A simple technique to improve pollutant reduction efficiency and mass removal by near-road vegetation barriers

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Abstract0

Well positioned vegetation barrier (VB) has been suggested as one of the green infrastructures that could help filter particles (pollutants) from our air, thereby improving air quality. Several studies have carried out the assessment of air quality benefit of VB using dispersion-related method while scant studies have done the same using deposition-related method. Decision-making on VB's configuration and placement for need-based maximum benefit requires combined assessment with both methods; this is lacking in related literatures.

Hence, this study made use of a Computational Fluid Dynamics (CFD) model, ENVI-met to evaluate the dispersion (Pollutant Reduction Efficiency, PRE and Filtration-Collection Efficiency, FCE) and deposition (mass removal) related benefit (or otherwise) of near-road VB. A simple technique based on distance between source and plume's maximum concentration (DMC) has been proposed for enhanced dispersion and deposition related benefit by VB. For the dispersion-related assessment, preliminary results show the PRE of VB could indicate positive and/or negative effects on near road air quality depending on prevailing wind condition, thickness of VB, nearness of VB and targeted location to road. By applying our proposed technique, the optimum distance of VB from source was determined and positive PRE was actualized. Furthermore, the technique is useful in determining the optimum thickness of VB for enhanced dispersion and deposition-based benefits. Overall, higher volume of VB can increase the overall mass removal within an area while the same volume could worsen the air quality of the same area. Hence, the benefit of roadside VB is need-based i.e. higher deposition or higher dispersion.

1. Introduction

Emission of particulate matter (PM) from open environment such as road-side, agricultural practices and industries has been worrisome in the past few decades (Guo and Maghirang, 2012). Traffic emission is one of the major and often dominant sources of PM in the 2.5 µm size range in a typical urban environment. Health problems such as exacerbation of respiratory conditions, risk of cardiopulmonary symptoms and diseases and premature death (Krzyzanowski et al., 2005) have been linked with inhalation of PM. Thus, different measures such as technological improvements (Kelly and Fussell, 2012), increasing area ventilation, maximizing pollutant deposition and dispersion (Pugh et al., 2012), planting of vegetation (Al-Dabbous and Kumar, 2014) and erection of roadside structural barriers (Brantley et al., 2013) have been suggested to ensure reduced PM exposure. In this study, the role of urban greening (vegetation barrier) was further investigated. Currently, there exist two creeds on the role of trees and vegetation barriers on air quality. Some studies (Nowak et al., 2006; and Tallis et al., 2011) support the claim that urban trees reduce air pollution while others (e.g., Gromke and Ruck 2012; Wania et al., 2012 and Vos et al., 2013) opposed it. The disagreements can be attributed to authors' definitions of 'improved air quality'(higher dispersion or higher mass removal?). In terms of dispersion, it is well known that vegetation acts as wind breaks or momentum sink thereby reducing mixing, dilution and ventilation. This leads to increased concentration around the vegetation and improved air quality downwind. This phenomena favors deposition theory which states that mass removal is directly proportional to concentration. In the present study, we attempted to investigate the combined role of near-road VB on dispersion and mass removal using a computational fluid model, ENVI-met which contain a Particle(gas) Dispersion and Deposition Module (PDDM). The study hinges on the research gap identified from previous studies (stated earlier) where the interaction between VB and air quality was considered in terms of either dispersion or deposition (not both) while the combination will help in designing urban vegetation related to air quality (Janhall, 2015).

2. Methodology

All simulations in this study were executed with a three dimensional (3D) Computational Fluid dynamics (CFD) model, ENVI-met V3.1 (http://www.envi-met.com). The model is suitable for simulating diverse planetary boundary layer processes such as wind flow, turbulence, micro-climate and pollutant dispersion. Using the Eulerian approach, mass, momentum, and energy budgets were computed. It uses the standard k-Ɛ turbulence model to close the Reynold Average Navier-Stokes (RANS) equation:

$$\frac{\partial \chi}{\partial t} + u_i \frac{\partial y}{\partial x_i} = \frac{\partial}{\partial x_i}\left(K_\chi \frac{\partial \chi}{\partial x_i}\right) + Q_\chi\ (x\ ,y,z)\ + S_\chi\ (x\ ,y,z) \qquad (1)$$

where $x_i = (x\ ,y,z)$ is Cartesian co-ordinate, $u_i = (u,v,w)$ is the corresponding wind velocity vector, χ is the local particulate matter. The presence of vegetation and its influence on atmospheric processes can be simulated by including Q_χ and S_χ which are the source and sink terms, respectively in the RANS equation. Traffic emissions prescribed as line sources can be parameterized using estimated emission rates from local traffic data for a particular road of interest. Mass removal by vegetation surface represented by a sink term is parametrized as follows:

$$S_{\chi} = V_{dp}.LAD.C \qquad (2)$$

Where LAD is the Leaf Area Density, C is pollutant concentration, V_{dp} is the deposition velocity towards leaf surfaces usually expressed as the inverse sum of aerodynamic and sublayer resistances and settling velocity (Bruse,2007). Although there are discrepancies between published V_{dp} values $(\sim 0.08\ -\sim 2.8cms^{-1})$ for $PM_{2.5}$ as reported by Litschke and Kuttler (2008), the calculated value ($0.022cms^{-1}$ for $PM_{2.5}$) by ENVI-met is rather too low. Hence, we applied a rather conservative value of $V_{dp} = 0.1cms^{-1}$ to leaf surfaces comparable to that of Petroff and Zhang, 2010. In grids without vegetation (LAD), V_{dp} is replaced with gravitational settling velocity (V_s). A detailed documentation of ENVI-met model and its particle/gas dispersion –deposition module (PDDM) including can be found in Bruse and Fleer, 1999 and Bruse , 2007.

2.1 Model setup and initialization

The computational domain for this study covers a horizontal area of 50 m x 30 m and a vertical height of 40 m with a uniform Cartesian grid and highest available resolution of 0.5 m in the horizontal scale. Each grid cell (L x W x H) was set to 0.5 m x 0.5 m x 2 m while a finer resolution of 0.5 m x 0.5 m x 0.4 m was set at the lowest five grid cells. Ten (10) nested grids were added to the computational domain to improve model accuracy and avoid numerical problems caused by model boundary interference with internal model dynamics model. Each run was simulated for four hours while the output of the 4th hour was used for further analysis (the previous 3 hours were taken as spin-up).The model layout represents a typical sub-urban to urban major roadway (leading to a densely populated city). In this kind of setting, VB is erected to protect populace on footpaths, cycling lanes, recreation grounds and surrounding building from traffic-induced noise and air pollution. The model was initialized and configured with meteorological parameters, road layout and pollutant emission rate and specie given in Table 1. Simulations in this study are divided into three (3) categories (see Table 2). A schematic layout of model setup is shown in fig.1

Table 1: Overview of input and test parameters

Parameter	**Definition**	**Value**
Meteorological conditions	Initial potential air temperature Relative Humidity at 2m Inflow direction Wind speed at 10m	29°C 80% 60° (Oblique), 90° (Perpendicular) 3m/s
Road layout	Length Width Carriage type	20m 8m Single (uni-directional)
Pollution source	Specie Source geometry Emission rate	2.5µm Line source at 0.5m 12.7µg/s/m
Vegetation barrier (VB)	Length Thickness and Height LAD Deposition velocity	20m varies per case (see Table 2) $2m^2/m^3$ 0.1cm/s

Table 2: Overview of simulation runs (cases) based on VB configuration and placement

Simulation runs	**Case code**	**H=2m,T=1m**		**Remarks**
		Height (m)	**Thickness (m)**	
Reference Case	RC	-	-	
Base Cases	BC-1	H	T	VB positioned 3m from road
	BC-2	H	T	Placed after DMC of each wind direction
	BC-3	H	8T	Thickness was determined by DMC of each wind direction
Design-test Case	DC	1.5H	8T	Thickness was determined by DMC for varying wind direction

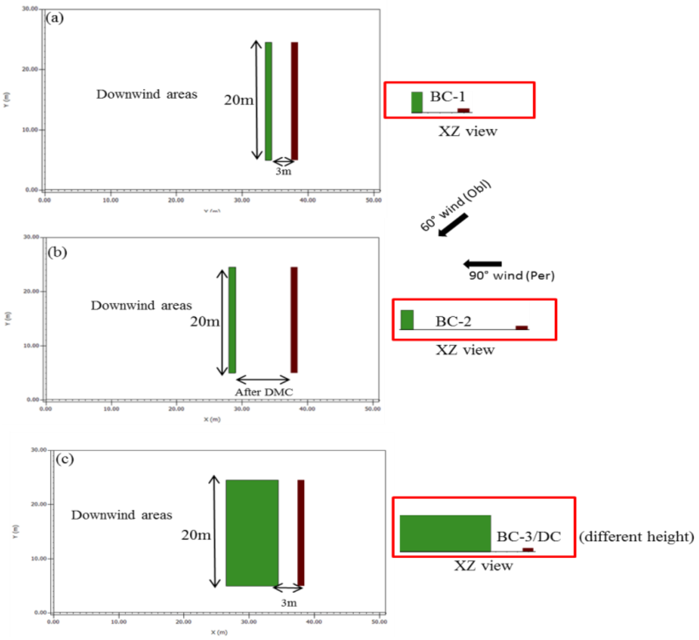

Fig. 1. *Schematic view of the model setup with the prevailing wind directions, source region (brown shaded), VB (Green) and downwind areas (walkway, playground, cycling path and faraway buildings). VB positioned 3m from road centre (a) , 2m after DMC with variation of VB dimension (b) and Design-test Case configuration (c).*

3. Results and discussion

3.1 Dispersion-related method for assessing air quality benefit of vegetation barrier

Some previous studies (Tiwary et.al 2006, Al-Dabbous and Kumar 2014, and Brantley et al.,2014) have reported the dispersion-related air quality benefit of VB by calculating the ratio of upstream (near-road) concentration (C_u) to downstream (behind VB) concentration (C_d) at a given particle size (in this study, $PM_{2.5}$) known as removal or collection efficiency or Pollutant Reduction Efficiency (PRE) between **two measuring or sampling points** at selected locations, mathematically given as:

$$PRE, \phi_{VB} = \left(1 - \frac{C_d}{C_u}\right) \times 100\% = (1-\gamma) \times 100\% \qquad (3)$$

To account for the flux through the VB, equation 1 has been re-written as equation 4 following Tiwary et.al 2008 and Guo and Maghirang, 2012

$$PRE, \phi_{VB} = u(H,L)\left(1 - \frac{C_d}{C_u}\right) \times 100\% = (1-\gamma) \times 100\% \qquad (4)$$

A major setback of equation 3 and 4 as applied in these studies is that it is sampling-point and most times wind direction dependent. As such, application would be limited to conditions which represent the ones presented in the studies. In the present study, equation 4 was reformulated to be independent of sampling point, to account for average PRE by a VB of certain volume and wind condition (see equation (5)).

$$\phi'_{VB} = \frac{1}{V_{VB}}\left[\int_0^L \int_0^H \int_0^W u(H,L)\left(1 - \frac{C_d}{C_u}\right) dLdHdW\right] \qquad (5)$$

Where V_{VB} is the volume of VB and $u(H,L)$ is the upwind velocity profile of the grid cell.
The total mass removed (FCE) through this process can then be calculated as:

$$FCE, \gamma'_{VB} = [\phi'_{VB} - \phi'_{ref}] \qquad (6)$$

The distribution of PRE on a VB (BC-1 and BC-2) under perpendicular and oblique wind direction is depicted in (see Fig.2). We observed that PRE across the entire length and height of a VB is not evenly distributed. It is stronger at the rear of a particular flow angle because of weaker velocity at that region allowing more retention of pollutant upstream and reducing mixing/dispersion. Moreover, in BC-1, we detected that PRE of VB at any sampling location is partially positive and negative especially above the source (see Fig.2a). This finding partially opposes previous studies (Tiwary et al., 2006; Tiwary et al., 2008, Al-Dabbous and Kumar, 2014 and Brantley et.al, 2014) that reported only positive PRE and determine the PRE of VB by a single sampling location. The reason for their result could be because coincidental sampling location (horizontal(y) and vertical (z)), different attribute of VB and prevailing wind. A negative PRE suggests the downstream pollutant concentration is higher than upstream due over-powering aerodynamic effect of VB over its reduction capacity (Vos et al., 2013). This pattern can also be observed if the VB is highly porous (Hagler et.al., 2012).

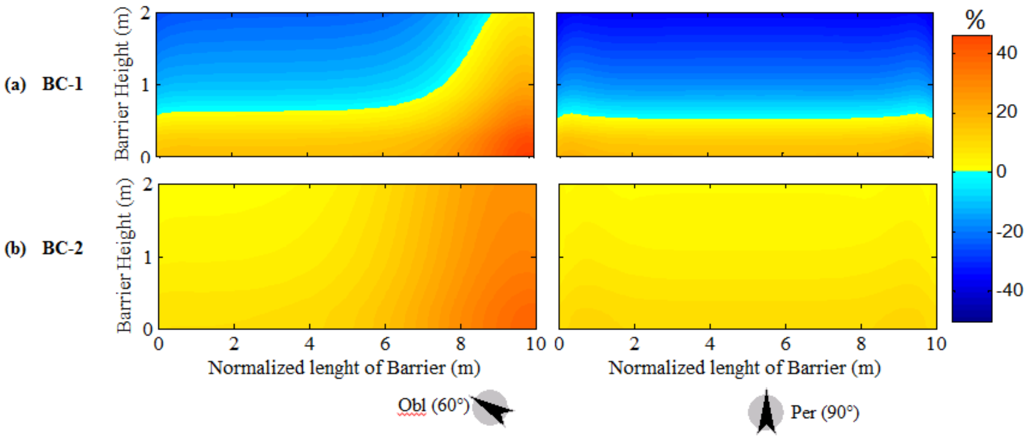

Fig.2. Spatial distribution of PRE of VB at its initial position (BC-1) and when positioned 2m after DMC (BC-2) under different prevailing wind direction

To avert negative PRE, we have applied two simple approaches based on DMC i.e. positioning VB after DMC and increasing the thickness of VB to cover the entire DMC. In this study, DMC is referred to as the distance between source and point of peak concentration before dwindling concentration downwind begins (see Figure 3) One of our simple approaches to avoid negative PRE and enhance positive PRE is to place VB behind DMC (for the prevailing winds condition). Comparison between PRE of VB at its initial position (BC-1) and when placed 2m after DMC (BC-2) indicates positive PRE in all cases irrespective wind direction (compare Fig.2a and b).While this method is useful in estimating the immediate reduction benefit (not overall removal in the domain), our results shows that PRE and FCE increase with increasing distance from source. This may suggest placement of VB farther away from source which negates the deposition theory.

Another approach to avoid negative PRE is to increase the thickness of VB to cover the entire DMC (for the prevailing winds condition) centered on the criterion that pollutant concentration downstream must be less than upstream i.e. $C_d << C_u$ at a target height (1.4m in this study). Testing this criterion, we compared the BC-1 and BC-3's PRE. We found higher and positive PRE in all wind direction in BC-3 unlike in BC-1. (see Fig.4b).

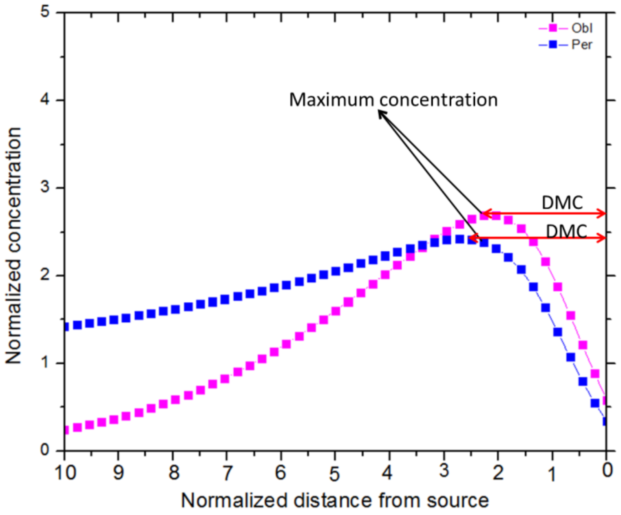

Fig. 3. Horizontal distribution of normalized pollutant concentration in reference case (RC) under different prevailing wind direction

3.2 Dispersion-Deposition related assessment of air quality benefit of VB

In this section, we compared the dispersion and deposition-related benefit (or otherwise) among all cases and normalized volume of VB (V_{vb}/V_d). Dispersion parameters are PRE, FCE and ARDC (Average Relative Difference in Concentration) while deposition parameter is the ratio of mass deposed to total mass in the domain $M_{vb}/M_{a.}$ In addition to previous runs discussed, DC was based on previous (summarized in Janhall,2015) and our new recommendations of designing VB for maximum removal as follows: Firstly, VB was positioned close to the road (source) , in this study 3m from the center line of the road. Secondly, VB's porosity ($2m^2/m^3$) was applied: considered to be porous enough to allow penetration/filtration and high surface area for maximum deposition.

Thirdly, optimum height of VB should be enough to capture the full plume height. Lastly, we used our proposed technique to determine the optimum thickness of such VB which states the VB should be at least thick enough to cover DMC. With these criterion both the dispersion and deposition-related benefit can be achieved in open areas with enough space

A comparative result is shown in Fig.4. It was observed that ARDC (a parameter that indicates the cleanness or dirtiness of the domain) increases with increasing V_{vb}/V_d. It is higher with oblique wind than perpendicular because more region of the VB interacts with flow .With BC-2 the domain is slightly cleaner than BC-1 although they have similar $V_{vb}/V_{d.}$ This is because of higher dispersion is induced when obstacle is farther from source. The PRE and FCE of embedded VB also increase with increasing V_{vb}/V_{d} (see Fig.4b and c). It is important to note that farther VB from source (BC-2) and increased thickness of VB (BC-3) resulted in higher value. Oblique wind indicates higher PRE and FCE because less region of the VB interact with the prevailing flow i.e. PRE and FCE also increases with reducing wind speed at the rear region. As expected, mass removal is higher in BC-3 and DC because they have higher volume of VB. Overall, we observed that our results confirms that the higher mass removal corresponds to worsened ‘dirtiness’ of the entire domain(ARDC) while the dispersion-related reduction benefit (PRE and FCE) increases with increasing volume of VB.

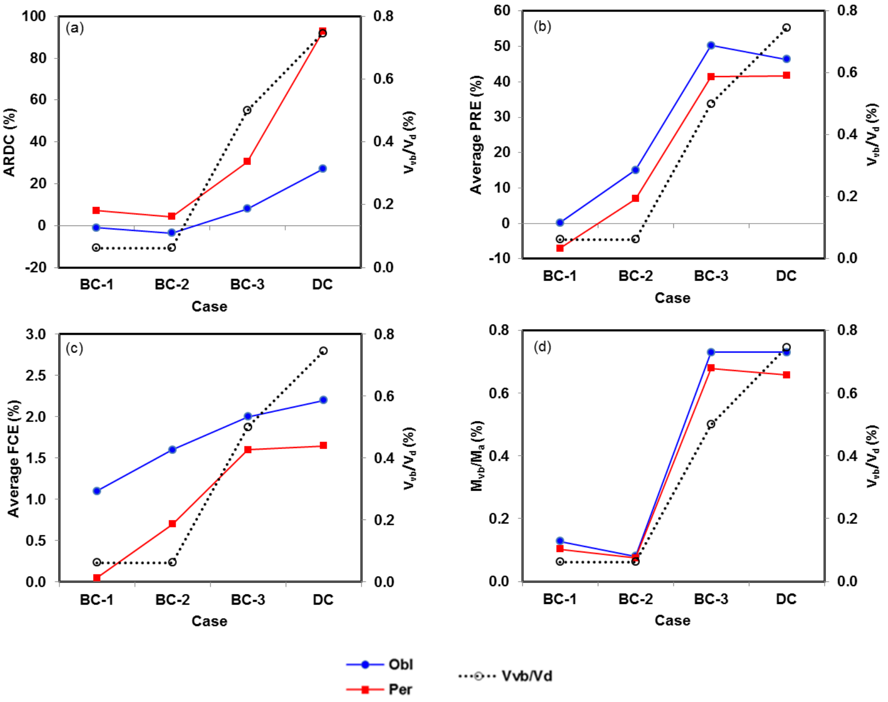

Fig. 4. Comparison of variation of ARDC(a), average PRE(b), average FCE(c) and normalized mass removal (c) per case and normalized volume of VB (dotted line)under perpendicular (red line) and oblique (inflow)

Summary, conclusion and recommendation

This study has employed a numerical micro-scale model (ENVI-met) to investigate and compare dispersion and deposition related benefit of near-road VB. Earlier we found that the dispersion-related effect of VB on near road air quality could either be positive or negative. Technique to avert the negative effect was presented which include placing VB behind DMC or extending the thickness of VB to cover DMC. In terms of deposition-related benefit, closer to source VB of higher volume suggest maximum removal. Overall, benefits from either perspective are possible when thicker VB is erected in areas with enough space. However, the overall concentration in the domain is higher. Findings from this study are not only useful for landscape and urban planning but also provide some insight in solving or eradicating the rising health concern from poor air quality. Nevertheless, configuration and placement of VB to simultaneously achieve these purposes might not be an easy task. Summarily, higher volume of VB can increase the overall mass removal of a city while the same could worsen the air quality of a surrounding area. Hence, the benefit of roadside VB is need-based: Higher deposition or higher dispersion.

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