 \\ C_1 + \frac{1}{2}\left(\frac{H}{g} - 1\right)(C_2 - C_1) & 1 \le \frac{H}{g} \le 2 \\ \frac{(C_1 + C_2)}{2} & \frac{H}{g} > 2 \end{cases} \quad (16)$$

where C_1 and C_2 are the concentrations assuming the ground level flow is in the opposite and same direction as the background flow respectively, calculated using the expression for concentrations given by (15). The travel times between the road centreline and output point location, plus initial mixing time, will be combined in the same way as the concentrations.

5.3 Recirculation region

For shallow canyons, the recirculation region will not occupy the full canyon cross-section, as schematised in Harman et al. [3] and reproduced in **Figure 6** below.

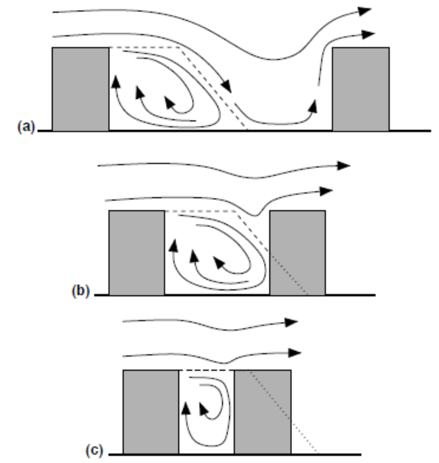

Figure 1. Schematic of the streamlines in the three flow regimes: (a) $L_r < W$ isolated roughness flow regime; (b) $L_r/2 < W < L_r$ wake interference flow regime; (c) $W < L_r/2$ skimming flow regime (flow regimes after Oke (1987)).

Figure 6 Figure 1 from Harman et al. [3]

In ADMS, the recirculation region is assumed to occupy the full canyon cross-section if any of the following criteria are met:

- The average height of the upstream canyon wall is at least the canyon width, $H_u \geq g$
- The average height of the upstream canyon wall is less than the (implied) width of canyon covered by overhanging features, $H_u < W_c$, where $W_c = \frac{gF_c}{2(1-\alpha)}$
- The average height of the upstream canyon wall is less than 0.5 m and the average height of the downstream canyon wall is at least half the canyon width, $H_u < 0.5$ m and $H_d \geq \frac{g}{2}$

No recirculation region is modelled if $H_u < 0.5$ m and $H_d < \frac{g}{2}$. Otherwise a partial recirculation region is assumed. The formulation for a full recirculation region is given in Section 5.3.1 while the formulation for a partial recirculation region is given in Section 5.3.2.

5.3.1 Full recirculation region

The analytical solution for flow within a deep cavity driven by perpendicular flow gives a series of counter-rotating vortices, each with a depth approximately equal to the cavity width. However, observations of real-world street canyon flows indicate that the actual number of vortices is typically limited to three [2]. The effects of recirculating flow in the canyon are therefore divided into a series of up to three cells, covering the full depth of the canyon.

The uppermost cell within the canyon extends from H_{min} to H_{max}. This cell does not exist for symmetric canyons. Conversely, if one canyon wall is absent this will be the only cell present. The lowest cell within the canyon extends from the ground up to $\min(h_1, H_{min})$. h_1 is defined as:

$$h_1 = z_s + 2H_0 + g \tag{17}$$

where z_s is the road height, H_0 is the initial mixing height for roads and g is the total canyon width. In shallow symmetric canyons, this will be the only cell present. In deeper asymmetric canyons, a middle cell exists between h_1 and H_{min}.

The concentration in the uppermost cell, C_3, is calculated as:

$$C_3 = \frac{H_{max} - H_{min}}{g} \frac{Q}{g\sigma_3(H_{max})} \tag{18}$$

where Q (g/m/s) is the emission rate from the road and $\sigma_3(H_{max})$ is a modified turbulent velocity at the top of the uppermost cell representing additional mixing from vortex shedding off building tops, given by:

$$\sigma_3 = \sqrt{\lambda(\sigma_u(H_{max}))^2 + (\sigma_w(H_{max}))^2} \tag{19}$$

$$\lambda = \min\left(\frac{H_{max} - H_{min}}{g}, 1\right) \tag{20}$$

σ_u and σ_v are the along-wind and vertical turbulent velocities, respectively.

The concentration in the middle cell is given by:

$$C_2 = C_3 + \max\left(\frac{H_{min} - h_1}{g}, 0\right) \frac{Q}{g\sigma_w(H_{min})} \tag{21}$$

The concentration in the lowest cell is given by:

$$C_1 = C_2 + \min\left(1, \frac{H_{min}}{g}\right) \frac{Q}{g\sigma_w(h_1)} \tag{22}$$

The concentration at the height of an output point, C_{op}, is linearly smoothed between the concentration in the containing cell and the concentration in the neighbouring cell if the point is within $L_n/2$ of the boundary between those two cells. The smoothing filter length, L_n, used at the boundary between cells n and $n+1$ is $\frac{1}{2}\min(g, D_n, D_{n+1})$, where D_n and D_{n+1} are the depths of the cells either side of the boundary. No vertical smoothing is applied near the ground or near the upper boundary of the top cell. The expressions for vertical smoothing are as follows, where C_n and h_n are the concentration and height of the cell in which the output point lies, respectively:

$$C_{op} = \begin{cases} C_{n-1} + \dfrac{z_{op} - \left(h_{n-1} - \frac{L_{n-1}}{2}\right)}{L_{n-1}}(C_n - C_{n-1}) & z_{op} < h_{n-1} + \dfrac{L_{n-1}}{2} \\ C_n & h_{n-1} + \dfrac{L_{n-1}}{2} \le z_{op} \le h_n - \dfrac{L_n}{2} \\ C_n + \dfrac{z_{op} - \left(h_n - \frac{L_n}{2}\right)}{L_n}(C_{n+1} - C_n) & z_{op} > h_n - \dfrac{L_n}{2} \end{cases} \tag{23}$$

After the calculation of the vertical variation of concentration, a lateral variation is applied to the recirculation concentration in the lowest cell (between the ground and h_1) if $H_{max} < z_s + 2H_0 + 2g$. The centre of the profile variation is at a factor β of the lowest cell height, with a value of 0.75. If the centre height is lower than $z_s + 2H_0$, no lateral profile is applied. No lateral profile factor is applied to output points below $z_s + 2H_0$.

The value of the lateral profile factor for points above $z_s + 2H_0$ but below the profile centre height is calculated as follows:

$$f = 1 + \frac{z_{op} - (z_S + 2H_0)}{\beta h_1 - (z_S + 2H_0)}\left(\frac{2y}{g}\right)\left(\frac{m-1}{m+1}\right) \tag{24}$$

where y is defined relative to the centreline of the canyon, positive towards the upstream side of the canyon in the main flow, and m is a shape factor with value 2.

Similarly, the value of the lateral profile factor for points above the profile centre height but below h_1 is calculated as follows:

$$f = 1 + \frac{h_1 - z_{op}}{(1-\beta)h_1}\left(\frac{2y}{g}\right)\left(\frac{m-1}{m+1}\right) \quad (25)$$

The lateral profile factor is scaled down towards 1 if $H_{max} > z_s + 2H_0 + g$, as follows:

$$f_{sc} = f + (1-f)\left(\frac{H_{max} - (z_S + 2H_0 + g)}{g}\right) \quad (26)$$

5.3.2 Partial recirculation region

When there is a partial recirculation region, the recirculation region is restricted to the part of the canyon cross-section within the right trapezium that extends from the upstream canyon wall with a ground-level base length of $2H_u$ and a top base length (and height) of H_u.

The fraction of the road within the partial recirculation region, F_r, is then calculated. If $F_r = 0$, there will be no contribution from the recirculation region source, nor from the across-canyon source nor the source representing escape of recirculating material from the top of the canyon.

The concentration in the partial recirculation region is given by:

$$C_1 = \min\left(1, \frac{H_u}{g}\right)\frac{Q}{\min(2H_u, g)\sigma_w(H_u)} \quad (27)$$

The same lateral variation applied to the recirculation concentration in the lowest cell for full recirculation regions (see equations (24) - (25)) is also applied to the partial recirculation region concentration, but y is defined relative to the ground-level centre of the recirculation region and g is replaced with the ground-level width of the recirculation region, i.e. $\min(2H_u, g)$.

5.4 Dispersion between the buildings

The dispersion between the buildings is represented by a ground level road source with flow parallel to the upstream wind direction. This source is modelled in exactly the same way as if the buildings were not present except it has a reduced source strength, q_4. The standard ADMS method for modelling road sources is described in the ADMS Technical Specification paper P31/01 (Road Sources).

5.5 Direct dispersion from the top of the canyon

Direct dispersion out of the top of the canyon is represented by a volume source directly above the canyon, modelled with upstream flow. This is modelled as a standard volume source with a total source strength per unit length given by q_5. The standard ADMS method for modelling volume sources is described in the ADMS Technical Specification paper P25/03 (Implementation of Area, Volume and Line Sources).

The base of the volume source is defined at the minimum of the downstream wall building heights and covers the whole horizontal area of the canyon, and the depth of the volume source is based on a maximum of:

- the range of building heights of the downstream canyon wall; and
- a minimum depth of twice the mixing height for road sources.

If there is a partial recirculation region, the base of the volume source is moved to the average height of the upstream canyon wall if it is lower than the initial base height. The source height is limited to be below the boundary layer height. The source depth is required to be less than twice the source height, as volume sources are not permitted to intersect the ground.

5.6 Escape of recirculating material from the top of the canyon

Dispersion due to the escape of recirculating material from the top of the canyon is represented by a volume source directly above the canyon, modelled with upstream flow. This is modelled as a standard volume source with a total source strength per unit length given by q_6. The standard ADMS method for modelling volume sources is described in the ADMS Technical Specification paper P25/03 (Implementation of Area, Volume and Line Sources).

If there is a full recirculation region, the volume source covers the whole horizontal area of the canyon and the base height and depth of the volume source are identical to those of the volume source used to model direct dispersion out of the top of the canyon (see §5.5). If there is a partial recirculation region, the volume source covers the horizontal area of the top of the recirculation region with its base at the minimum of the upstream wall building heights and a depth that is the maximum of:

- the range of building heights of the upstream canyon wall; and
- a minimum depth of twice the mixing height for road sources.

5.7 Dispersion from the end of the canyon

The dispersion of material leaving the network from the end of a canyon is represented by a volume source at the end of the canyon, modelled with upstream flow. This is modelled as a standard volume source with a total source strength per unit length given by q_7. The standard ADMS method for modelling volume sources is described in the ADMS Technical Specification paper P25/03 (Implementation of Area, Volume and Line Sources).

The base of the volume source is on the ground and covers the last 20 m of the downstream end of the road source. The depth of the volume source is half of the smallest of:

- the average height of the canyon (or the average height of the upstream canyon wall if there is a partial recirculation region), or
- the vertical spreading along the canyon length of material released at the start of the canyon, in cases where this is insufficient for material to reach to top of the canyon.

The effects of the volume source are limited to areas downwind of a line perpendicular to the downwind end of the road source.

6. Source weightings

This section describes the weighting between the seven component sources used in the advanced canyon model. For total source strength, q, the source strengths for the individual component sources are:

1. along the street, q_1;
2. across the street, q_2;
3. within the recirculation region, q_3;
4. between the buildings, q_4;
5. direct dispersion from the top of the canyon, q_5;
6. escape of recirculating material from the top of the canyon, q_6; and
7. from the end of the canyon, q_7.

6.1 Standard mode

If no buildings are present then only source 4 contributes and so $q_4 = q$ and the others are all zero, leading to results identical to modelling the road without a canyon. If buildings are present the contributions to total concentration from the six contributing sources (in standard mode q_7 is always zero) are weighted based on the canyon width, g, the average building height, H, and the building porosity, α.
The total source strength at street level is given by

$$q = q_1 + q_2 + q_4 \tag{28}$$

The weighting between q_1 and q_2 is given by

$$q_1 = q_{12} \max(1 - \gamma(\sin^2(\phi_c - \phi_w)), 0) \tag{29}$$

$$q_2 = q_{12} - q_1 \tag{30}$$

where $q_{12} = q_1 + q_2$ and $\gamma = \frac{1}{\sin^2(\Delta\varphi_{cr})}$, where γ has a value of 4, corresponding to a critical wind direction difference of 30°. The weighting between q_{12} and q_4 is given by

$$\begin{aligned} q_4 &= C\alpha^m q \qquad & q_{12} &= C(1-\alpha^m)\left(\frac{H}{g}\right)^n q \qquad & \frac{H}{g} &< 1 \\ q_4 &= \alpha^m q \qquad & q_{12} &= (1-\alpha^m) q \qquad & \frac{H}{g} &\geq 1 \end{aligned} \tag{31}$$

where

$$C = \left[\alpha^m + (1-\alpha^m)\left(\frac{H}{g}\right)^n\right]^{-1} \tag{32}$$

and the value of m is 2 (porosity power) and of n is 0.5 (aspect ratio power).

If there is no recirculation region or the road is fully outside a partial recirculation region, q_2 is reset to zero, and q_4 to $1 - q_1$. Note that q_2 is not altered if the road is only partially within a partial recirculation region, since the dispersion calculations already consider only the part of the road within the partial recirculation region (see §5.2.1). However, q_4 is increased outside the partial recirculation region by $(1 - F_r)q_2$, where F_r is the fraction of the road within the recirculation region, to account for the lost across-canyon emissions from the part of the road outside the recirculation region.

The material in source 3 (the recirculation region) comes from source 2 (the dispersion across the canyon) and so

$$q_3 = F_c q_2 \tag{33}$$

where F_c is one or the fraction of the road within the recirculation region if there is a partial recirculation region.

The material dispersing directly from the top of the canyon comes from source 1 (the dispersion along the canyon) and so

$$q_5 = q_1 \tag{34}$$

and the material escaping from the recirculation region at the top of the canyon comes from source 3 and so

$$q_6 = q_3 \tag{35}$$

Mass is conserved by this system because the sources have different regions of influence, for instance, q_5 applies outside the canyon, whereas q_1 applies within the canyon.

6.2 Network mode

In network mode additional properties are calculated:

- the length of canyon upstream of the current road, L_u;
- the distance taken for material to disperse from the road surface to the top of the canyon, L_t; and
- the fraction of emissions which are not channelled into another canyon, γ.

The calculation of L_u and γ are described in Section 4. L_t is calculated from the in-canyon wind speed and vertical turbulence along with the canyon height.

A critical length scale L_c is then calculated:

$$L_c = MIN(L_t, L_R + L_u) \tag{36}$$

which represents the downstream distance taken for material to reach the maximum vertical dispersion within the canyon.

Source 5 emissions are then reduced for canyons with no (or very little) upstream canyon to represent the time taken for material to reach the top of the canyon:

$$if\ L_c > L_u\ then\ q_5 = q_5 - q_1 * \frac{L_c - L_u}{L_R} \tag{37}$$

For the most downstream segment of a canyon the source 7 weighting is calculated as

$$q_7 = \gamma \frac{L_c}{L_R}\ q_1 \tag{38}$$

where γ is the fraction of emissions which are not channelled into another canyon. For the segments of a canyon source which are not at the most downstream end of the source q_7 is 0.

The weightings of sources 1 to 4 remain the same, although the length of source 1 is increased by the upstream length so the total emissions from source 1 are increased.

7. Complex canyon geometries

This section clarifies some additional considerations for complex source and canyon geometries, specifically for asymmetric canyons and elevated road sources, which have been omitted from the general description of the model for clarity.

7.1 Asymmetric canyons

If the canyon is asymmetric, such that the two sides have different heights and/or porosities, the following rules are applied:

- If the wind direction is within a small angle of parallel with the canyon, average height and porosity values are used for all calculations, as upstream and downstream edges cannot be defined with confidence.
- The calculation of H/g uses average height in all cases.
- The overall porosity used in the calculation of the source weightings is calculated with a wind-direction dependence, as follows:

  $$\alpha = \min(\alpha_u, \alpha_d)\sin^2(\phi_c - \phi_w) + 0.5(\alpha_u + \alpha_d)\cos^2(\phi_c - \phi_w) \quad (39)$$

  where subscripts u and d indicate upstream and downstream values respectively.
- If the downstream building is taller than the upstream building, the across-canyon source weighting, q_2, is reduced by the ratio $(H_d - H_u)/H_d$ (limited to a maximum of 0.3), with a corresponding increase in q_4. Conversely, if the upstream building is taller than the downstream building, the along-canyon source weighting, q_1, is reduced by the ratio $(H_u - H_d)/H_u$, with a corresponding increase in q_4.
- If the canyon height on one side of the canyon is zero, the 'width' for this side of the canyon is set to 1.1 times the width on the side with non-zero height, in order to avoid a symmetric solution. The porosity is set to one for a canyon side with a building height of zero. The width of the along-canyon plume is only limited on a side where the building height is non-zero.

7.2 Elevated roads

In the case of an elevated road within a canyon, as illustrated in **Figure 7**, the following assumptions are made:

- If the height of the road is greater than, or less than 2 m below, the average height of the canyon, it is not treated as being in a canyon.
- Dispersion from sources 1 and 2 does not affect receptors below the height of the road, but the recirculation region is considered to extend upwards from the base of the canyon, hence affecting receptors below the height of the road.
- The velocity at the source height is calculated based on the full in-canyon velocity profile starting from the base of the canyon.

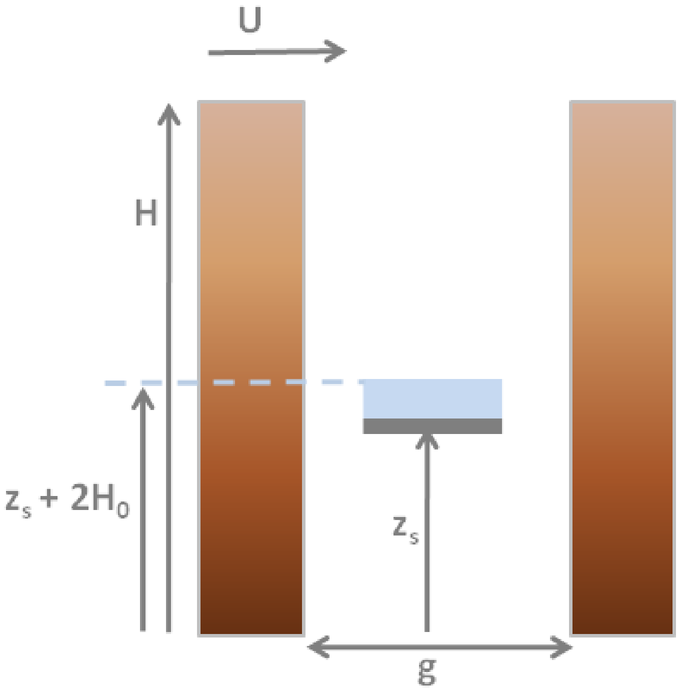

Figure 7 Diagram of an elevated road source within a street canyon. Points below the height of the road, z_s, have concentration contributions only from sources 3 (recirculation) and 4 (dispersion between buildings).

8. Canyon chemistry

In ADMS, a concentration-weighted average of the times taken for concentrations from each source to reach an output point is used to determine the progression of chemical transformations, as described in the ADMS Technical Specification paper P18/03. For the street canyon modelling described in this document, the following 'ages' are applied to concentrations from each of the component sources:

- Along-canyon: the along-canyon distance from the element to the output point, divided by the along-canyon velocity at the plume centreline, plus the initial mixing time, $\frac{H_0}{\sqrt{{\sigma_w}^2(H_0)+{\sigma_{w_o}}^2}}$. The elements are divided into 'near' and 'far' sources for chemistry according to the associated ages.
- Across-canyon: the distance from the centre of the part of the road within the recirculation region to the output point, divided by the velocity perpendicular to the canyon axis at the source height, plus the initial mixing time, $\frac{H_0}{\sqrt{{\sigma_w}^2(H_0)+{\sigma_{w_o}}^2}}$. This source is always considered to be 'near' for chemistry. When the canyon is deep and the concentration is calculated based on flow in both directions, the weighting expressions given in equation (16) for concentrations are also applied to times.
- Recirculation: For a full recirculation region, the residence time is calculated separately for each cell of the recirculation region, cumulatively from the lowest cell upwards. The age in the lowest cell, T_1, is calculated as:

  $$T_1 = \frac{h_1}{\sigma_{W_1}} \tag{40}$$

  where h_1 is the height of the lowest cell and $\sigma_{W_1}$is the vertical turbulent velocity at this height. The age in each subsequent cell upwards is calculated incrementally as:

  $$T_n = T_{n-1} + \frac{g}{\sigma_{W_n}} \tag{41}$$

  where g is the total canyon width. The expressions for vertical smoothing applied to concentration values (equation (23)) are also applied to the ages at output points within $L/2$ of a boundary between two cells. The cells are divided into 'near' and 'far' sources for chemistry according to the associated ages.

  For a partial recirculation region, the residence time is calculated as:

  $$T = \frac{H_u}{\sigma_w} \tag{42}$$

  where H_u is the average height of the upstream canyon wall and is the vertical turbulent velocity at this height.
- Non-canyon: the standard time calculated by ADMS for dispersion from the road source.
- Canyon top (direct): the standard time calculated by ADMS for dispersion from the volume source above the canyon, plus an estimate of the time taken for emissions from the along-canyon source to reach the top of the canyon.

- Canyon top (escape of recirculating material): the standard time calculated by ADMS for dispersion from the volume source above the recirculation region, plus the recirculation region residence time (of the uppermost recirculation cell if there are multiple cells).
- Canyon end: the standard time calculated by ADMS for dispersion from the volume source at the end of the canyon, as the concentration is dominated by material released near the end of the canyon.

The overall concentration-weighted average of the ages is calculated as:

$$\frac{\sum_i c_i t_i}{c} = \frac{c_1 t_1 + c_2 t_2 + c_3 t_3 + c_4 t_4 + c_5 t_5 + c_6 t_6 + c_7 t_7}{c} \tag{43}$$

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