PARTICULATE MATTER MODELING IN NEAR-ROAD VEGETATION ENVIRONMENTS

Contract AQ-04-01: Developing Effective and Quantifiable Air Quality Mitigation Measures

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By

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Abstract

Background: Due to concern over near-road pollutant concentrations, recent work has examined how near-road barriers such as sound walls affect air quality proximate to roads. This research contributes to the sound wall literature by assessing the benefits of vegetation screens near roadways; it was motivated by the potential for vegetation to reduce pollution and the ability to leverage existing state department of transportation standard operating procedures to install and maintain landscaping enhancements along roadways.

Methods: We developed a model based on a computational fluid dynamics code to tree plantings in the near-road environment. We used this model to solve for steady-state airflow in the near-road environment and then used these results to calculate particulate matter (PM) flows within three tree canopy configurations. For an elementary school case study site (Willett Elementary School; located near a freeway in Davis, California), particulate matter capture was approximated based on a probabilistic calculation of the number of particles impacting the tree surface.

Results: The effectiveness of PM removal via tree plantings depends on characteristics of the species chosen (e.g., foliage characteristics, canopy structure, and life span) and varies by particulate size. The Willett Elementary School case study showed that for the number, size, and distribution of modeled particles, up to 74 percent of $PM_{1.0}$ impacted a tree surface under the configuration scenarios. Total leaf surface area, particulate distribution, and drag coefficients were key model parameters in this study. More research is needed to better model and assess the parameterization of interactions that take place between near-road pollutants and individual vegetation elements. However, this work clearly shows the potential of the developed tool to assist in policy decision making.

About The U.C. Davis-Caltrans Air Quality Project

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Mission: The Air Quality Project (AQP) seeks to advance understanding of transportation related air quality problems, develop advanced modeling and analysis capability within the transportation and air quality planning community, and foster collaboration among agencies to improve mobility and achieve air quality goals.

History: Since the 1990s, the U.S. Federal Highway Administration and Caltrans have funded the AQP to provide transportation-related air quality support. Caltrans and AQP researchers identify and resolve issues that could slow clean air progress and transportation improvements.

Accessibility: AQP written materials and software tools are distributed through our website, peer-reviewed publications, conference presentations, training classes, formal reports and technical memoranda, and periodic newsletters.

Research: AQP investigations focus on project-level, regional-scale, and national-level assessments. Tools and publication topics cover pollutant-specific problems such as those involving particulate matter, carbon monoxide, carbon dioxide, ozone and air toxics; activity data collection and assessment for on- and off-road vehicles and equipment; mitigation options such as transportation control measures; policy analyses addressing transportation conformity and state implementation plan development; litigation support; and goods movement assessments.

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1. Introduction

The relationship between particulate matter (PM) and urban trees has been a subject of interest since at least the early 1970's. Research into this relationship has covered both emissions from and filtration effects of trees in urban environments. Within recent years there has been elevated interest in understanding the ability of urban trees to filter hazardous air pollutants and this paper attempts to further that understanding by exploring the filtering effect of tree plantings in a near-road environment. PM deposition models have been formulated and refined throughout the past several decades; however, these efforts have been largely focused on regional models that average out small-scale effects of individual canopy elements (i.e. principally leaves and branches). Unfortunately, these small-scale effects are essential in modeling PM transport and deposition in near-road tree canopies. In order to adequately approach this problem, computational fluid dynamics (CFD), which is a mathematical and numerical way to analyze the dynamics of fluid flows, is needed. CFD software has traditionally been restricted to high performance computers, becoming commercially available in the 1970's and widely desktop accessible within the past decade. CFD modeling is used in a diverse spectrum of industrial applications; however, very little literature exists on the simulation of PM transport through tree canopies. The literature that does exist mainly pertains to airflow through canopies and particulate transport in crops (see, for example, Arritt, Clark et al. (2007); Da Silva, Sinfort et al. (2006); Gross (1987); Hiraoka (1993); Hiraoka and Ohashi (2008); Marcolla, Pitacco (2003)). Two key papers, Endalew, Hertog et al. (2006) and Endalew, Hertog et al. (2009), couple realistic 3D representations of trees with CFD modeling to investigate airflow through plant canopies; these papers informed our approach.

This paper addresses a unique problem facing transportation agencies across the country; reducing near-road sensitive receptor (e.g. children) exposure to hazardous particulate matter from roadways. Particulate matter transport is modeled under three scenarios and initial results from these scenarios are discussed.

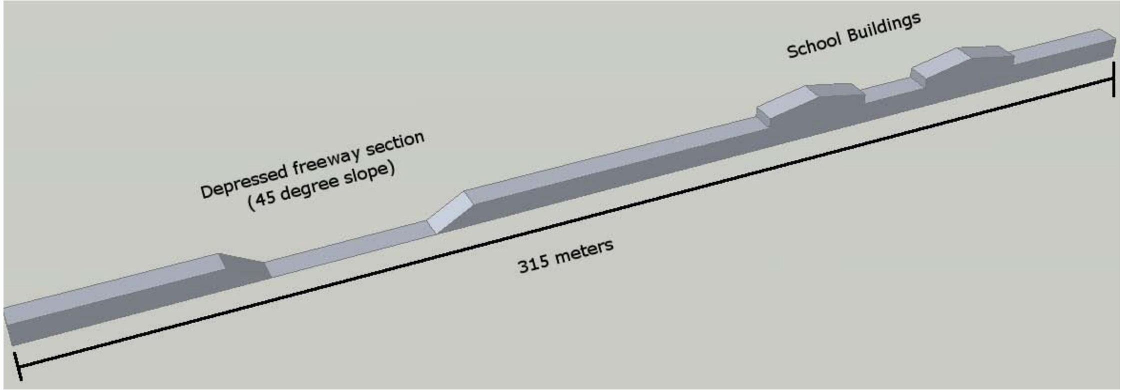
2. Methods

The first step in our work was to build a computer representation of a case study site; we chose this site to be Willett Elementary School (**Figure 2.1**), located in Davis, California. The closest school building is located approximately 96 meters from the edge of roadway (Hwy 113).

Source: www.google.com
Note: Edge of roadway to edge of playground is 70 m

FIGURE 2.1: WILLETT ELEMENTARY SCHOOL SITE AERIAL

In order to accomplish this, we constructed a 3-D representation of the school site in AutoCAD version 9.2. Using primitive solids (e.g. 3-D wedges and cubes), we re-created the site as shown in **Figure 2.2**.



Note: Edge of roadway to edge of closest school building is 96 m

FIGURE 2.2: 3-D RENDERING OF THE WILLETT ELEMENTARY SCHOOL SITE

The next step in our model building was to attempt to represent a Digger/Foothill/Gray Pine (*Pinus sabiniana*) tree, **Figure 2.3**, in AutoCAD. The reasons behind our selection of the Foothill Pine tree are explained in Appendix A: Species Selection Methodology.

Source: www.google.com

FIGURE 2.3: *PINUS SABINIANA*

A major consideration in reproducing the Foothill Pine in AutoCAD stemmed from a requirement of the CFD software used in this work, the commercial code Flow-3D. In order to import the geometry of the school site and tree into the CFD software, the file had to be in a stereolithography (STL) format. The STL format allows the surface geometry of a three dimensional object to be described through simple triangles. This format did not prove to be a problem for modeling the trunk and branches of the Foothill Pine. Dimensions of the modeled tree were based on information from Howard (1992) and observations of actual trees in Davis, California. The leafless model is shown in **Figure 2.4**. We attempted to construct a realistic representation of the Foothill Pine leaves in STL format; however, the computational expense of such a model were beyond the scope of this project (our modeling was performed on a workstation consisting of an Intel Core 2 Duo CPU at 3.00 GHz with 3.25 GB of RAM). As a result, we substituted a porous cylinder for realistic leaves (**Figure 2.5**), which approximates the general shape of the pictured *Pinus sabiniana*. While *Pinus sabiniana* was chosen as a real-world illustration, our model is an approximation of the Foothill pine and is therefore appropriately generalizable to any cylindrically-shaped tree with similar leaf surface area and element dimensions (i.e branches and trunk). In a future stage, more details could be added to the tree representation.

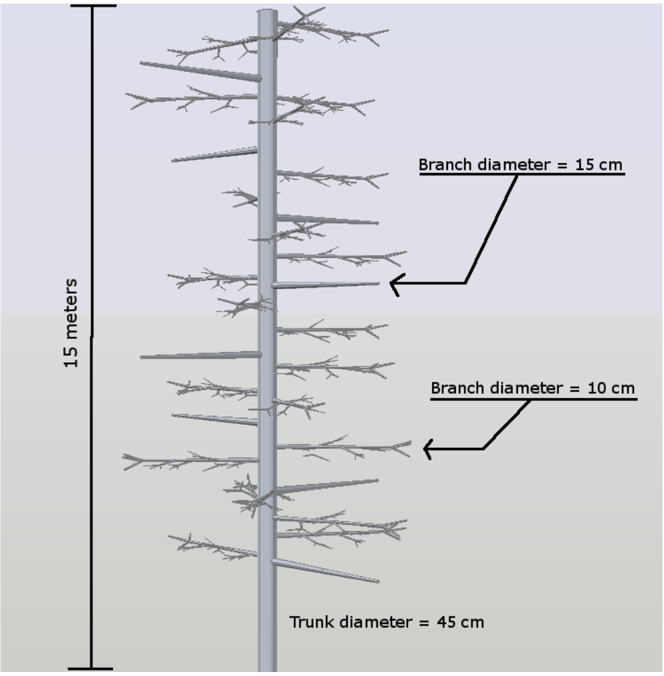
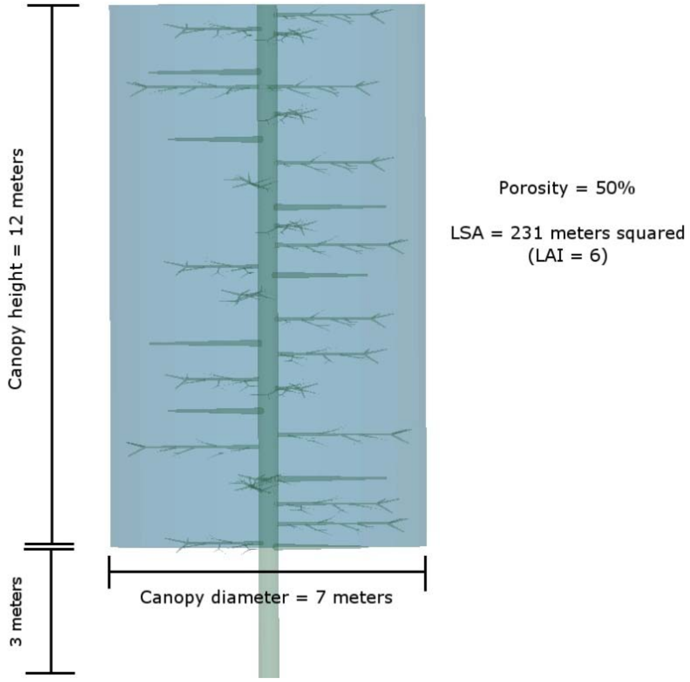


FIGURE 2.4: ***PINUS SABINIANA* (*LEAFLESS*)**



Note: Blue porous cylinder represents leaves

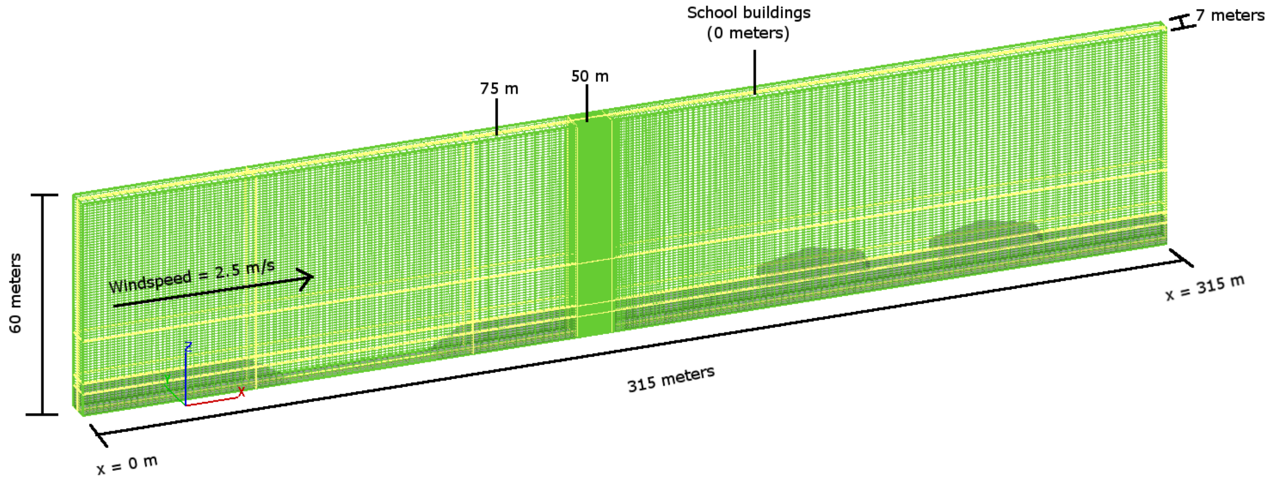
FIGURE 2.5: MODEL REPRESENTATION OF *PINUS SABINIANA*

The porous cylinder approach, while not only necessary, provided the added benefit of allowing us to easily vary the porosity and leaf surface area (LSA) of the tree. A 50 percent porosity value and a LSA of 231 m^2 were chosen for all of our modeling runs. The LSA was an important consideration in the model and we chose a value that reflected a conservative real-world leaf area index (LAI). The leaf area index is a dimensionless ratio of leaf area to canopy projection area (the amount of ground covered by the canopy); the lower the LAI value, the less leaf surface area. The LAI varies among tree species and is subject to the effects of environmental stress (soil conditions, weather, irrigation, wind); however average values do exist in the literature. Nowak et al. (2006) used a LAI of 6, which was based on a single-sided leaf area, a coniferous tree mix of 10 percent, and included canopy layering. The use of an LAI of 6 in the model represents a conservative estimate for pines, which can range from an LAI of 6 (less leaf surface area) to 12 (more leaf surface area) according to Lorenz and Murphy (1989). A report by Scurlock et al. (2001) reported on worldwide historical estimates of leaf area index from 1932 to 2000. This report found that the mean LAI of all biomes was 5.23, the mean LAI for plantations (managed forests) was 8.72, and the mean LAI for temperate, evergreen, needle-leaved forests was 6.70.

Once the AutoCAD model was developed, we imported the model into Flow-3D. Flow-3D is CFD software produced by Flow Science, Inc. and is based on fluid dynamics methods pioneered in 1963 at Los Alamos National Laboratory. CFD modeling generally entails the following steps: pre-processing, solving, and post processing. The pre-processing step is the first step in flow modeling and includes generating the regional geometry, creating a suitable computational mesh, and applying case-specific boundary conditions and materials properties. The subsequent solving step uses the model governing equations embedded in the software to solve flows under user-defined conditions in the region of interest. The final step, post processing, involves the interpretation and presentation of simulation results (e.g. images and animations).

Simulation Domain Modeling

For our application, we chose a domain based on the Willett Elementary School site and applied this domain to all of our simulations. As shown in **Figure 2.6**, the simulation domain measured 315 meters long (length of school site) by 7 meters wide (diameter of tree canopy) by 60 meters high (height was set to be 4h or four times the height of the tree, which was 15 meters). The simulation was two dimensional. The domain inlet was set to position x=0 meters and the outlet was set to position x=315 meters. A westerly, constant, and uniform flow was introduced at the inlet with an initial velocity of 2.5 meters per second. This initial wind speed represents an average of values collected by the Department of Water Resources' California Irrigation Management Information System (CIMIS) from June 2000 to June 2009 at Station 6 (wind speed is measured at 2 meters above ground), located at the Campbell Tract research facility at UC Davis (less than 3 miles southwest of Willett Elementary School). Other than at the inlet and outlet, the domain lower walls were set to a no slip boundary condition, which in our case means that the air will have zero velocity at the domain boundaries. In the top boundary, a symmetry plane was adopted. Three different tree configurations were modeled: one tree placed at 50 m, one tree placed at 75 m, and four trees placed at 50 m from the school buildings.



Note: Light-green bar at 50 m is the result of a more dense mesh used for the near-tree region. The bar also appears around 75 m for the one tree at 75 m simulation

FIGURE 2.6: SIMULATION DOMAIN

The software calculates results for the user-defined model by employing what is called a computational mesh, essentially a grid where the model governing equations are calculated at the intersections (nodes) of the grid (mesh). Since calculations are made at the nodes, it is necessary that the mesh be appropriately scaled to the object of interest. For instance, you could not model airflow around a dime with a grid measuring 1 meter cubed because the model would not "see" the dime; the mesh would need to be appropriately scaled to the dimensions of the dime. As illustrated above in **Figure 2.4**, the smallest tree element measured 10 cm in diameter. This was an important consideration in the mesh construction since the mesh must be scaled to the smallest element if effects associated with that element are to be calculated. In Flow-3D, the mesh consists of rectangular grid elements that can be defined in the x-y-z plane. Accordingly, the mesh in the tree region was set to a width of 10 cm and the mesh in the rest of the domain was appropriately scaled to the objects by the Flow-3D code. **Figure 2.7** shows a close-up view of the mesh in the tree region; note how the code attempts to smooth the transition between the tree region mesh and the larger mesh used for the rest of the domain.

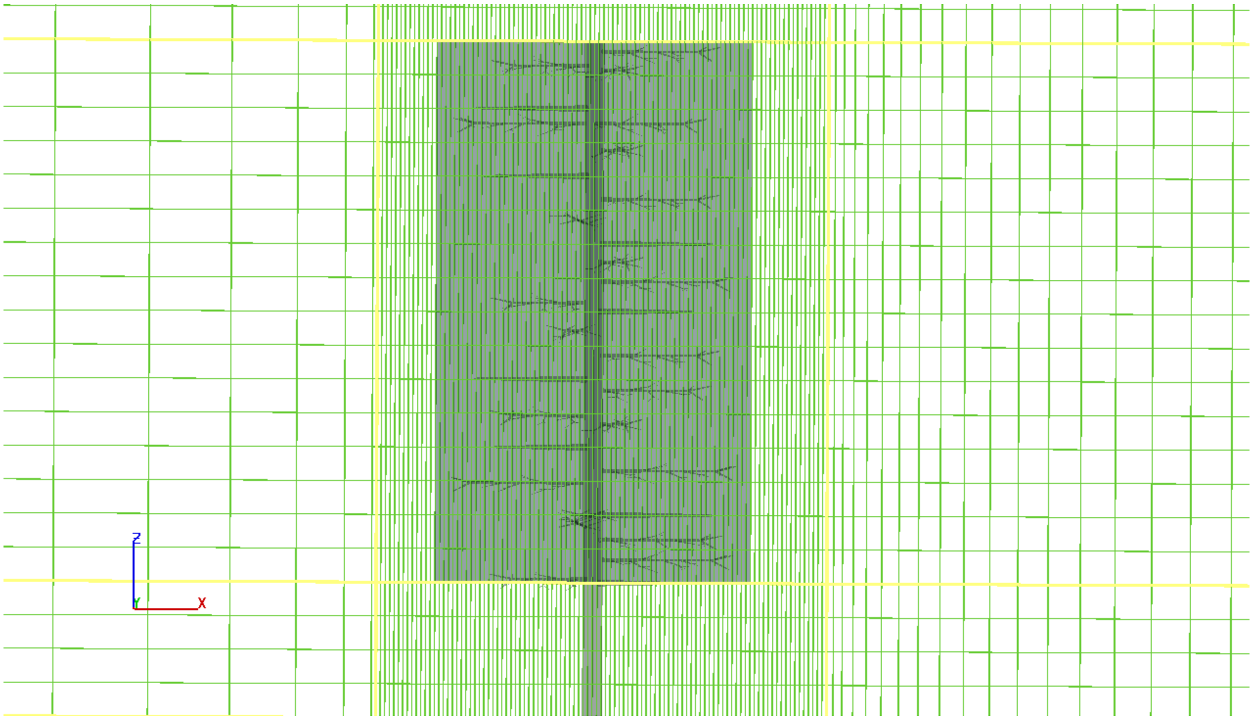


FIGURE 2.7: TREE REGION MESH

Modeling Approach

We selected a so-called Eulerian-Lagrangian approach. This means that the air flow was simulated as a continuum, while the particles were represented individually. Whereas other alternatives are implemented in Flow-3D, we decided that this approach was the most convenient for the problem at hand.

Turbulence Modeling

As previously mentioned, particulate transport and deposition in near-road vegetation canopies is affected by the flow turbulence. One way to account for these effects is to use the large eddy simulation (LES) technique. This numerical technique solves the equations governing complex turbulent flow by directly computing the energy-containing scales of motion (the large eddies) and by modeling the smallest scales of turbulence (the small eddies). Using this approach, LES can resolve turbulent flows involving flow separation; exactly what is needed for modeling particulate transport through a tree canopy. The LES technique was used in all of our simulations.

Key Modeling Parameters

For our modeling scenarios, we considered the diffusion of 100 particles from the depressed freeway section under the following initial conditions: particulate diameter equal to 1 micron, particle distribution initialized in a randomized block with dimensions 30 m (width) by 10 m (height), and particle density equal to 2.6 kg/m^3. The particle mass density used in the model was chosen so that we could visually identify the PM on screen. Using particle densities with significantly lower mass (for instance, 15 μg/m^3) than that modeled in our analysis will not alter the presented results. **Figure 2.8** illustrates the initial conditions employed for the PM in all of the runs. To gauge the potential for PM to impact the tree surface, the coefficient of restitution was set to a negative value. The coefficient of restitution is a measure of the loss of a particle's kinetic energy in a particle-surface collision. A negative coefficient means that when a particle impacts a surface, it will lose all kinetic energy and adhere to that surface. In Flow-3D, particle impaction is influenced by porosity; at porous structures, particles are transmitted according to a calculated probability proportional to the porosity of the canopy (Flow Science 2009). All tree canopies were set to 50 percent porosity with 231 m^2 of leaf surface area. The tree surfaces, along with the ground in the simulation domain, were set to a roughness length of 0.005 m Endalew, Hertog et al. (2009). The roughness length is a parameter used to describe how rough a surface is. The value used in the model represents a rough ground surface with no notable obstacles. For reference, a dry lake bed could have a roughness length of 0.003 m.

FIGURE 2.8: PARTICULATE MATTER INITIAL CONDITIONS

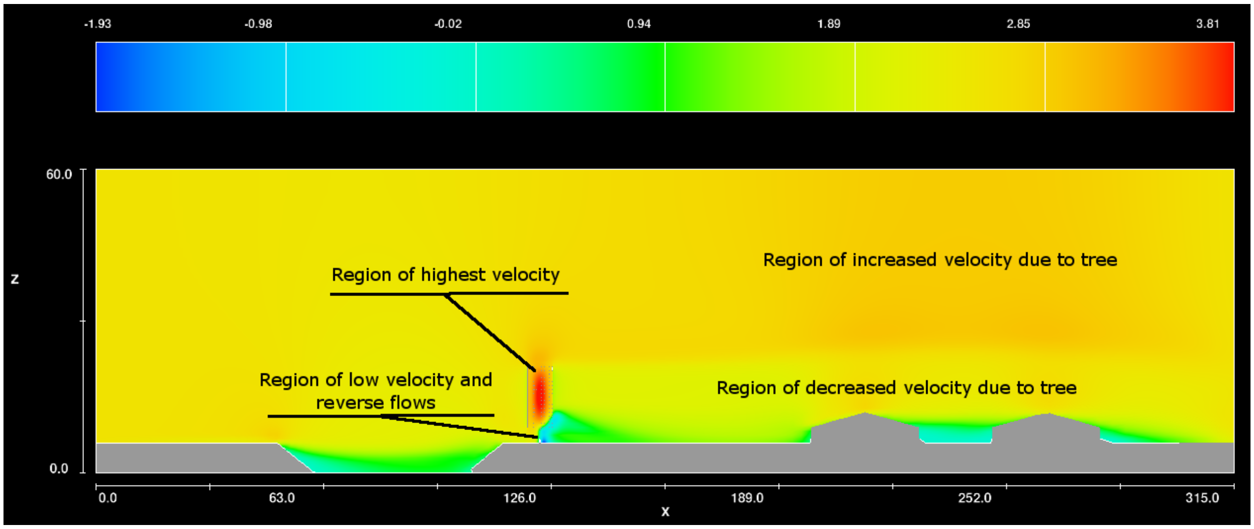
3. Results

In this study we report the results from three principal simulations; one tree placed at 50 m (46 m), one tree placed at 75 m (21 m), and four trees placed at 50 m (46 m) from the school buildings (edge of roadway). In all three of our runs we first set the simulations to run for 300 seconds; this allowed them to reach a steady state. A steady state is valid for our analysis given that we imposed a constant uniform wind as part of our initial conditions. After 300 seconds, when a steady state had been established, the particles were initialized in the model and allowed to be transported in the steady state flow for 150 seconds (total time equal to 450 seconds). This time length allowed the particles to move through the vegetation and past the school buildings.

Simulation #1: one tree at 75 m

As shown in **Figure 3.1**, the steady state flow differs from the flow that would be expected without vegetation. In the absence of the tree, we would expect to observe essentially a uniform 2.5 m/s flow throughout the domain with only the depressed freeway section, ground, and school buildings producing any observable change in velocity. Note that **Figure 3.1** illustrates only the x-velocity and while there are observable velocity changes in the z direction, the x-velocity component is the overriding concern in our analysis. Simulation #1 results show us that the singular tree (LAI=6) causes an increase in the x-velocity (the red coloring indicates velocities up to 3.81 m/s) in the inner tree canopy that is centered on the trunk region.

Conversely, in the understory, an area of low velocity (the green and blue coloring indicates less than 0.94 m/s) and reverse flows (indicated by the blue regions and associated negative x-velocities) develops.



Note: The figure shows the x-velocity only. Velocity units are in m/s and distance units are in meters.

FIGURE 3.1: SIMULATION #1 STEADY STATE

In order to get an idea of the trajectories that the particles would be subject to in the steady state flow, streamlines were plotted in the domain (**Figure 3.2**). The figure illustrates how flow separation is occurring in the canopy region due to individual tree elements and also indicates that there is a minimum trajectory height for particle impaction to tree surfaces. Airflow does not seem to be significantly perturbed in the presence of one tree with LAI=6.

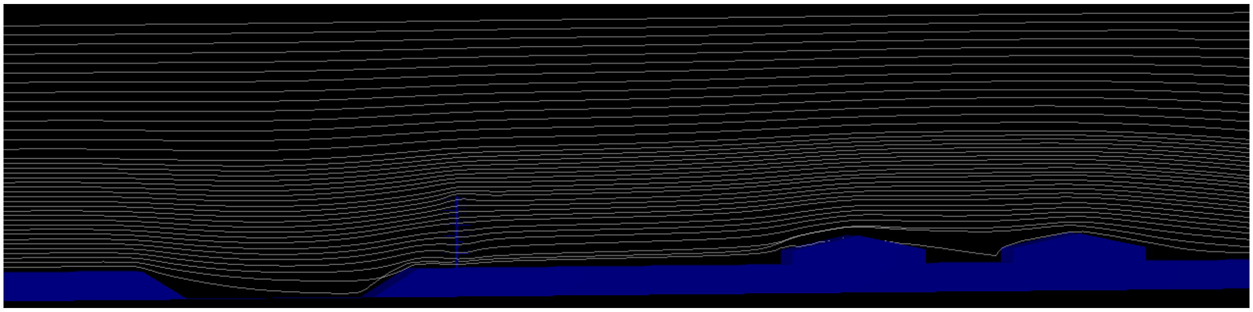


FIGURE 3.2: SIMULATION #1 STREAMLINES

As previously mentioned particles were introduced into the steady state flow and allowed to diffuse for 150 seconds. **Figure 3.3** shows the simulation domain at t=450 seconds. Out of the initial 100 one micron particles, 43 particles adhered to a tree surface (ground and building adhesion were not considered) for a particle impaction percentage of 43%. It is vital to note that the term used in this report, impaction, is distinctly different from the deposition concept in that our results disregard, at this time, real-world phenomena that significantly influences deposition (e.g. bounce-off and re-suspension). These effects could be added in future simulations. The results in **Figure 3.3** and **Figure 3.4** simply indicate that under the modeled conditions, we could expect 43% of one micron particles released from the initial position (**Figure 2.8**) to impact a tree surface. The initial distribution of the PM is instrumental in its probability of impacting a tree surface. This is illustrated by the streamlines in **Figure 3.2**; if all of the particles were released at ground level, the likelihood of impaction would be dramatically reduced as the particles would be expected to follow the ground-level streamlines and flow under the tree canopy (3 meters tall).

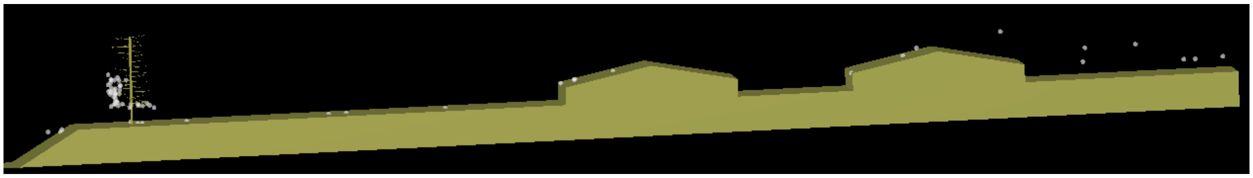


FIGURE 3.3: PARTICULATE DISTRIBUTION AT T=450 SECONDS

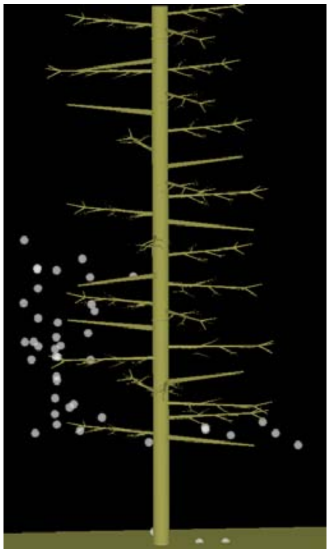
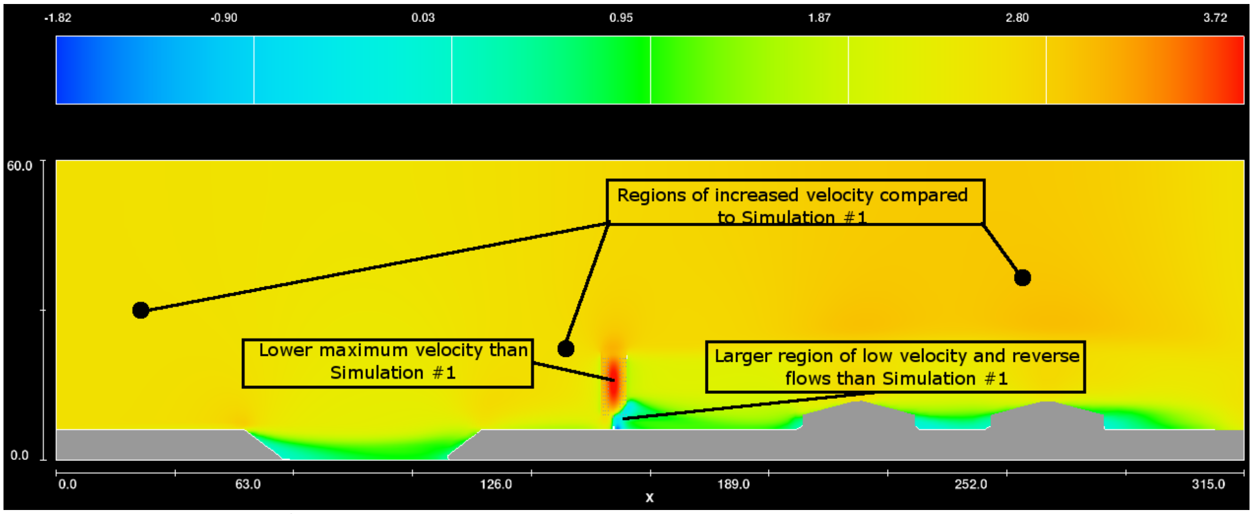


FIGURE 3.4: PARTICULATE IMPACTION TO TREE SURFACE (43%)

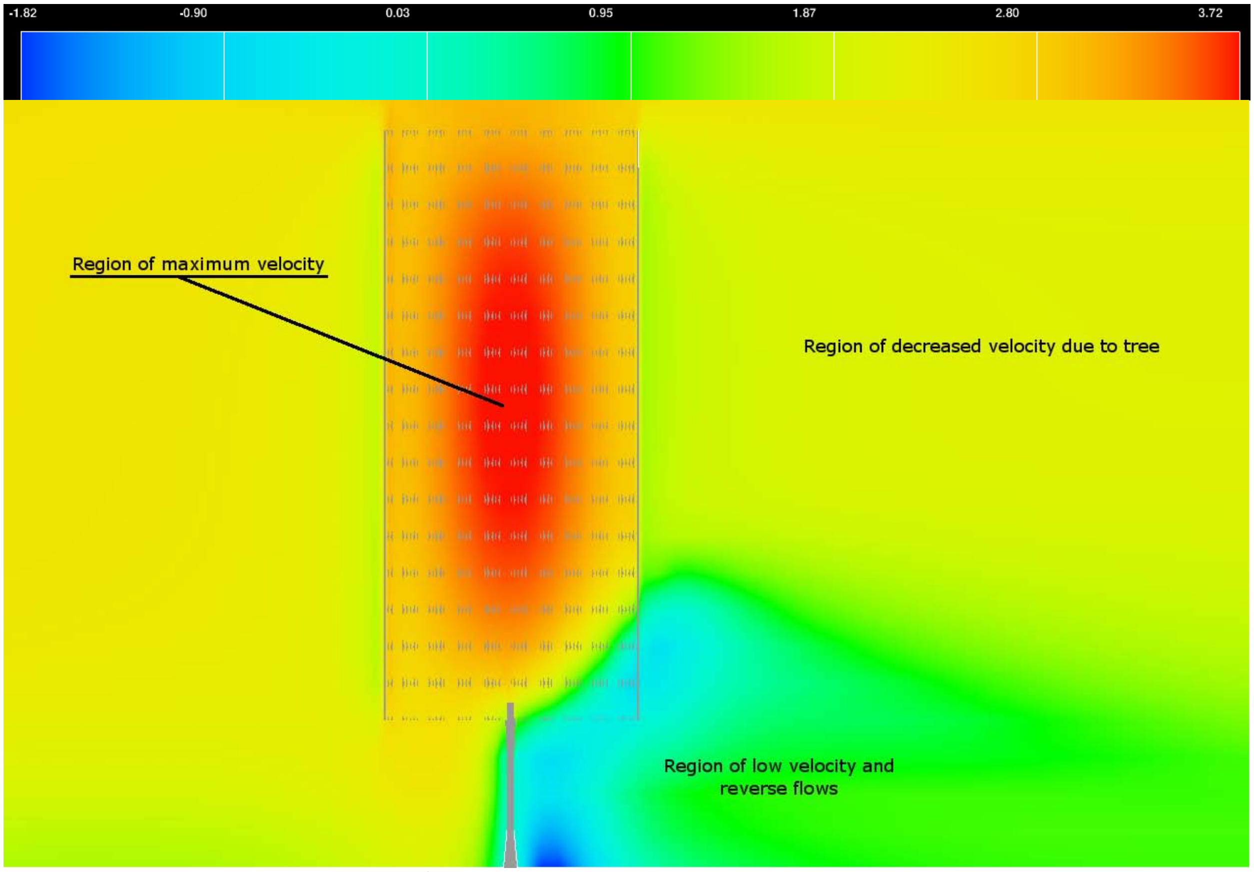
Simulation #2: one tree at 50 m

The steady state flow illustrated in **Figure 3.5** differs slightly from the flow observed in Simulation #1, with the main differences being increased x-velocity regions in front of the tree and above the tree and school buildings, a lower maximum velocity within the tree canopy (3.72 m/s compared to 3.81m/s), and a larger region of low velocity and reverse flows behind the trunk of the tree. **Figure 3.6** provides an enlargement of the velocity regions near the tree.



Note: The figure shows the x-velocity only. Velocity units are in m/s and distance units are in meters.

FIGURE 3.5: SIMULATION #2 STEADY STATE



Note: The figure shows the x-velocity only. Velocity units are in m/s.

FIGURE 3.6: SIMULATION #2 VELOCITY REGIONS NEAR THE TREE

Flow-3D calculated streamlines for Simulation #2; the results are presented in **Figure 3.7**. While there are no overall significant differences between the streamlines of Simulation #1 and #2, there is one notable observation that is likely attributable to the change in distance of the tree from the roadway. The proximity of the tree to the roadway in Simulation #1 appears to keep the lowest flow trajectory (height of the lowest streamline is 6 meters) closer to the ground. The effect of this constraint on PM impaction is observable in **Figure 3.8**. Note the increased impaction to the ground and school buildings in **Figure 3.3** compared to **Figure 3.8**. This result suggests that the closer a tree (with a bottom canopy 3 meters above ground) is placed to a roadway, the closer the lowest airflow region is to the ground.

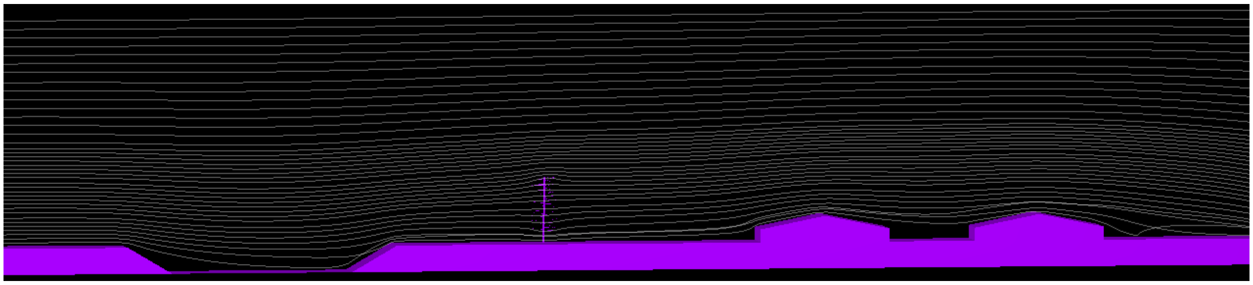


FIGURE 3.7: SIMULATION #2 STREAMLINES

FIGURE 3.8: PARTICULATE DISTRIBUTION AT T=450 SECONDS

While the tree configuration in Simulation #1 might constrain PM flow closer to the ground than the configuration of Simulation #2, it is clear that both scenarios keep PM flow low to the ground due to the open understory and, therefore, within the breathing zone of schoolchildren. In addition, a negligible difference in PM adhesion (44 out of 100 particles or 44% impaction) to tree surfaces was observed between Simulation #1 and #2 (**Figure 3.9**). This supports the contention that PM and airflow did not significantly differ in the tree region between the two scenarios.

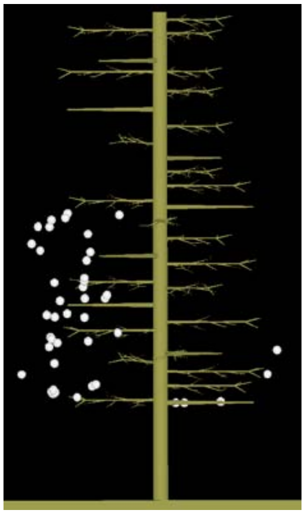
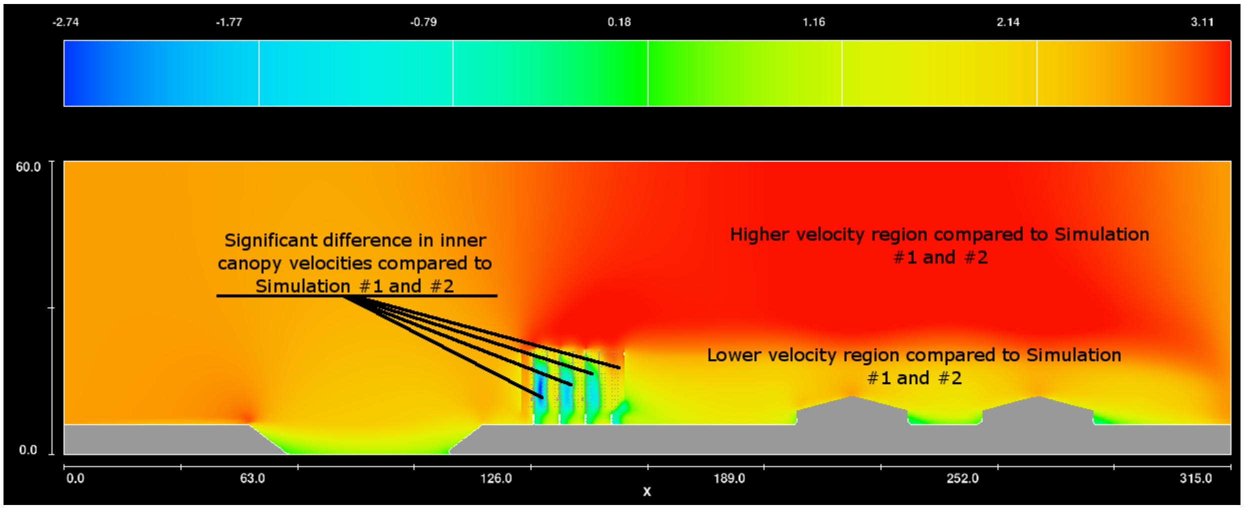


FIGURE 3.9: PARTICULATE IMPACTION TO TREE SURFACE (44%)

Simulation #3: four trees at 50 m

For our final run, we evaluated the impact of planting four closely-spaced rows of trees (trees were positioned in a single column with the first tree 50 m from the school buildings; total tree planting measured 28 m in width). The results, presented in **Figure 3.10**, show significant differences as compared to Simulation #1 and #2. The group of four trees (LAI=6 for each tree; total LSA=924 m^2) appears to behave similarly to a solid obstacle with respect to the well-defined region of high velocity above the trees and school buildings, the definition of a shielded zone behind the trees where low velocities occur, and an observable reattachment of the airflow just before x=315 meters (where the single-family residences are located).



Note: The figure shows the x-velocity only. Velocity units are in m/s and distance units are in meters.

FIGURE 3.10: SIMULATION #3 STEADY STATE

In addition to the regional differences, significant differences are observable within the tree canopies. **Figure 3.11** shows that in stark contrast to Simulation #1 and #2, low velocity and strong reverse flows (-2.74 m/s) occur within the tree canopy. This result is an important finding as it indicates that the airflow is significantly retarded within the canopies. Vegetation with high surface area adequate to slow, but not stop, wind will maximize particle removal rates since motion scales by the amount of time the particles are close to a surface (Cahill 2008). From the results in **Figure 3.10 and 3.11**, it appears that a configuration of four trees with LAI=6 is sufficient to provide adequate leaf surface area to significantly slow inner-canopy airflow. The decreased canopy velocities provide particles with greater canopy residence times and result in higher diffusion deposition rates. The streamlines illustrated in **Figure 3.12** further suggest that inner-canopy flows are fundamentally different than previously modeled configurations and should result in higher impaction to tree surfaces.

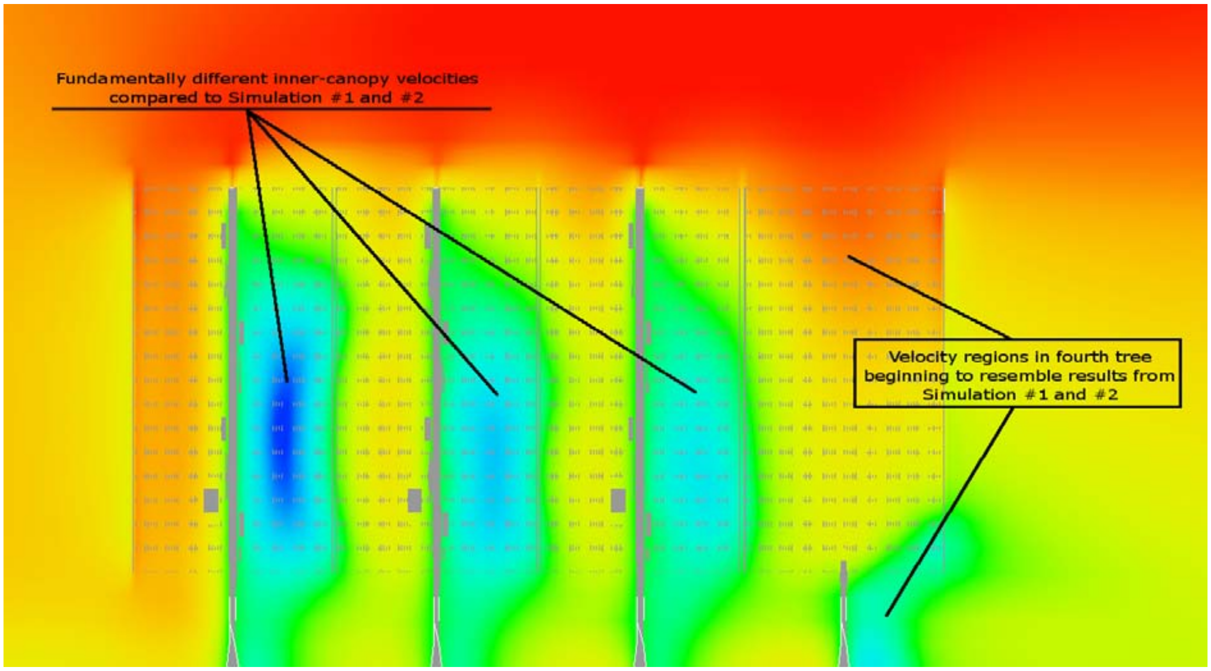


FIGURE 3.11: SIMULATION #3 INNER-CANOPY VELOCITIES

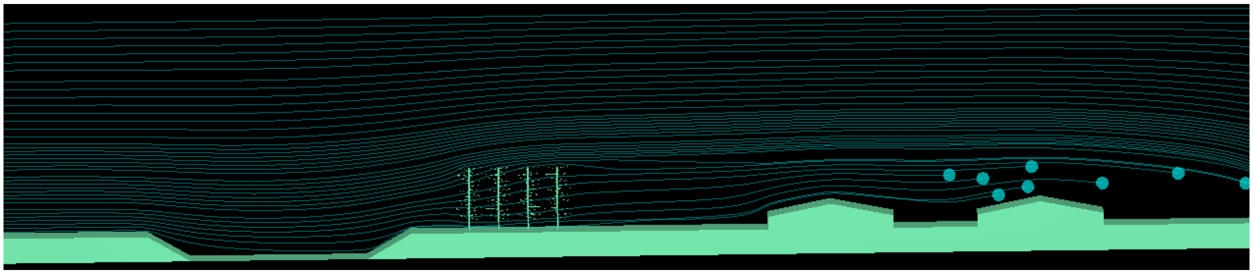


FIGURE 3.12: SIMULATION #3 STREAMLINES

As suggested by the initial results presented in **Figure 3.10 – 3.12**, the results shown in **Figure 3.13** and **3.14** confirm that the four tree configuration resulted in significantly more impacted particles. Out of the 100 one micron particles released at t=300 seconds, 73 impacted a tree surface for an impaction percentage of 73%.

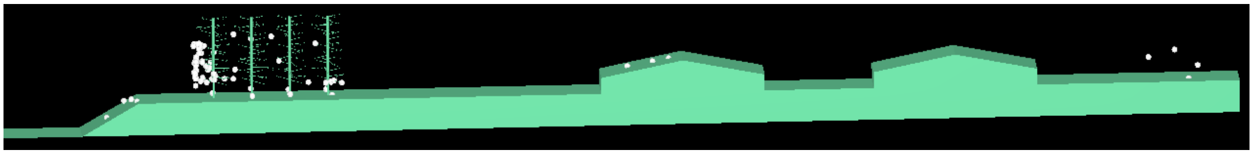


FIGURE 3.13: PARTICULATE DISTRIBUTION AT T=450 SECONDS

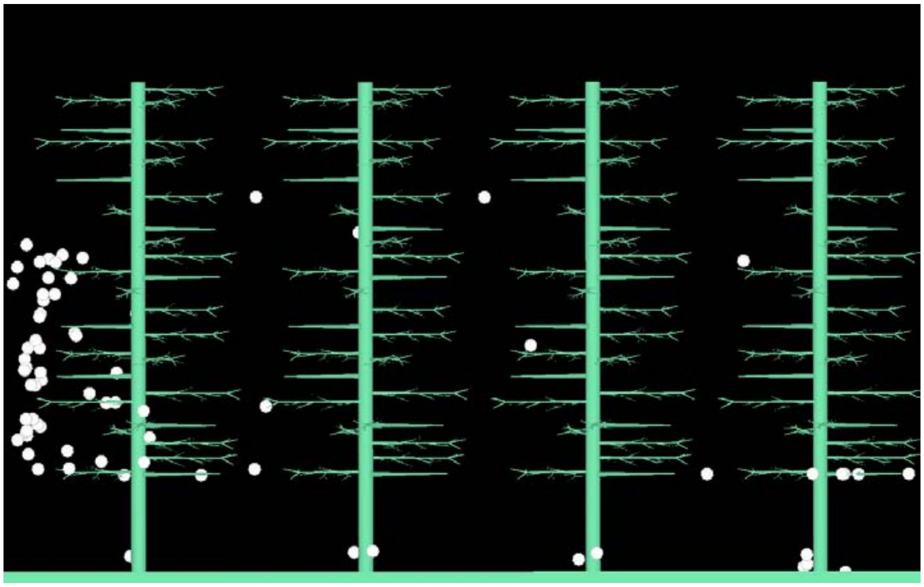


FIGURE 3.14: PARTICULATE IMPACTION TO TREE SURFACE (73%)

4. Conclusions and Further Research

Initial results from our investigation into the effectiveness of using trees as a vegetation barrier between a freeway and an elementary school suggest that multiple rows of trees (LAI=6) should be planted to maximize the potential for impaction. Diesel particulate matter, the control of which motivated this study, is comprised mainly of fine and ultrafine particles measuring less than 2.5µm. In fact, it has been reported that "[a]mbient ultrafine particles (UFPs) that have an aerodynamic diameter of <0.18µm are by far the most abundant particles by number in urban environments…" (Araujo, Barajas et al. 2008). While modeling results show the potential for impaction, submicron particles ($PM_{1.0}$) are the overriding concern in near-road environments and diffusion is the dominant deposition mechanism in this particulate diameter range. Accordingly, maximizing deposition by diffusion should be the primary goal and is essential in the consideration of appropriate near-road vegetation configurations. **Table 4.1** summarizes the results from our simulations and clearly finds that the four-tree configuration maximizes the potential for impaction. In addition, the four-tree configuration shows potential for maximizing deposition by diffusion since it significantly reduces the inner-canopy velocity. By reducing the inner-canopy velocity, PM residence time within the tree canopy increases and allows the PM time to diffuse to a tree surface. While the presented results are promising, they are only valid for the simulated model. Further research needs to be completed in order to elucidate the relationship between the reported impaction percentage and actual deposition to tree surfaces.

TABLE 4.1
SUMMARY COMPARISON OF SIMULATED CONFIGURATIONS

Simulation	Maximum x-velocity	Region of maximum velocity	Minimum x-velocity	Region of minimum velocity	Sheltered region velocity	Conclusion
One tree 75 m from school buildings	3.81 m/s	Inner-canopy, centered on trunk	-1.93 m/s	Understory, behind trunk	~2.3 m/s	⇨ 43% impaction ⇨ does not maximize impaction
One tree 50 m from school buildings	3.72 m/s	Inner-canopy, centered on trunk	-1.82 m/s	Understory, behind trunk	~2.1 m/s	⇨ 44% impaction ⇨ does not maximize impaction
Four trees 50 m from school buildings	3.11 m/s	In atmosphere above school (21m ≤ z ≤60m)	-2.74 m/s	Inner-canopy, centered behind trunk	~1.8 m/s	⇨ 73% impaction ⇨ maximizes impaction

Note: “Sheltered region velocity” refers to the leeward area behind the trees that has reduced velocity due to the presence of the obstacle.

From the urban forest research literature, it is apparent that tree plantings can be used and optimized to reduce particulate matter exposure near freeways provided that the planting: is close to the pollution source, is characterized by rough and sticky surfaces, creates a buffer between the source and receptor, consists of a fine, complex foliage structure that allows significant in-canopy airflow (conifers), has a high surface area, retains foliage throughout the year (evergreens), consists of large-statured trees that are hardy and have a long life span, and has a low biogenic volatile organic compound (BVOC) emission rate (Beckett, Freer-Smith et al. 1998; Norbeck, Durbin et al. 1998b; Freer-Smith, Beckett et al. 2005; Houtte 2007; McDonald, Bealey et al. 2007). However, in order to apply these literature findings to CFD modeling, key model parameters need to be determined that appropriately reflect empirical observations. These parameters include the drag coefficient, roughness length, coefficient of restitution, and diffusion coefficient. Once model parameters have been defined, true deposition functionality must be integrated into the CFD model.

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Appendix A

Species Selection Methodology

Literature indicates that coniferous evergreens possess characteristics that make them preferable as a potential barrier for particulate reduction purposes; however, localized conditions (e.g., weather characteristics) should be of primary concern in the consideration of appropriate species. To assist in the determination of suitable species for the Willett School plot, we employed a U.S. Forest Service tool called the "Species Selector" program. The Species Selector program is part of a peer-reviewed suite of software called "i-Tree" (v2.1) developed by the Forest Service in cooperation with Horticopia, Inc (i-Tree 2008). The program is based on detailed information for 1,585 species and incorporates values for tree hardiness, tree size, shading coefficients, leaf area, leaf biomass, transpiration rates, physical characteristics of leaves, VOC emissions, leaf persistence, and pollutant sensitivity. The detailed information and basic user inputs are used to produce a list of suggested species. Program inputs include: city, state, height constraints (optional), importance of several environmental functions and pollutants (the user is asked to rate the importance of a particular function and/or pollutant on a 0-10 scale, with 10 signifying very important), and output format (the top 10 percent of results or simply all results). For our scenario the location was set to Davis, California, no height constraints were entered (the site does not present any height barriers such as overhead power lines), air pollutant removal was rated at 10 for all pollutants listed (carbon monoxide, ozone, nitrogen dioxide, particulate matter, and sulfur dioxide), low VOC emissions, wind reduction, and carbon storage were each set to 10, and the top 10 percent of results was selected for output. As noted in the program documentation on page 112, "Since only city hardiness zone, tree height and user functional preference are used to produce the list, there may well appear many species on the list that are unsuitable to the local context for a variety of reasons. […] For these reasons, the user should treat the list produced as a beginning, rather than an end" (i-Tree 2008). The initial list produced by the Species Selector was subsequently paired down by first selecting only those species that were not sensitive to pollution and then cross-referencing the remaining species with the *Guide to Estimating Irrigation Water Needs of Landscape Plantings in California* (referred to as WUCOLS, the acronym for Water Use Classifications of Landscape Species) to ensure that the potential species were not invasive and required low to very low irrigation. This filtering process resulted in the five species listed in **Table A.1**. It should be noted that an additional resource available to help during species selection is the Federal Highway Administration guidance on near-road landscaping titled "Roadside Revegetation: An Integrated Approach to Establishing Native Plants."

TABLE A.1
CANDIDATE SPECIES LIST FOR DAVIS, CALIFORNIA

Botanical Name	Common Name	Irrigation Classification	Drought Tolerant	Foliage	Growth Rate Per Year
Pinus pinea	Italian Stone Pine	Low	Yes	Evergreen	25-40 inches
Pinus sabiniana	Digger/Foothill/Gray Pine	Very Low	Yes	Evergreen	28 inches
Celtis occidentalis	Northern/Common Hackberry	Low	Yes	Deciduous	12-18 inches
Quercus Suber	Cork Oak	Low	Yes	Evergreen	24 inches
Ulmus Pumila	Siberian Elm	Low	Yes	Deciduous	>18 inches

Note: Prioritized results from Species Selector v2.1. For our scenario the location was set to Davis, California, no height constraints were entered (the site does not present any height barriers such as overhead power lines), air pollutant removal was rated at 10 for all pollutants listed (carbon monoxide, ozone, nitrogen dioxide, particulate matter, and sulfur dioxide), low VOC emissions, wind reduction, and carbon storage were each set to 10, and the top 10 percent of results was selected for output.

From **Table A.1** it appears that *Pinus sabiniana* (**Figure 2.3**) could be suited for the example location since it is a coniferous evergreen that requires very little irrigation, is drought tolerant, and has a very fast growth rate. While the species in **Table A.1** might be appropriate choices, it is important to note that these species are a product of the filtering criteria employed and that other species could prove equally or more beneficial with differing assumptions, filters, and constraints. Most notably, the irrigation and drought tolerance criteria eliminated a large portion of evergreen conifers that have much denser canopies and higher leaf surface areas. The methodology employed behind **Table A.1** was simply for illustrative purposes. Ideally, species selection should be performed by a qualified arborist with localized species knowledge and with consideration of the optimization characteristics described in the literature.