19th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
3-6 June 2019, Bruges, Belgium

ON THE INFLUENCE OF TREES ON VENTILATION OF A REAL STREET IN PAMPLONA (SPAIN)

Jose Luis Santiago[1], Riccardo Buccolieri[2], Esther Rivas[1], Beatriz Sanchez[1], Alberto Martilli[1], Rocio Alonso[1] and Fernando Martín[1]

[1]Atmospheric Pollution Division, Environmental Department, CIEMAT, Spain
[2]Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, University of Salento, Lecce, Italy

Abstract: This paper is devoted to the quantification of changes in ventilation of a real neighbourhood located in Pamplona (Spain) due to street trees. We extend our previous Computational Fluid Dynamics (CFD) modelling study of pollutant dispersion (Santiago et al., 2017, Atmosphere 8, 131) to analyse the variation of street ventilation in several scenarios, without trees and considering trees with different leaf area density (LAD). Flow rates and wind speed across lateral sides and top of the street are computed to evaluate changes between the different scenarios. Additionally, vertical profiles of average flow properties over the study street are analysed. Taking into account that the inlet wind flow is almost perpendicular to the study street, results show that as LAD increases, wind speed decreases which induces an increase of average concentration in the whole neighbourhood. On the other hand, the inclusion of trees in a street produces an increase of average pollutant concentration within this street, in particular for the scenario with highest LAD. It is caused by the reduction of ventilation in the direction parallel to the street and the decrease of turbulent kinetic energy within the vegetation. Therefore, average concentrations in a street and in the whole neighbourhood are related to the average flow properties of the street.

Key words: CFD modelling, street ventilation, trees, urban air quality

INTRODUCTION

Trees and green infrastructures in general are often used in the urban environment as pollution mitigation strategy. The impact of urban vegetation on air quality, in particular in streets, is however complex, inducing aerodynamic effects (i.e. the presence of trees modifies wind flow around them changing the distribution of pollutants) and deposition effects (i.e. a fraction of pollutant is removed from the air by means of deposition on tree leaves and absorption through stomata) (Buccolieri et al. 2018). Aerodynamic effects on pollutant concentration usually seem to be stronger than leaf-deposition within the streets; however these variations of airflow have not been analysed in detail, particularly in real neighbourhoods (Abhijith et al., 2017). In this context, the starting point of the present paper is the Computational Fluid Dynamics (CFD) modelling study carried out in a Pamplona neighbourhood indicating that the aerodynamic effects of street trees on pollutant concentration are stronger than deposition (Santiago et al., 2017a). We extend the analysis by quantifying the variation of street ventilation in several scenarios, without trees and considering trees with different leaf area density (LAD). The impact of tree foliage on urban air quality is thus analysed, which could provide useful information to urban planners for the selection of suitable vegetation. Flow rates across lateral sides and top of the street are computed to evaluate changes between the different scenarios. These are relevant in order to establish simple relationships between the presence of vegetation, ventilation reduction and pollutant concentration variation.

DESCRIPTION OF THE STUDY AREA AND SCENARIOS INVESTIGATED

The study area is a portion of 1.3 km x 1.3 km of the II Ensanche neighbourhood in Pamplona (Spain) (Figure 1). Here, building heights range from 11 m to 50 m, even if most of the buildings have the same height with a mean value of 20 m. An air quality monitoring station (AQMS) from Regional Government of Navarra is located in a square in the centre of the neighbourhood (Figure 1). Small parks and trees within most of streets are present in this zone covering 13.8 % of the plan area (i.e., the extent of vegetation projected in a horizontal plane respect to the total plan area of the streets and squares). The mean height of trees ranges from 5 m to 12 m as estimated with satellite images from Google Earth®.

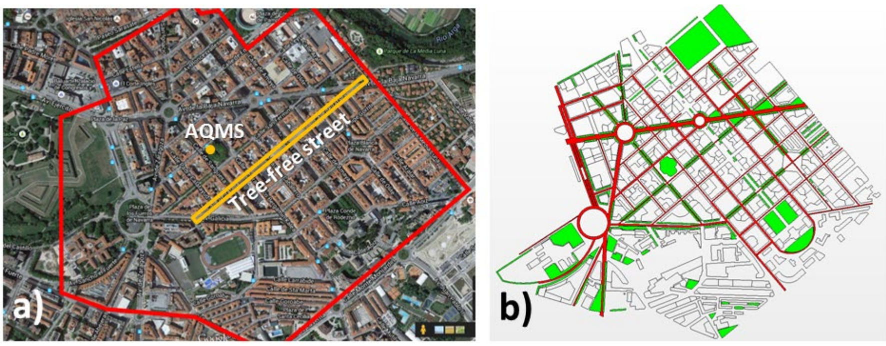

Figure 1. a) Study area. b) Numerical domain including emissions (red) and trees (green).

Several scenarios, both real and virtual, have been investigated by means of CFD modelling (Table 1). In this neighborhood, there is a tree-free street (Tafalla Street) (Figure 1) where the possible impact of new trees planted is simulated. These new trees are virtually located in the center of the street and their crowns located at the same height (from 4 m to 10 m tall). The study is focused on the worst case in terms of air quality, i.e. meteorological and emission conditions corresponding to 8 a.m. of a winter day. AQMS data indicate that concentrations during winter at this hour, which corresponds to the highest traffic emissions, are higher than in other seasons. March 2015 is selected because LAD (= 0.1 $m^{-2}m^{-3}$) is low, and nitrogen oxides (NOx) levels are still high. Typical meteorological conditions (predominant wind direction (Northwest) and average wind speed) at this hour were computed from meteorological data recorded at a station close to the study area. Additionally, a wide range of deposition velocities induced by vegetation (0, 0.005, 0.01, and 0.03 m s^{-1}) were considered.

Table 1. Study scenarios

Trees LAD (m^2 m^{-3})	Location of Vegetation	Wind Direction
0.1 (deciduous)	Current location	Northwest (predominant wind direction, March 2015)
0.5 (evergreen)		
0.1(deciduous)	Current location + New trees in one tree-free street	
0.5 (evergreen)		

CFD SIMULATION SET-UP

The CFD model used (Star-CCM+ from Siemens) is based on Reynolds-Averaged Navier-Stokes (RANS) equations with Realizable k-ε turbulence model. The aerodynamic effects of vegetation were modelled by means of a sink of momentum and sinks/sources in turbulence equations (Santiago et al., 2017a, b). Dispersion of NOx was performed by means of a transport equation with a mass sink representing pollutant deposition on the vegetation leaves (Santiago et al., 2017a; Buccolieri et al., 2018). Traffic emissions are distributed along each street considering road widths and an emission height of 1 m in order to take the initial dispersion into account. Emissions were considered proportional to daily mean traffic intensity throughout each street. Numerical domain was built following best practice guidelines (Franke et al., 2007). Outlet and inlet were further than 8 times the building heights and the top of domain was located 7 times the height of the tallest building (50 m). Based on grid sensitivity tests, the domain was discretized using 7.4 x 10^6 cells, with ad hoc refinements in narrowest streets. Buildings and ground were modelled as walls and symmetry conditions (zero normal velocity and zero normal gradients of all variables) were imposed at the top of domain symmetry. Neutral inlet profiles of velocity, turbulent kinetic energy and its dissipation were used (see Santiago et al. 2017a for further).

MODEL EVALUATION

Modelled NOx concentrations over the neighbourhood were evaluated by using hourly data recorded at AQMS from 1st to 14th March 2015 (Santiago et al., 2017a). The modelling approach was also previously evaluated against wind tunnel experiments (Krayenhoff et al., 2015; Santiago et al., 2017b).

EFFECTS OF TREES ON NO_X CONCENTRATION

The increase of vegetation LAD induces higher deposition. However, Santiago et al. (2017a) showed that aerodynamic effect is stronger and spatial averaged NOx concentration at 3 m (pedestrian level) over the study zone increases for all deposition velocities analysed as LAD increases. More complex is the impact of new trees in the tree-free street. The differences of average concentration at 3 m in the whole neighbourhood are negligible, however local changes of wind flow due to new vegetation increases or decreases concentration not only in the street but also in nearby areas. This fact is more important for higher LAD scenarios (Santiago et al., 2017a).

In this study, to analyse the aerodynamic effects we focus on scenarios without considering deposition. Considering the whole neighbourhood with the current vegetation location, a LAD variation from 0.1 to 0.5 m^2 m^{-3}increases the spatially-averaged concentration at 3 m height by 7.2 %. However, the inclusion of new trees induces changes in average concentrations less than 0.09 % and 0.18 % for LAD = 0.1 m^2 m^{-3} and 0.5 m^2 m^{-3}, respectively. Focusing on the tree-free street, the averaged concentration within this street at 3 m height increases up to 1.3 % as LAD increases and by 1.8 % and 12 % when new trees with LAD = 0.1 m^2 m^{-3} and 0.5 m^2 m^{-3} are considered, respectively (Table 2). Note that the concentration within this street is not only due to local emissions, but there is also a contribution of pollutants released in other streets which is transported. Vertical profiles of spatially-averaged concentration over this street are also analysed (Figure 2). Santiago et al. (2017b) found local changes in concentrations around the study street, however these results show that only the inclusion of new trees with LAD = 0.5 m^2 m^{-3} significantly modify the average concentration over this street. Then, the flow patterns and street ventilation are considerably affected by the new trees configuration. In the next section, average street ventilation is assessed in order to relate the changes in concentration with variations of street ventilation.

Table 2. Spatially-averaged concentrations for each scenario

Trees LAD (m^2 m^{-3})	**Location of Vegetation**	**Spatially-Averaged Concentration (μg m^{-3})**	
		Whole Neighbourhood	**Study street**
0.1 (deciduous)	Current location	105.3	141.9
0.5 (evergreen)		112.9	143.7
0.1(deciduous)	Current location + New trees in one tree-free street	105.4	144.4
0.5 (evergreen)		113.1	161.0

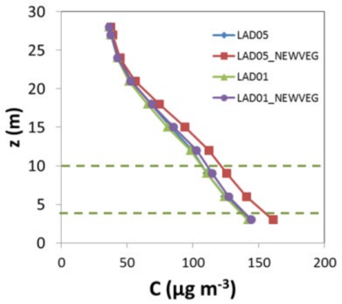

Figure 2. Vertical profiles of spatially-averaged concentration within the study street. Dashed lines indicate new trees location.

VENTILATION ASSESSMENT

To analyse the street ventilation a prism composed by 4 lateral planes (Planes 1-2 parallel to the street and 3-4 perpendicular to the street) and a plane in the top (Plane 5) has been selected (Figure 3). Note that the height of buildings are not equal and Plane 5 is located 1 m above the height of the tallest building (z = 28 m). Northwest is the predominant wind direction, which is almost perpendicular to street orientation (Figure 3), and then most part of flow enters into the street through Plane 1.

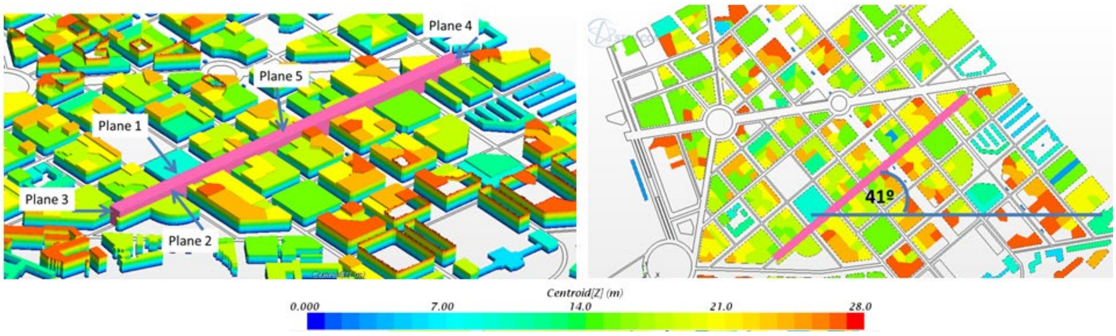

Figure 3. Planes used for street ventilation assessment (l.h.) and street orientation (r.h.).

At each plane of the street, average flow rate (q, equation 1) and velocity perpendicular to each plane (V_n) are computed. Percentage at each plane of the total flow rate which enters in the street is shown in Table 3. Negative values indicate flow direction is towards outside the street (i.e. air leaving the street).

$$q = \int_{PLANE} V_n dS \qquad (1)$$

Table 3. Percentage at each plane of the total flow rate and average perpendicular velocity to each plane for all scenarios.

Trees LAD (m^2 m^{-3})	Location of Vegetation	q (%)				
		Plane1	Plane2	Plane3	Plane4	Plane5
0.1 (deciduous)	Current location	100	-95.2	-1.1	-0.3	-3.4
0.5 (evergreen)		99.2	-95.1	-1.3	0.8	-3.6
0.1(deciduous)	Current location + New trees in one tree-free street	99.8	-95.2	-0.9	0.2	-3.9
0.5 (evergreen)		99.2	-95.0	-0.8	0.8	-4.2
Trees LAD (m^2 m^{-3})	**Location of Vegetation**	**V_n (m s^{-1})**				
		Plane1	**Plane2**	**Plane3**	**Plane4**	**Plane5**
0.1 (deciduous)	Current location	1.49	-1.63	-0.33	-0.08	-0.04
0.5 (evergreen)		1.47	-1.62	-0.40	0.24	-0.04
0.1(deciduous)	Current location + New trees in one tree-free street	1.50	-1.65	-0.26	0.06	-0.04
0.5 (evergreen)		1.48	-1.62	-0.23	0.25	-0.05

The higher concentrations in the whole neighbourhood for these scenarios are related to the decrease of average velocity normal to Plane 1 found as tree LAD increases. . The new vegetation configuration (new trees) reduces the average flow rate in the parallel direction increasing it at the top plane. Additionally, new trees modify the flow rate at the perpendicular planes to street direction (3 and 4). In particular, for LAD = 0.5 m^2 m^{-3}, the flow outward the street decreases up to 40 % approximately for plane 3. However, these average values are not representative for the whole street. Due to street intersections, there are parts of the street with horizontal vortices and others with channelling in different directions. Vertical profiles of average wind flow properties (wind speed normal to street (V_n) and parallel to street (V_p), vertical wind speed (W) and turbulent kinetic energy (TKE)) over the study street are analysed (Figure 4). New trees modify vertical and parallel wind speeds and turbulent kinetic energy. Average parallel wind speed decreases for new vegetation scenarios, especially within and below the vegetation canopy. Concerning vertical wind speed, downward wind speed within and below the vegetation canopy is lower for new vegetation scenarios, while upward motion over the new trees is stronger with vertical velocity at the top of street higher than for scenarios with the free-tree street. New trees configuration also induces a decrease of turbulent kinetic energy within vegetation canopy. These processes are stronger for new trees configuration with LAD = 0.5m^2 m^{-3}.

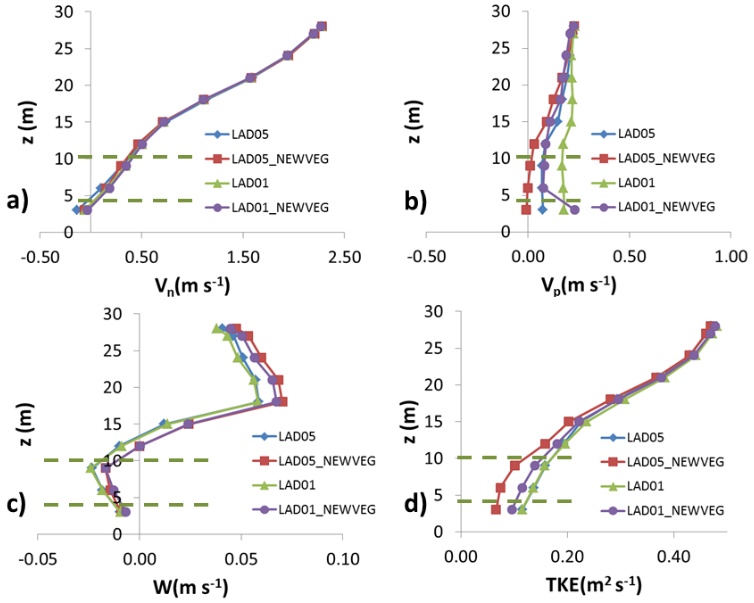

Figure 3. Vertical profiles of average flow properties over the study street. a) wind speed normal to street (V_n); b) wind speed parallel to street (V_p); c) vertical wind speed (W); and d) turbulent kinetic energy (TKE). Dashed lines indicate new trees location.

CONCLUSIONS

Average concentrations computed over a whole neighbourhood of Pamplona and an specific tree-free street have been related to the average flow properties. Average concentrations in the whole neighbourhood are related to the increase of LAD due to the fact that average wind speed is lower and therefore concentration increases. Within the specific street studied, the inclusion of a new trees configuration (in the center of the street) induces an increase of average concentration because: a) average wind speed parallel to the street (parallel ventilation) is reduced; b) downward vertical wind speed within new vegetation canopy is reduced (weaker ventilation within and below the vegetation canopy) and vertical wind velocity is increased over the trees (slight increase of ventilation at the top of the street); c) TKE decreases within and below new vegetation canopy. These issues are more pronounced for LAD = $0.5m^2\ m^{-3}$. These results could be useful for urban planners to build sustainable design of vegetation within streets.

REFERENCES

Abhijith, K.V., P. Kumar, J. Gallagher, A. McNabola, R. Baldauf, F. Pilla, B. Broderick, S. Di Sabatino, B. Pulvirenti, 2017: Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments—A review. *Atmospheric Environment* **162**, 71–86.

Buccolieri R, JL Santiago, E Rivas, B Sanchez, 2018: Review on urban tree modelling in CFD simulations: Aerodynamic, deposition and thermal effects. *Urban Forestry & Urban Greening* **31**, 212-220.

Franke, J., H Schlünzen, B Carissimo, 2007: Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment. COST Action 732—Quality assurance and improvement of microscale meteorological models; Distributed by University of Hamburg (Germany), Meteorological Institute: Hamburg, Germany, 2007; ISBN 3-00-018312-4.

Krayenhoff, E.S., J.L. Santiago, A Martilli, A Christen, TR Oke, 2015. Parametrization of drag and turbulence for urban neighbourhoods with trees. *Boundary-Layer Meteorology*, **156**, 157–189.

Santiago, J.-L., A Martilli, F Martin, 2017b: On Dry Deposition Modelling of Atmospheric Pollutants on Vegetation at the Microscale: Application to the Impact of Street Vegetation on Air Quality. *Boundary-Layer Meteorology* 162, 451–474.

Santiago JL, E Rivas, B Sanchez, R Buccolieri, F Martin, 2017a: The Impact of Planting Trees on NOx Concentrations: The Case of the Plaza de la Cruz Neighborhood in Pamplona (Spain). *Atmosphere* **8 (7)**, 131.