URBAN CANOPY FLOW 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 urban canopy flow module in ADMS. This module modifies the standard ADMS vertical profiles of atmospheric velocity and turbulence, as described in the Boundary Layer Structure Specification document (P09/01), to take account of the effects of buildings in an urban area.

As wind approaches an urban area consisting of relatively densely packed buildings, the wind profile is displaced vertically by a height related to the mean height of the buildings (see for example [1]). The flow within the building canopy is related in magnitude to the upwind flow, but is reduced relative to this flow due to the presence of the buildings. The turbulence within the building canopy is also reduced relative to the upwind flow due to the presence of the buildings.

These features of the urban canopy flow field are based on the mechanical effects of the presence of buildings in an urban area. The heat effects of buildings in an urban area are not taken into account by the urban canopy flow module.

In the urban canopy the flow field depends on parameters that are calculated on a 'neighbourhood by neighbourhood' basis, primarily the displacement height and surface roughness. The use of neighbourhood values of these parameters results in a flow field that varies both horizontally and vertically within the urban area. There is also a uniform urban canopy flow option where the user can specify a single set of urban canopy parameters to be used across the entire modelling region, in which case the flow field is only vertically varying, and becomes the upwind flow condition used for any grid source dispersion.

Note that flow within an individual street canyon is not included in this formulation. The variation of velocity and turbulence used to predict dispersion within a canyon is detailed in the Advanced Street Canyon Module Specification document (P28/02). Additional turbulence due to moving vehicles is also not included in this formulation, as it is included in road source modelling.

Section 2 lists the data used in the urban canopy module to characterise urban areas. Section 3 describes the calculations of velocity profiles and Section 4 the turbulence profiles. A description of the flow regimes used to cover the full range of displacement height and roughness length values with smooth transitions between flow fields is given in Section 5.

2. Data used in the urban canopy module

2.1 User inputs

The input data for the urban canopy module are defined below. The definitions of the area ratios λ_P and λ_F are illustrated in **Figure 1**.

H	average building height within the cell (m)
G	average street canyon width within the cell (m)
λ_P	ratio of the sum of the plan area occupied by buildings (A_P) to total plan area (A_T) within the cell (must be between 0 and 1)
$\lambda_F(\phi_1 \text{to } \phi_2)$	ratio of total frontal area of buildings perpendicular to a specified wind direction (A_F) to total plan area (A_T) within the cell (may be greater than one), for a range of wind directions $\phi_1$to ϕ_2 in degrees

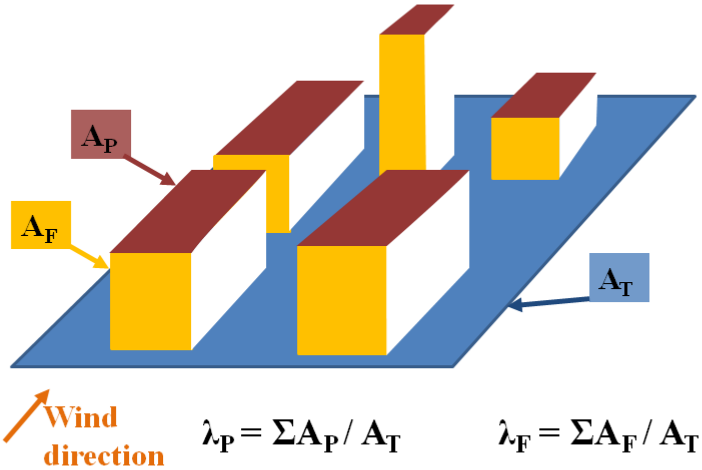

Figure 1 Illustration of the parameters λ_P and λ_F for a schematic urban neighbourhood

If using the uniform urban canopy flow option, only one set of the above parameters are provided and describe the entire modelling region, otherwise one set of parameters per cell are provided.

2.2 Characterisation of an urban area

The user input data values are used to calculate the local values of surface roughness, z_{0b}, and displacement height, d, according to expressions from Macdonald *et al.* [2]:

$$\frac{d}{H} = 1 + (\lambda_P - 1)\alpha^{-\lambda_P} \tag{1}$$

$$\frac{z_{0b}}{H} = \left(1 - \frac{d}{H}\right) \exp\left\{-\left[\frac{0.5\beta C_D \lambda_F}{\kappa^2}\left(1 - \frac{d}{H}\right)\right]^{-0.5}\right\} \tag{2}$$

where κ =0.4, the drag coefficient C_D~1, and α and β are constants. The values of α and β are chosen to represent a staggered array of buildings, giving values of 4.43 and 1.0 respectively, following di Sabatino *et al.* [3].

The roughness length within the canopy, z_{0s}, represents the value of extrusions from the roads and pavements in an urban area; a constant value of 10 cm is therefore representative.

The minimum boundary layer height is set to the maximum of the standard ADMS limit and twice the maximum displacement height over all urban canopy grid cells.

3. Velocity profiles

The mean wind profile consists of the standard upwind profile displaced vertically upwards a distance d above the ground, with a reduced wind speed profile within the building canopy; a transition layer exists separating the two flow regimes in order to allow for a continuous vertical profile; this is calculated using linear interpolation. The resultant wind speed profile is referred to as U.

The above-buildings wind flow is discussed in Section 3.1, and the flow within the canopy is discussed in Section 3.2. The flow in the transition layer is described in Section 3.3.

3.1 Above the buildings ($z > 2d$)

Displacing the standard wind speed profile used in ADMS vertically upwards a distance d above the ground gives the mean velocity profile above buildings, $U_a(z)$, as:

$$U_a(z) = \frac{u_{*b}}{\kappa}\left\{\ln\left(\frac{z-d}{z_{0b}}\right) - \psi\left(\frac{z-d}{L_{MO}}\right)\right\} \quad . \tag{3}$$

Here, u_{*b} is the frictional velocity representative of the buildings, L_{MO} is the Monin Obukhov length and $\kappa = 0.4$ is von Karman's constant. The function ψ is taken as in the standard ADMS wind speed profile, described in P09/01, and d is the displacement height for the neighbourhood, as calculated from equation (1).

It is possible to calculate u_{*b} from the geostrophic wind (wind at the boundary layer top), which is unchanged over the urban area, giving

$$u_{*b} = \frac{U_u(h)\kappa}{\ln\left(\frac{h-d}{z_{0b}}\right) - \psi\left(\frac{h-d}{L_{MO}}\right)} \tag{4}$$

where h is the boundary layer height and $U_u(z)$ is the upstream mean flow profile.

3.2 Near the surface ($z < d$)

Within the building canopy, the wind speed profile, $U_c(z)$, follows a logarithmic expression:

$$U_c(z) = \frac{u_{*S}}{\kappa}\ln\left(\frac{z}{z_{0_S}}\right) \tag{5}$$

where u_{*S} is the frictional velocity representative of the wind profile within the building canopy.

The magnitude of u_{*S} is derived from the above-building flow and the building density. That is, if the buildings are widely spaced, then wind speed within the building canopy will be close in magnitude to the flow above the buildings, whereas for more densely packed buildings, the flow within the canyon is significantly less than the flow above. Taking the above-building flow at $z = 2d$ as representative and using λ_P to indicate building density, the following condition can be used to evaluate u_{*S}:

$$U_c(z = d) = (1 - \lambda_P)^n\, U_a(2d) \tag{6}$$

where the exponent n has the value 2.

3.3 Transition layer ($d < z < 2d$)

There is a linear transition from the wind speed profile within the building canopy (5) to the displaced upstream wind profile (3); the transition occurs in the region above the building canopy i.e. $d < z < 2d$.

4. Turbulence profile

The turbulence formulation follows that described in Section 3 for the flow field. That is, above the buildings, the standard ADMS profiles are used. Within the building canopy, simplified turbulence velocity profiles are used. The resultant transverse and vertical turbulence velocity profiles are referred to as σ_v and σ_w respectively, and have units of m/s.

4.1 Above the buildings ($z > d$)

Above the building canopy, the standard ADMS turbulence profiles are used, as detailed in P09/01. There are three sets of formulae depending on whether $h/L_{MO} < -0.3$, $-0.3 \leq h/L_{MO} \leq 1$, or $h/L_{MO} > 1$, when the conditions correspond to unstable (convective) conditions, near neutral flow and stable conditions, respectively.

In unstable conditions ($h/L_{MO} < -0.3$) the mixed layer velocity scale is given by

$$w_*^3 = \frac{hu_*^3}{\kappa|L_{MO}|}. \tag{7}$$

where $u_*$is the upstream value of friction velocity. Note that the effects of the urban area on local heat flux (the 'urban heat island' effect) are not included in the urban canopy flow module.

We take the transverse turbulent velocity to be:

$$\sigma_v^2 = 0.3w_*^2 + 4.0[T_{wN}(z)]^2 u_{*b}^2 \equiv \sigma_{vc}^2 + \sigma_{vN}^2 \tag{8a}$$

and the vertical turbulent velocity to be:

$$\sigma_w^2 = 0.4\widehat{w}_*^2\left[\hat{T}_{wC}(z)\right]^2 + 0.4\widetilde{w}_*^2[T_{wC}(z)]^2 + [1.3T_{wN}(z)u_{*b}]^2 \equiv \sigma_{wc}^2 + \sigma_{wN}^2 \tag{8b}$$

where

$$T_{wC}(z) = 2.1\left(\frac{z-d}{h}\right)^{1/3}\left(1 - 0.8\frac{(z-d)}{h}\right) \tag{9a}$$

$$\hat{T}_{wC}(z) = 2.1\left(\frac{z}{h}\right)^{1/3}\left(1 - 0.8\frac{z}{h}\right) \tag{9b}$$

$$T_{wN}(z) = 1 - 0.8\left(\frac{z-d}{h}\right) \tag{9c}$$

$$\widehat{w} = (1 - \lambda_p)^{1/3} w_* \tag{9d}$$

$$\widetilde{w} = \sqrt{w_*^2 - \widehat{w}_*^2} \quad (9e)$$

and σ_C and σ_N denote the contributions from convectively driven and mechanically driven turbulence respectively.

In neutral conditions ($-0.3 \leq h/L_{MO} \leq 1$),

$$\sigma_v = 2.0 u_{*b} T_{wN}(z), \quad (10a)$$

$$\sigma_w = 1.3 u_{*b} T_{wN}(z), \quad (10b)$$

and in stable conditions ($h/L_{MO} > 1$),

$$\sigma_v = 2.0 u_{*b} (1 - \alpha_s (z-d)/h)^{3/4}, \quad (11a)$$

$$\sigma_w = 1.3 u_{*b} (1 - \alpha_s (z-d)/h)^{3/4}. \quad (11b)$$

The parameter α_s is taken to be 0.5, which is generally appropriate for the complex urban areas discussed here.

Above 1.2 times the boundary layer height, the urban canopy turbulence values are set equal to the upstream turbulence values, which are constant with height above this level. An interpolation between the urban canopy and upstream turbulence values is performed between the boundary layer height and 1.2 times the boundary layer height.

4.2 Near the surface ($z < d$)

Below the displacement height, we assume that transverse turbulence decays exponentially with height:

$$\sigma_v = \gamma_v \exp\left(-\frac{(d-z)}{2G}\right) \quad (12)$$

where $\boldsymbol{\gamma_v = \sqrt{0.3 w_*^2 + 4.0 u_{*b}^2}}$ in unstable conditions ($\boldsymbol{h/L_{MO} < -0.3}$), and $\boldsymbol{\gamma_v = 2.0 u_{*b}}$ otherwise.

The vertical turbulence decays according to:

$$\sigma_w^2 = 0.4 \widehat{w}_*^2 \left[\widehat{T}_{wC}(z)\right]^2 + \gamma_w^2 \exp\left(-\frac{(d-z)}{2G}\right) \quad (12b)$$

where $\boldsymbol{\gamma_w = 1.3 u_{*b}}$ for all meteorological conditions.

5. Flow regimes

In order to maintain smooth transitions between built-up urban areas with large values of displacement height and roughness and surrounding areas with lower values of displacement height and roughness, four flow regimes have been defined within the urban canopy module. For the highest values of displacement height, the full urban canopy calculations described in sections 3 and 4 are carried out. For very low values of displacement height, no urban canopy calculations are carried out and the upstream flow profile is used.

Two intermediate regimes are considered: 'no displacement', where the standard ADMS velocity profile is used with no displacement but including the local values of roughness length and friction velocity calculated from the input urban canopy parameters; and 'low displacement', where an interpolation between the 'no displacement' and 'full urban canopy' solutions is performed, depending on the value of displacement height. The upper limit on displacement height for the 'no displacement' solution, of $H/10$, corresponds to a value of λ_P of 0.045, indicating an area covered by buildings within the grid cell of only 4.5% of the total area. Limiting values of displacement height and roughness length for each regime are given in Table 1.

Table 1 Displacement height ranges used to define flow regimes with associated roughness length limits

Displacement height ranges		**Flow regime**	z_{0b} **Roughness length ranges**	
Lower limit (m)	**Upper limit (m)**		**Lower limit (m)**	**Upper limit (m)**
0	0.001	No urban canopy	[not calculated]	
0.001	$\max\left(1, \frac{H}{10}\right)$	No displacement	$1x10^{-7}$	$\max\left(0.5, \frac{H}{20}\right)$
$\max\left(1, \frac{H}{10}\right)$	$\max\left(2, \frac{H}{2}\right)$	Low displacement	z_{0s}	$d/2$
$\max\left(2, \frac{H}{2}\right)$	H	Full urban canopy	z_{0s}	$d/2$

References

[1] Belcher S.E, O Coceal, JCR Hunt, DJ Carruthers, AG Robins (2013) A review of urban dispersion modelling. ADMLC report available at http://webarchive.nationalarchives.gov.uk/20131103234051/http://www.admlc.org.uk/ADMLCReport7.htm (accessed August 2014)

[2] Macdonald RW, Griffiths RF, Hall DJ. 1998 An improved method for estimation of surface roughness of obstacle arrays. *Atmos Environ* **32**:1857–1864.

[3] Di Sabatino S., Leo, L. and Cataldo, R. (2010) Construction of Digital Elevation Models for a Southern European City and a Comparative Morphological Analysis with Respect to Northern European and North American Cities. *J. Appl. Met. & Clim.* **49**:1377-1396.