LOCAL AIR QUALITY AND ITS INTERACTION WITH VEGETATION IN THE URBAN ENVIRONMENT, A NUMERICAL SIMULATION USING ENVI-MET

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Abstract: Local air quality in an urban environment is sensitive to building patterns and the presence of vegetation along urban streets. In this study, a number of different idealized urban geometries that are representative for Flanders were selected and studied using the ENVI-met model. This allowed us to assess the effect of geometry, road layout, tree implantation and vegetation buffers on the PM10, EC and NO2 concentrations on street level. The selected scenarios were modelled under both worst case and normal meteo and background. Next to the enhanced background in the worst case, the most significant difference between these two is the rotation of the wind field w.r.t the street canyon over 45° in the normal case. A number of guidelines that can serve as input for urban planning and development were drafted.

Key words: ENVI-met, Computational Fluid Dynamics, Urban Planning, Air Quality

INTRODUCTION

Local air quality in an urban environment is very sensitive to the building patterns and the presence of vegetation in the streets. In this study, a number of semi-idealized urban building patterns that are representative of Flanders were selected and modelled using ENVI-met (Bruse, M. and H. Fleer, 1998). ENVI-met is a 3D atmospheric CFD model using the Reynolds Averaged Navier-Stokes approach with the k-ε turbulence model. Next to the flow solver, ENVI-met implements a detailed description of the radiation balance, shading effects and heat exchange at building walls. It is coupled with a soil model and contains an extensive vegetation module including soil moisture and stomatal resistance effects. Vegetation elements in ENVI-met are described via their leaf area density or LAD (m²/m³). Deposition speeds are computed based upon a resistance scheme explained in more detail in (Vankerkom J., et al., 2007). The model was recently extended with an implementation of the O₃ photo-chemistry and therefore allows us to assess on a micro-scale level, the effect of canyon geometry, road layout, tree implantation, squares and vegetation buffers on the PM₁₀, EC as well as NO₂ pollutant dispersion. 5 specific scenarios were defined, each having a base and a structural variation. Schematic representations of these are given in Figure.

The scenarios include: (1) a typical urban highway, with or without a tree-buffer, (2) an urban approach road with a cycling strip and tree lining either at the centre or at the building walls, (3) a narrow approach road either with or without a break-up of the continuous building wall at the windward side of the canyon, (4) a classic high street with or without tree lining in between parked cars and last, what we have designated as, a street canyon (5) again either with or without break-up of the continuous building wall at the leeward side. Widths and H/W ratios are given in Figure. Note that a direct scaling of the concentrations in terms of H/W ratio is not fully applicable as the emission sources do not have the same relative location w.r.t. the building walls in each of the scenarios. It was chosen to model more representative road-layout patterns. For the urban highway a building free zone of 50 m between the highway and the building wall was taken, which in case 1b was lined with a 30 m wide tree buffer starting at 10 m from the highway. The input for the geometry of the scenarios was obtained from an indicative measurement of road layout based upon orthographical pictures above Flanders at selected locations.

For each of the scenarios we have defined a set of normal (NCS) and worst case scenario (WCS) as to meteorological conditions and background concentrations in order to assess the effectiveness of structural variations to the local air quality in both cases. The parameters used are given in Table 1:

1 http://www.agiv.be/gis/diensten/geo-vlaanderen/
Table 1: Meteorological conditions and pollutant background concentrations for the modelled cases in both worst and normal case scenarios. O$_3$ and NO concentrations as such were not part of this study, however their background concentrations do need specifying in order to satisfy the ozone chemistry implementation in ENVI-met.

<table>
<thead>
<tr>
<th>Meteorological conditions</th>
<th>Background concentrations [µg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WCS</td>
</tr>
<tr>
<td>Temperature</td>
<td>22 °C</td>
</tr>
<tr>
<td>Wind speed</td>
<td>1.5 m/s</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>60 %</td>
</tr>
<tr>
<td>Cloud Cover</td>
<td>0 %</td>
</tr>
<tr>
<td>Wind direction</td>
<td>90°</td>
</tr>
</tbody>
</table>

For the definition of the worst case scenario we have based ourselves upon a historic dataset of an urban background measurement station in Antwerp$^2$, where we have averaged concentrations and meteor parameters for days for which the PM$_{10}$ as well as NO$_2$ and O$_3$ concentrations were above their respective 80 percentile values. The NCS simply represents an averaged condition. As ENVI-met has a full implementation of the O$_3$ + NO $\leftrightarrow$ NO$_2$ equilibrium reaction, we needed to specify the O$_3$ and NO background concentrations as well. Note that the concentrations for NO$_2$, O$_3$ and NO have to be in chemical equilibrium, this was accomplished by altering the NO concentration as a function of the required O$_3$ and NO$_2$ concentrations and meteo in both NCS and WCS. The meteor parameters themselves were obtained from ECMWF. Traffic composition, intensities & average speed were kept constant between the canyon configurations to ensure the best comparability between the cases. The emissions were calculated using the MIMOSA 4 model, based upon COPERT IV.

MODELING SETUP
As no full size distributions are implemented in ENVI-met yet, we implemented EC as a passive tracer having 200 nm as representative aerodynamic diameter in the deposition scheme (Cohen D.D., et al., 2000). It is interesting to note that this value corresponds to a regime where the effects of Brownian motion start taking over from pure sedimentation, yielding higher deposition speeds with decreasing particle sizes. PM$_{10}$ was implemented in ENVI-met as the sum of 2 fractions, having respectively 0.75 µm (near the minimum of the deposition velocity curve) and 3.75 µm as aerodynamic diameters. The modelling domain was discretized on a rectangular mesh with a horizontal resolution of 1 x 1 m for cases 2 through 5. Cells in front of the facades and near the building roofs and ground were subdivided, thereby locally increasing the resolution to 25 cm. For case 1, a horizontal resolution of 2 m was adopted. In vertical direction a telescopic mesh was applied starting above the local refinements at the roof level. This ensures that the domain reaches a high enough altitude with a manageable amount of vertical cells. This is important to minimize possible effects of vertical exchange at the domain top level. The total amount of cells added up from ~1 to 1.4 million depending on the domain.

In order to set up a representative simulation of an urban geometry, we need to build up an urban roughness layer much in the same way as one puts roughness elements in front of a model inside a wind tunnel. In ENVI-met one can accomplish similar effects using cyclic boundary conditions for the turbulent energy along with putting a parallel building row in front of the street canyon under study in order to lift up the flow field such that we obtain a parallel flow w.r.t. the ground at the roof level. This setup was thought to represent the most generic situation for the semi-idealized urban environment studied here. Next, we will highlight a selection of interesting results from this study.

EFFECTS OF SQUARES AND BREAK-UP OF CONTINUOUS BUILDING WALLS
Cases 3 and 5 allow to study the break-up of a continuous building wall and the construction of squares within the urban environment. This clearly has a large influence on the concentrations in the canyon. Strikingly though, in both WCS and NCS, squares that break-up the windward building wall do seem to be relatively spared from the adjacent road emissions. This is because of the helical structure of the flow field. One must be aware though of a local increase in concentrations in both NCS as well as WCS due to the reduction in wind speed in the street canyon in the presence of a square.

From the model results it was observed as well that the overflow to the downwind street canyon is quite limited (Figure , right), with e.g. for PM$_{10}$ a maximum contribution of 4% near street level at the leeward wall in each of the modelled scenarios.

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2 See: [http://www.irceline.be](http://www.irceline.be), station 42R801.
Figure 2: Left: Effect of a 35 x 35 m\(^2\) square in the windward wall under normal case. The contour plot shows the PM10 concentrations at reference height, the stream traces show the flow field. Right: Concentration \(z\) (normalized to canyon height) profiles behind the buildings at the windward wall under normal (left) and worst case (right) scenario.

It is clear that the mechanical turbulence at the top of the canyon and therefore enhanced mixing as well as the vortex structure of the wind field itself inside the canyons cause the concentration levels at ground level in the parallel downwind canyon only to be minimally increased.

**MODELLED EFFECTS OF URBAN VEGETATION**

Next to an obvious reduction in wind velocity, a clear enhancement of the turbulent energy behind and above the tree buffers is observed (Figure). This effect induces an increased vertical mixing of the pollutants. The effect of pollutant deposition is found to be relatively limited in comparison to the aerodynamic effects. Immediately behind the second vegetation buffer an increase of the pollutant concentrations is seen due to the reduction in the wind speed. The enhanced vertical mixing does induce a stronger negative gradient in the concentration profile as can be seen in Figure, right. However, this effect is broken down by the presence of a building block, for which the mechanical turbulence is dominant. The need for a minimum building distance behind a vegetation buffer can be inferred from this. Note that in this study however atmospheric stability effects were not taken into account and can play a significant role. For the cases 2-5, the effects of mechanical turbulence inside the street canyons are thought to dominate w.r.t. atmospheric turbulence, however this is clearly not the case anymore for the urban highway scenario.

Figure 3: Left: Relative effect of a 30 m tree buffer on the wind speed and turbulent kinetic energy. Right: Comparison between the NO\(_2\) concentration x-profiles in the normal case for the urban highway. The green line corresponds to the base scenario, without the tree buffer, the red line corresponds to the variation with the tree buffer.

The effect of tree planting in the case of the classic high street, apart from a small reduction in the wind velocity, seems to mainly affect the turbulent energy in the street canyon. A clear reduction of TKE is observed in Fig. 4. For the low wind speeds in the street canyon, the vegetation elements therefore can be imagined to act in a similar way to honeycomb grating which is often used in wind tunnels to break down larger eddies. This decrease of TKE reduces the diffusion of the pollutants and therefore causes a concentration increase (Figure, left). The magnitude of this increase is strongly dependant on the leaf area density, geometry and layout of the tree lining. This can be seen from Figure, where we have compared a continuous tree line in scenario 4 with different tree heights and leaf area density parameters, each time also compared to a reference scenario without tree-planting. We do observe quite significant effects in the simulation on the pollutant concentrations at the leeward side of the canyon. The small decrease in concentrations at the windward side in the presence of the tree line is
interesting. This effect, although very small, can be attributed to a tunnelling effect in between the vegetation line and the building wall at the windward side.

Figure 4: Left: Effect of the tree planting in the case of the classic high street. The green line corresponds to the base scenario without trees, the red line corresponds to the variation with trees. In this case a Leaf Area Density (LAD) profile between 0.5 and 1.

Figure 5: Comparison between different tree heights (right) and Leaf Area Density values (left) in the case 4 scenario.

IN SUMMARY
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