PRACTICAL MITIGATION MEASURES FOR DIESEL PARTICULATE MATTER: NEAR-ROAD VEGETATION BARRIERS

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 complements the sound wall literature by assessing the benefits of vegetation screens near roadways; it was motivated by the potential for vegetation to reduction pollution and the ability to leverage existing state department of transportation standard operation procedures to install and maintain landscaping enhancements along roadways.

Methods: We reviewed sound wall literature and studies that explored the effect of vegetation on pollutant concentrations and identified key factors influencing the ability of trees to efficiently reduce particulate matter pollution. A conceptual dry deposition model was developed and incorporated in a spreadsheet tool. We then applied the tool to an elementary school case study site (Willett Elementary School; located near a freeway in Davis, California) to estimate the amount of particulate matter that might be removed by near-road vegetation.

Results: The effectiveness of PM removal via tree plantings depends on characteristics of the species chosen (e.g., foliage surface, canopy structure, and life span) and varies by particulate size. The case study showed that vegetation at the Willett Elementary School plot could be expected to remove approximately 120 kg/year of PM (about 0.04 $\mu g/m^3$ per second), which represented an estimated PM concentration reduction of approximately 4.6% per hour given the assumed mixing height and area. Leaf area index and dry deposition rate were key model parameters for modeling PM removal in this study. Further work is needed to better model and assess the interactions that take place between near-road pollutants and vegetative screens.

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

http://AQP.engr.ucdavis.edu/

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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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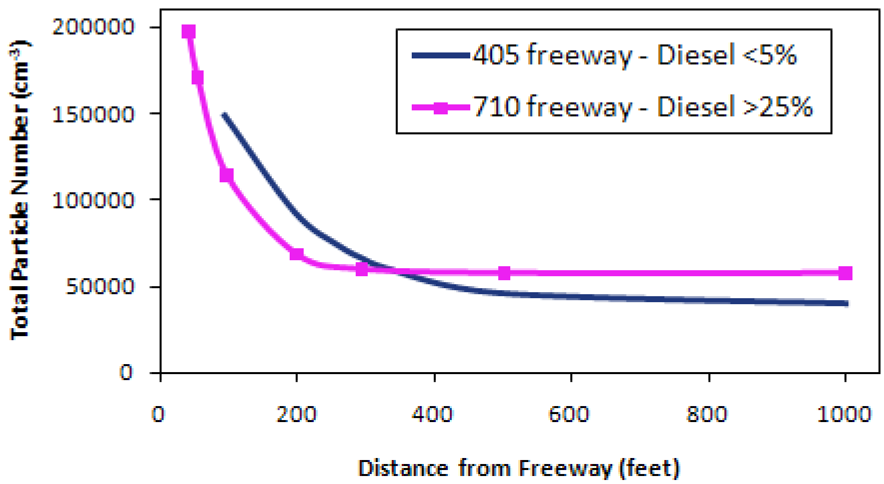
1. Introduction

In recent years there has been growing concern over sensitive near-road land uses (schools, day care centers, playgrounds, medical facilities, residences) and potential exposure to near-road pollutant concentrations, especially from freeways and other heavily traveled roads, since these concentrations tend to be elevated above background concentrations. For example, research by Zhu et al. (2002b) in the vicinity of the 405 freeway in Los Angeles, California found that particle number concentrations were 25 times that of background ambient concentrations. Recent studies by Zhou (2007) and Brugge (2007) have supported the relationship between mobile source pollutant concentration and distance from a roadway. This relationship is illustrated by **Figure 1.1**, using the Los Angeles 405 and 710 freeways:



Source: Reproduced from CARB (2005); originally sourced from Zhu et al.(2002a)

FIGURE 1.1: RELATIONSHIP BETWEEN POLLUTANT CONCENTRATION AND DISTANCE

Elevated particulate matter (PM) concentrations near roadways are of concern because PM has been linked to increased rates of mortality and morbidity (Samet, Dominici et al. 2000; Ostro, Broadwin et al. 2006). Recent literature indicates that $PM_{2.5}$ pollution has greater adverse health effects than PM_{10} and 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, pg 1). Diesel particulate matter, the control of which motivated this study, is comprised mainly of fine and ultrafine particles measuring less than 2.5µm. In April 2005, the California Air Resources Board (CARB) published the *Air Quality and Land Use Handbook: A Community Health Perspective*. The document found that proximity to freeways should be a consideration in the siting of sensitive land uses and issued an advisory recommendation to "avoid siting new sensitive land uses within 500 feet of a freeway, urban roads with 100,000 vehicles/day, or rural roads with 50,000 vehicles/day" (CARB 2005). While section 17213 of the California Education Code and section 21151.8 of the California Public Resources Code restrict the siting of new schools within 500 feet of a freeway, exposure at existing schools presents a significant challenge: "close to 10% of California public schools, enrolling 721,363 children (12.4% of students), are close to medium or high traffic volume [roads], defined as being within 150 m of a road segment with AADT [Average Annual Daily Traffic] of 25,000 or more vehicles" (Green, Smorodinsky et al. 2004, pg 4).

This study is part of a larger UCD research that has explored measures for reducing diesel particulate matter (DPM) emissions from transportation operations. *A Review of On-Road Vehicle Mitigation Measures* (Yura 2006) provided a literature review of mobile source control strategies with special emphasis on DPM. *What Affects Diesel Particulate Matter Emissions* (Houtte 2007) reviewed what is currently known about the variables and mechanisms that affect DPM emissions and identified implications for transportation facility design and operation. The following is a summary of the measures suggested by Houtte (2007) and Yura (2006):

- Improve traffic flow
- Reduce number of stops and sharp turns
- Reduce number and slope of uphill grades
- Enforce speed limits
- Impose weight restrictions
- Limit multiple trailers
- Introduce new vehicle standards
- Retrofit existing vehicles
- Use fuel additives
- Improve vehicle inspection and maintenance programs
- Increase use of alternative fuel vehicles
- Implement fleet retirement/replacement programs
- Install High Occupancy Vehicle (HOV) lanes
- Implement congestion pricing/establish toll roads
- Implement ramp metering
- Enhance roadside assistance
- Reroute trucks
- Reduce truck or vehicle idling

State and regional agencies currently employ most of these measures; however, the primary intent of currently implemented measures is to reduce traffic congestion, improve safety, and reduce emissions of carbon monoxide (CO) and pollutants contributing to ozone formation (hydrocarbons and oxides of nitrogen, or NOx); these measures are typically not focused on reducing PM emissions or exposure. In addition, many of these measures are best applied on a regional scale. The intent of this study was to assess a potential approach to mitigate DPM emissions at the project site level. In addition, key consideration was given to the implementation of mitigation where existing institutional infrastructure could be readily utilized.

While Houtte (2007) and Yura (2006) identified regional transportation system management measures that could reduce emissions, few feasible reduction options exist at the project site level. As suggested by the CARB *Air Quality and Land Use Handbook*, a buffer of at least 500 feet would be beneficial in reducing schoolchildren's exposure to near-road pollutant concentrations; however, approximately 10 percent of California public schools are already sited within this buffer (Green, Smorodinsky et al. 2004). For those schools currently sited within the recommended buffer, filtration has been suggested as a solution to reducing exposure. Emerging interest in heating, ventilation, and air conditioning (HVAC) systems as a viable reduction measure has resulted in real-world implementation efforts. A 2005 court settlement agreement between the Sierra Club and Nevada Department of Transportation (NDOT)/Federal Highway Administration (FHWA) required mobile source air toxic (MSAT) monitoring and HVAC filtration at several schools along US 95 in Las Vegas, Nevada to determine removal efficiencies of new filtration systems. Two schools were fitted with "minimum efficiency reporting value" (MERV) 11-rated filters and one school with a MERV 14-rated filter. MERV 11 and MERV 14-rated filters arrest particulates between 1.0-3.0μm and 0.3-1.0μm, respectively. According to one study, adding the new HVAC filtration systems significantly reduced indoor concentrations of black carbon (BC) (Roberts and McCarthy 2008). Black carbon is a component of DPM that is considered a surrogate to the measurement of DPM. While these initial results are encouraging, the study lists significant gaps that must be addressed prior to the generalization of results. One significant limitation of the Nevada study is that the filtration systems deployed (MERV 11 and 14) did not filter ultrafine particulates (less than 0.1μm). As mentioned previously, ultrafine particulates constitute a majority of particle number concentrations in urban environments. In order to effectively filter these particles, high efficiency particulate air (HEPA) and ultra-low particulate/penetration air (ULPA) technologies that are usually applied in specially designed environments (such as clean rooms, MERV 17-20) are required along with high-efficiency pre-filters and charcoal filters. In addition, the entire building must be managed as a system with "continuous positive pressure to prevent infiltration" of unfiltered outside air (OEHS 2008). According to the California Office of Environmental Health and Safety, the cost to upgrade the top ten schools most at risk from air pollution to MERV 10 would be $1 million, to MERV 14 at the end of the HVAC system life would be $5.1 million beyond the cost of the basic system, and to MERV 14 immediately would be $31.7 million for a total system replacement. The costs, technological requirements, and the questionable feasibility of managing school buildings as a system limit the applicability and effectiveness of upgraded filtration systems in schools.

A potential alternative to mechanical filtration is the use of trees or other vegetation as a natural filtration system. For example, the Sacramento Metropolitan Air Quality Management District recommends, "Projects that propose sensitive receptors adjacent to sources of particulate matter such as freeways, major roadways, rail lines, and rail yards should strongly consider tiered plantings of redwood and/or deodar cedar in order to reduce toxic exposures," although the agency also noted that further research was needed to examine the effectiveness of vegetative screens (SMAQMD, 2009; pp. 21-22). This study further assesses vegetative screens as a near-road mitigation option.

A large body of literature exists (mainly from the urban forest sector) regarding the filtration of ambient air pollution by the urban forest. **Table 1.1** summarizes the filtration factors and their impacts as described in example literature covered as part of this review. The table shows that there are several key factors that influence the ability of trees to efficiently reduce particulate matter pollution. The effectiveness of PM removal can be increased if species with fine, complex foliage structure (K. Paul Beckett 2000), such as conifers, are chosen. Additional tree characteristics can also contribute to the effectiveness of PM removal for certain particulate size ranges. Plantings that maximize surface area (leaf, bark, and shoot) and provide stickier surfaces increase coarse PM capture; plantings that have greater surface area and allow for significant in-canopy airflow are more efficient scavengers of fine and ultra fine PM due to the turbulence created by the complex foliage structure (Gallagher, Beswick et al. 1997; Beckett, Freer-Smith et al. 1998; McDonald, Bealey et al. 2007).

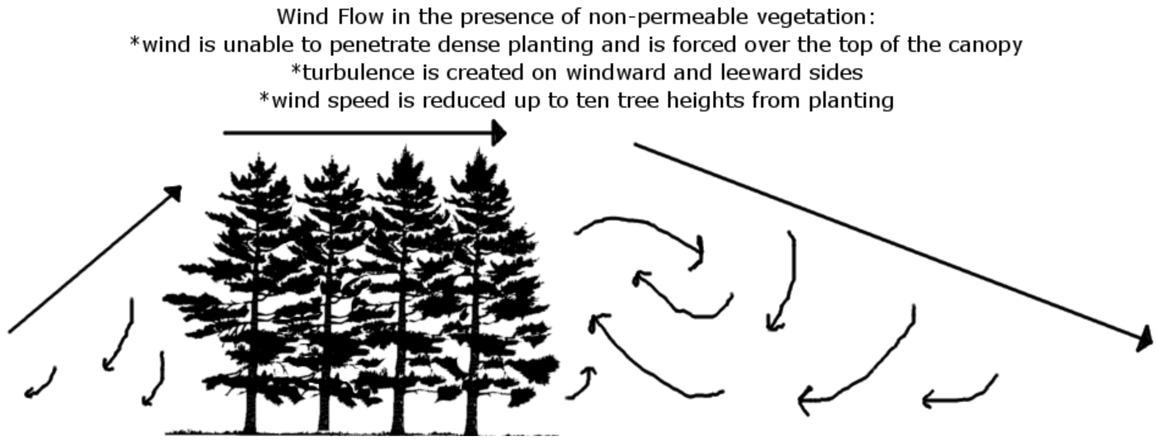
TABLE 1.1
FILTRATION FACTORS AND IMPACTS

Factors	Impact
Wind Speed	Highly correlated with deposition rate[17]
	Wind speed and flow inside tree canopy affected by leaf area density: as density increases, wind speed decreases[33]
	Wind fluctuations strongly increase sub-micron (d_p<1µm) particle deposition[9]
	Below 1 m/s, 30-80% of very fine particles (0.09µm<d_p<0.26µm) removed[4]
	Vegetation with high surface area adequate to slow wind maximizes PM removal rate[4]
Vegetation Characteristics	Canopies that have high leaf surface area and allow for significant airflow increase deposition of small particles[9]
	Pollutant uptake decreases as canopy decreases[35]
	Trees create more turbulent mixing than shorter vegetation[14]
	Tree bark can be a significant PM sink[7]
Species Selection	Long-lived, healthy, hardy trees that have high surface area are more beneficial[21]
	Evergreen species are beneficial since PM removal occurs mostly during in-leaf season[20]
	Conifers capture larger amounts of PM than broad-leaved trees on a per tree basis[14]
	Select low VOC emitting trees[25]
	Trees with the largest surface area have the greatest PM removal potential[19]
Foliage Characteristics	Needle-shaped leaves more effective than flat-shaped leafs for PM capture[14]
	Increased stickiness facilitates greater coarse PM capture[2]
	Increased roughness (creates more turbulence) facilitates greater fine PM capture[2]
Particle Diameter (d_p)	Diffusion accounts for most of PM removal for d_p<0.1µm[14]
	Interception and impaction important for PM where 0.1<d_p≤10µm[14]
	Gravitational sedimentation effective for PM where d_p>8.0µm[14]
	As particle diameter decreases below 0.3µm, deposition rate increases Deposition rate increases as particle diameter increases above 0.3µm[8]
	Smallest particles (d_p=0.001µm) last for about 10 minutes in the atmosphere and then agglomerate to form accumulation size particles (0.05<d_p<2.0µm)[31]
	Deposition efficiency (diffusion) increases as particle diameter decreases[9]
	Impaction efficiency increases as deposition rate increases[19]
Plot Location	Greater particulate removal at more polluted sites[8]
	PM removal effectiveness greatest when trees are close to the pollutant source[2]

Sources: See "Summary of Key Literature" table in Appendix A.

2. Conceptual Analysis

A tree planting configuration can have significant effects on wind flows. The alteration of wind flows near the planting depends on many factors. For instance, a dense configuration can have a similar effect as a sound wall on wind flows. **Figure 2.1** illustrates wind flow in the presence of a non-permeable vegetation screen.

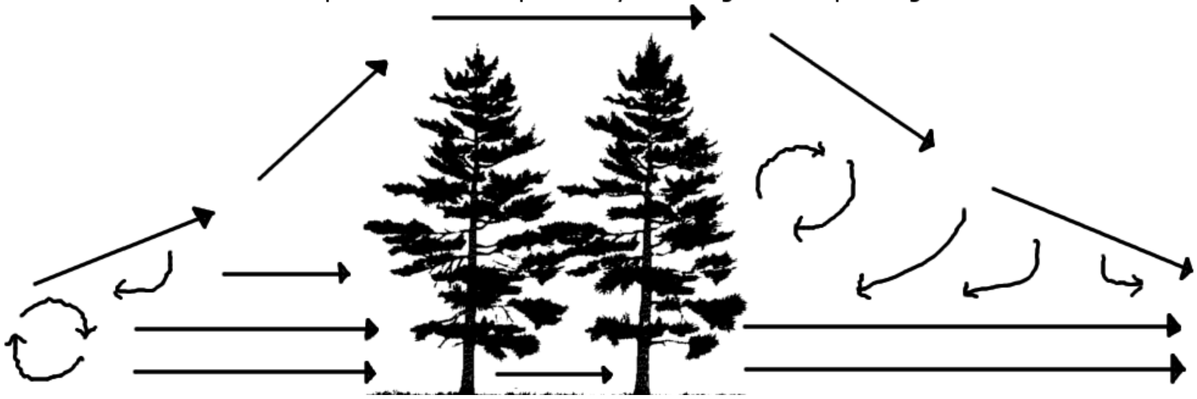


Source: Gardiner et al. (2006)

FIGURE 2.1: WIND FLOW IN THE PRESENCE OF NON-PERMEABLE VEGETATION

The vegetation configuration in Figure 2.1 effectively acts similar to flows around sound walls. Some studies have explored the effect of a sound wall on pollutant concentrations (Nokes and Benson 1984; Lidman 1985; Bowker, Baldauf et al. 2007). While these studies found that a sound wall acts to increase concentrations near the windward (upwind) side of the wall and to decrease concentrations near the leeward (downwind) side of the wall, Nokes and Benson (1984; pg. 12) concluded that "…no significant net change in CO concentrations at residential receptors and public facilities can be attributed to the presence of a sound wall." Bowker et al. (2007) analyzed the effects of a six-meter high sound wall (located 12 m away from the road) on near-road pollutant concentrations and found that while concentrations in the lee of the sound wall were reduced by approximately 60 percent (as compared to concentrations in the absence of a sound wall), concentrations where the pollutant plume reattached were approximately 35 percent higher (as compared to concentrations in the absence of a sound wall). The six-meter sound wall effectively acted to: (1) reduce pollutant concentrations up to about 80 meters behind the wall, (2) increase pollutant concentrations beyond 80 meters behind the wall relative to what they would have been at those locations without the wall, and (3) increase pollutant concentrations at the sides of the sound wall (lateral transport of pollution to the edges of the barrier). There are tradeoffs between reducing or eliminating pollutant concentrations immediately adjacent to a road, and increasing pollutant concentrations further downwind and to the sides of a barrier. Barriers shift receptor locations, and shift the degree of exposure. Bowker et al. observed that concentrations downwind of a barrier (at the point of the plume reattachment) were lower than the concentrations that would occur immediately adjacent to the road in the absence of a barrier.

Tree plantings can also act as windbreaks if they are planted in a semi-permeable configuration. **Figure 2.2** illustrates wind flows in the presence of a semi-permeable vegetation screen.



Source: Gardiner et al. (2006)

FIGURE 2.2: WIND FLOW IN THE PRESENCE OF SEMI-PERMEABLE VEGETATION

Figure 2.2 shows that tree plantings can act as windbreaks by sheltering the leeward area behind the trees and can create turbulence that encourages deposition to the vegetation. Gardiner et al. (2006) reports that semi-permeable (40-60 percent porosity) tall plantings that are uniform in height can shelter a downwind area that extends up to 30 times the vegetation height. Uniform height of the vegetation is important to particulate filtration since it helps to direct air through the trees, providing an opportunity for deposition by impaction and diffusion. While not easily quantifiable, it is apparent that the sheltering effect of tree plantings is beneficial to leeward pollutant concentrations since wind flows near vegetation behave similar to flows reported by Bowker et al. (2007) for a sound wall. Although wind flows near sound walls and tree plantings have been shown to be similar, tree plantings are potentially more beneficial to ambient particulate matter reduction since trees allow for airflow through the canopy and promote deposition to vegetation surfaces.

As illustrated by **Figure 2.3**, deposition to the canopy occurs in three main ways, each a function of particle diameter (d_p): Brownian diffusion dominates the transport across the boundary layer for $d_p \leq 0.1\mu m$, impaction and interception is important for $0.1\mu m < d_p \leq 10\mu m$, and gravitational sedimentation is effective for $d_p > 8.0\mu m$ (K. Paul Beckett 2000).

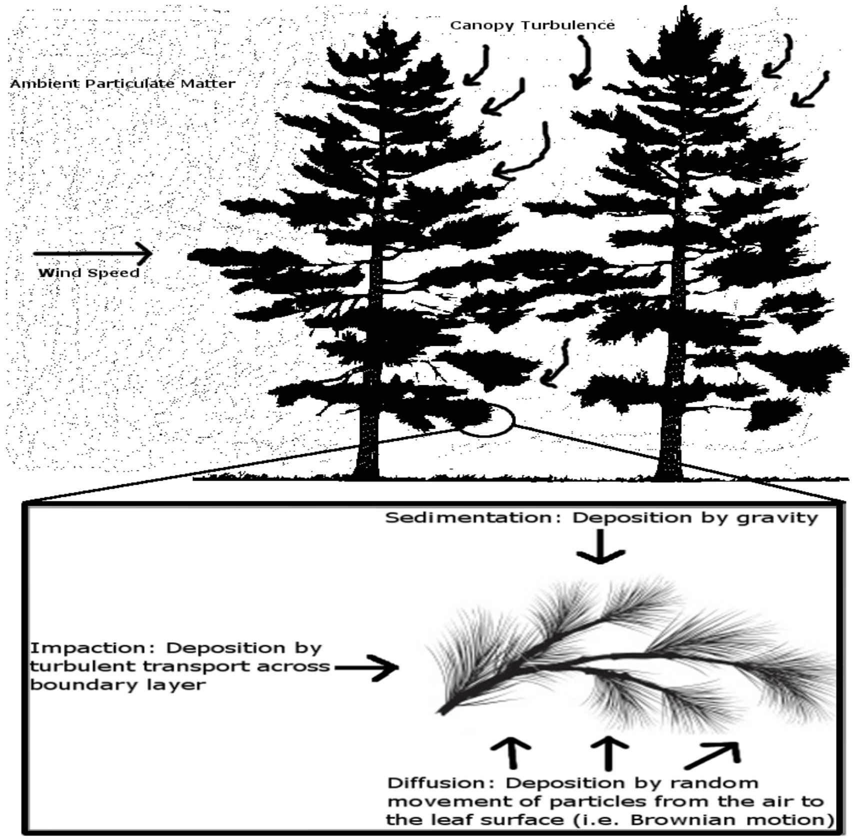


FIGURE 2.3: DRY DEPOSITION ILLUSTRATION

In an urban environment, ultrafine particles (particle diameter less than 0.1µm), a large fraction of which originate from motor vehicles, constitute approximately 80 percent of the particle number concentration (Zhu, Hinds et al. 2002b). Deposition to trees by diffusion is very efficient in this particulate range and Cahill (2008) found that redwood vegetation removed 79 percent of 0.17µm diameter particulate matter in a wind tunnel experiment. Data from the wind tunnel experiment and deposition rate data from Seinfeld and Pandis (1998) was used by Cahill to estimate PM removal in the ultra fine range ($d_p \leq 0.1$µm), with the results presented in **Table 2.1**.

TABLE 2.1
ESTIMATED PM REMOVAL BY REDWOOD VEGETATION

Particle Diameter (µm)	Deposition Rate (cm/s)	Percent Removal by Redwood Vegetation
0.10	0.0125	83%
0.075	0.015	86%
0.050	0.02	90%
0.035	0.045	95%
0.015	0.25	99%

Note: Percent removal are estimations by Cahill (2008) based on measured wind tunnel data for dp=0.17µm and deposition velocities from Seinfeld and Pandis (1998).
Source: Cahill (2008)

In summary, from the 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.

3. Methodology

In order to illustrate how the literature findings might apply to real-world situations, we chose to apply key concepts from the literature (listed in **Table 1.1**) to a school that was located near a freeway and to quantify the potential for reduction from an urban planting. Willett Elementary School, located at 1207 Sycamore Lane, in Davis, California, abuts Highway 113 (33,000 annual average daily trips) at approximately 60 m downwind (east) as shown in **Figure 3.1**. The proximity of the school to Highway 113 places it well within the 500 foot buffer zone discussed by Green et al. (2004) and CARB (2005) and thus provides for a suitable real-world application. We evaluated the effects of a hypothetical tree planting area of approximately 30 m by 200 m for this particular site. Based on information obtained from the literature review – see, for example, Seinfeld and Pandis (1998) – a particulate matter deposition model was formulated and applied to the 30 m by 200 m plot.

Source: Google.com

FIGURE 3.1: AERIAL VIEW OF WILLETT ELEMENTARY SCHOOL

Species Selection

Literature indicates (**Table 1.1**) 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 3.1**. 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 3.1
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 3.1** it appears that *Pinus sabiniana* (**Figure 3.2**) and/or *Pinus pinea* (**Figure 3.3**) could be suited for the example location since both are coniferous evergreens that require very little irrigation, are drought tolerant, and have very fast growth rates.

Source: Google.com
FIGURE 3.2: *PINUS SABINIANA*

Source: Metrotrees.com
FIGURE 3.3: *PINUS PINEA*

While these species 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 3.1** 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 (**Table 1.1**). While species selection is an integral part in the reduction of ambient PM, the approach (the one presented in this paper) to estimating vegetation's ability to remove PM is more dependent on the division and genera of the tree than the species. The limited availability of species-specific leaf surface area measurements results in the need to use averages for a wide range of species within a division. The approach outlined in this paper and illustrated later in this discussion (**Figure 3.4**) employs a leaf surface area based on an average for trees in the division Pinophyta (also known as Coniferae) and genera classified as evergreen since the literature suggests that these types of trees are more efficient scavengers of PM.

Dry Deposition Model Formulation

In order to estimate the PM removal potential of the example planting, we employed a dry deposition model that assumes the flux (the rate of flow of particulate matter) is directly proportional to the concentration and the dry deposition rate.

$$F(d_p) = C(d_p)*V_d(d_p) \quad (1)$$

Where:

F represents the vertical flux in units $\mu g/m^2$ per second
C represents the concentration in units $\mu g/m^3$
V_d is the dry deposition rate in units m/s

All of the terms in the model are a function of d_p, the particle diameter (μm). To estimate the amount of PM removed (PM_r), the flux calculation is multiplied by the leaf surface area (LSA) of the planting:

$$PM_r = F(d_p)*LSA \quad (2)$$

The LSA is in m^2, $F(d_p)$ is in $\mu g/m^2*s$, and PM_r is in µg/s. **Figure 3.4** presents a flow diagram illustrating how the conceptual model can be used to estimate PM removal. We employed the model to simulate the effects of a 30 m by 200 m planting area for the Willett School. As shown in **Figure 3.4**, the model user is required to input the following parameters:

- starting concentration (PM_{10} concentrations before interception by the vegetative barrier)
- planting area (length and width of the vegetative screen site, in m^2)
- percent coverage (inverse of the vegetative screen's porosity)
- tree height (this parameter is optional; 15 meters is assumed as a default)

For the Willett School illustration, we used a starting PM_{10} concentration equal to the 2006 annual average for an air quality monitor (the Woodland-Gibson Road monitor) located approximately 8 miles north of the school site along Highway 113. Although the Woodland-Gibson PM_{10} concentration may have had numerous sources (background plus site specific), for purposes of this illustration we treated the PM_{10} value as if it originated entirely from diesel exhaust emitted on Highway 113. This enabled us to hypothesize the effect of the vegetative barrier on a starting PM_{10} concentration linked to values observed in the area. We distributed the PM mass concentration according to percentages from diesel emissions profiles reported by Norbeck et al. (1998a). Diesel PM accounts for approximately 70 percent of vehicular traffic cancer risk and diesel profiles are similar to gasoline emission profiles (Norbeck, Durbin et al. 1998b; CARB 2005). It should be noted that the percentages do not sum to one since there is a small portion of emitted particles in the $d_p > 10\mu m$ range. The particles in this range were not included in the calculation because gravitational sedimentation is largely responsible for deposition in this range and the presented model does not fully account for this process; the model only accounts for gravitational sedimentation for particles in the range $8.0\mu m < d_p \leq 10\mu m$. In addition, since the $d_p > 10\mu m$ range constitutes a very small percentage of the overall concentration, its inclusion would not appreciably affect the results. The deposition rate for $d_p \leq 1.0\mu m$ was taken from Cahill (2008) while the values for the remaining particle diameters were taken from Lorenz and Murphy (1989). The flux was calculated by simply multiplying the values for deposition rate and concentration together. The last two inputs required from the user are percent coverage and planting area. The percent coverage is multiplied by the planting area to obtain the total ground area that would be covered by the tree canopy (referred to as the canopy projection area, CPA). The CPA is then related to the leaf surface area by multiplying the CPA by the single-sided leaf area index (LAI), assumed to be 6 (Nowak, Crane et al. 2006). The leaf surface area (CPA multiplied by LAI) is then multiplied by the flux to estimate PM removal. To estimate PM removal in $\mu g/m^3$, pollutant removal is simply divided by the volume of the planting (the plot area multiplied by a default average tree height, which in our case study is assumed to be 15 m). The concentration reduction is calculated according to the following equation:

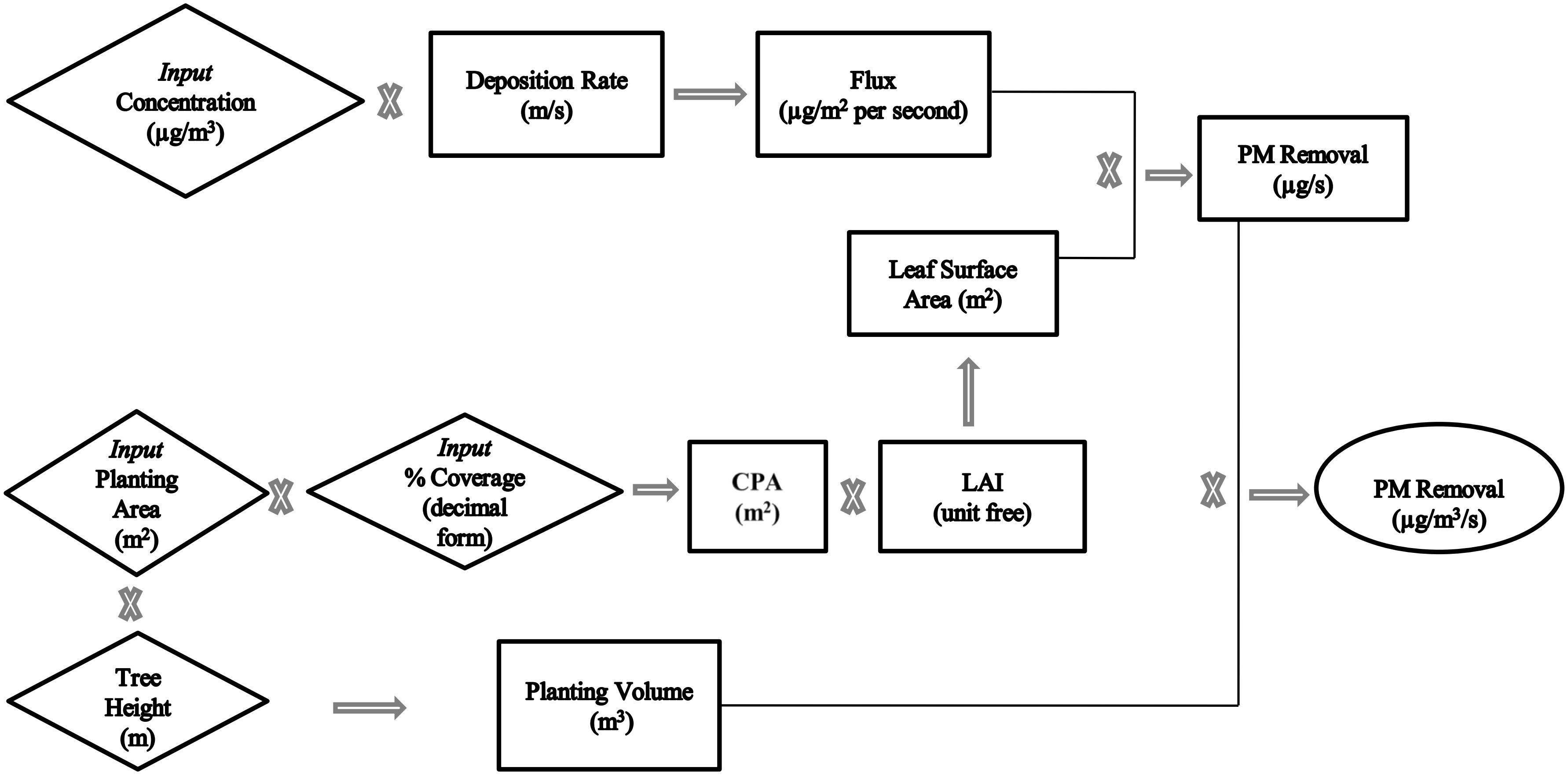
$$R = A/(A + C) \qquad (3)$$

Where:

R is concentration reduction (in percent)

A is amount of PM removed by the vegetative screen in kilograms (kg)

C is starting concentration in kg; obtained by multiplying concentration (kg/m^3) by volume of the area being studied (m^3)



Canopy Projection Area – the area of ground covered by the canopy
Concentration **–** the near-road PM10 concentration as measured or estimated at the site (ambient concentrations can be used in place of near-road)
Deposition Rate **–** the rate at which particles deposit on a surface
Flux **–** the rate of flow of particulate matter
Planting Area **–** the rectangular area (length multiplied by width) defining the boundaries of the trees
% Coverage **–** the percentage of the planting area covered by the tree canopy
LAI **–** the leaf area index is the ratio of the single-sided leaf surface area to the canopy projection area
Leaf Surface Area **–** is an estimation of the single-sided leaf surface area based on the amount of leaf area (LAI) per unit of ground covered by the canopy (CPA)
Tree Height **–** the average height of the trees as measured from ground level to top-of-canopy
Planting Volume **–** a box that encompasses the total volume of the planting area (defined by the length and width of the planting area and the tree height)

FIGURE 3.4: MODEL FLOW DIAGRAM

4. Recommendations and Future Research

The dry deposition model presented in this paper is based on a key assumption of a well-mixed boundary layer, which is appropriate on a regional scale. In near-road applications such as the Willett Elementary School scenario, the boundary layer is likely not well-mixed due to non-uniform complex flow characteristics associated with the unique environment. To accurately capture near-road conditions, geometry, land use characteristics, traffic flow, pollutant emissions, meteorological conditions, and wind flow features must be adequately considered. Models that attempt to account for complex near-road conditions have been introduced within the past decade and are being studied and refined as computing power continues to improve. These models use computational fluid dynamics (CFD), a way in which to solve and analyze problems involving airflow over objects, to predict wind flows in the near-road environment. Once wind flows have been predicted, dry deposition models can be used to estimate particulate removal. One key difference between CFD models and the presented model is that the presented model relies on leaf surface area as observed from the top of the canopy. CFD models model wind flow from a horizontal perspective (as the wind flows from the road through the vegetation) and thus require a leaf surface area as observed from the side of the canopy. Because the amount of particulate matter removed is a function of the available leaf surface area, accurate leaf surface area assumptions are central to the estimation of PM removal. We based the leaf surface area assumptions in this paper on literature that assessed worldwide measurements from 1932 to 2000; these measurements relate leaf surface area (as observed from the top of the canopy) to ground area covered by the tree canopy (Scurlock, Asner et al. 2001). Unfortunately, we did not find and are not aware of any literature relating leaf surface area as observed from a horizontal perspective. Accordingly, it is unclear how to relate percent coverage in the dry deposition model to percent coverage in a horizontal perspective model (such as a CFD model). Percent coverage in CFD models is heavily dependent on canopy distribution and trunk dimensions and research is needed to find averages for major species. Additional research on leaf capture efficiency (Cp) is also needed.

While there is general agreement in the literature about the capture efficiency of leaves, Cp is dependent on meteorological and environmental conditions. The findings of Cahill (2008) suggest that more research on Cp in the near-road environment under complex wind flow and non-uniform pollutant distribution is needed. However, in order to address capture efficiency, details of pollutant transport through different vegetation configurations must be further studied. Semi-qualitative information from available sound wall and wind break literature (refer to the Conceptual Analysis section) can be applied to non-permeable and semi-permeable plantings, but more detailed modeling is needed in order to accurately analyze pollutant transport and deposition in a variety of near-road planting configurations.

The use of a computational fluid dynamics model would resolve many of the uncertainties associated with the application of the presented dry deposition model to near-road environments. Even with the uncertainties of the presented model, existing literature supports the idea that there are likely to be pollution reduction benefits associated with planting trees between high volume roads and sensitive land uses. In addition, implementation of tree plantings has the ability to mitigate roadway noise and improve visual aesthetics for near-road communities, and can utilize existing infrastructure employed by state departments of transportation and other agencies charged with maintaining existing landscaping.

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Appendix A: Summary of Key Literature

SUMMARY OF KEY LITERATURE			
Key Literature	**Summary**	**Key Findings**	**Air Quality Benefit**
(Scott, McPherson et al. 1998)	Dry deposition model employed to estimate air pollutant uptake by Sacramento, California's urban forest (19,058 total hectares in study area)	• 1,457 metric tons of pollutants absorbed annually • Implied value of US$28.7 million • Daily PM_{10} uptake during growing season approximately 2.7 metric tons per day • Pollutant uptake rates decreased with canopy decrease	Uptake of 2% of daily anthropogenic emissions for Sacramento County
(Lovett 1994)	Summarizes current understanding of deposition processes	• Particles > 2µm diameter deposited efficiently by gravitational sedimentation • Submicrometer particles are inefficiently deposited • "Big Leaf" models treat surface as single layer (big leaf)	
(Nowak, McHale et al. 1998)	Uses UFORE application from iTree to estimate pollution removal by trees in Philadelphia, Pennsylvania	• Trees remove gaseous pollutants primarily by stomatal uptake; particulate matter primarily by dry deposition • Vegetation is temporary retention site for particulate matter	Average air quality improvement for PM_{10} was 0.72%
(K. Paul Beckett 2000)	Quantification of PM pollution reduction by pine, cypress, maple, whitebeam, and poplar trees	• Finer, more complex foliage structure of conifers responsible for greater PM capture effectiveness • Trees create more turbulent mixing than shorter vegetation • Brownian diffusion accounts for most of PM removal where $D_p<0.1\mu m$ • Interception and impaction important for PM where $0.1<D_p\leq10\mu m$ • Gravitational sedimentation effective for PM where $D_p>8.0$ µm	
(Nowak, Crane et al. 2006)	Modeling study estimating pollution removal by urban trees in the United States	• Pollution removal affected by tree cover, pollution concentration, length of in-leaf season, precipitation, and other factors • Total air pollution removal in US: 711,000 metric tons valued at $3.8 billion • Total PM_{10} removal in US: 214,900 metric tons	Estimated percent air quality improvement for PM_{10} ranged from 0.1-3.5%
(McPherson, Simpson et al. 1999)	Benefit-cost analysis of Modesto's urban forest	• Urban forest air pollution uptake totaled 143 metric tons valued at $1.4 million • PM_{10} uptake accounted for $272,000 • Air pollution benefits can be diminished due to replacement of large-statured trees by medium-statured trees and short-lived species	
(Freer-Smith, El-Khatib et al. 2004)	A comparison of deposition velocities and capture efficiencies of species typical of semi-arid areas	• Ficus nitida (weeping fig) has good PM uptake and is drought tolerant • Tree bark can be a significant PM sink • Deposition velocities and capture efficiencies greater to leaves than to stems for species that have small leaves and large stem diameters	

Summary of Key Literature			
Key Literature	**Summary**	**Key Findings**	**Air Quality Benefit**
(McPherson, Nowak et al. 1994)	A three year study of Chicago's urban forest to quantify the effects of urban vegetation on the local environment	• The higher the boundary layer, the less effective trees are in reducing overall air pollution concentrations • Removal occurred mostly during in-leaf season • Trees larger than 46 cm DBH accounted for 83% of PM_{10} removed on a per tree basis • PM removal of 28.3 kg/ha/yr in study area (Chicago, Cook County, and DuPage County)	Daily PM_{10} reduction: **Study area** Maximum = 0.5% Average = 0.4% **100 percent forested area** Maximum = 2.5% Average = 2.1%
(Freer-Smith, Beckett et al. 2005)	Derivation of deposition velocities for field grown trees: Whitebeam, Field Maple, Poplar, Corsican pine, and Leyland cypress	• Conifers have been shown to capture larger amounts of particulate matter than broadleaved trees • Deposition velocity increases as particle diameter decreases • Corsican pine showed significantly more ultra-fine foliage capture and both coniferous species captured the largest mass of ultra-fines • Particle uptake governed by tree structure, wind speed, and particulate concentration • Greater particulate uptake at more polluted sites, especially for conifers and $PM_{2.5}$ • Ohm's Law analogy for calculation of deposition velocity is more relevant to the flux of smaller particles by Brownian motion than to uptake of larger particles (> 1µm) by impaction	
(Lorenz and Murphy 1989)	A study of dry deposition of particles to a pine plantation	• Leaf area index (LAI) of pine plantation varied from 6 (winter) to 12 (end of growing season) • Deposition velocity highly correlated with either wind speed or friction velocity	
(Nowak, Crane et al. 2006)	Details the effects of urban forests on air quality in 13 US cities, Beijing, China, Toronto, Canada, and Fuenlabrada, Spain	• PM_{10} removal ranged from 6.6 to 27.5 grams per year per square meter of canopy cover • In the US, urban forests are estimated to remove about 711,000 metric tons of air pollution per year at an estimated value of $3.8 billion • "Strategic tree planting" can be incorporated into State Implementation Plans to help meet EPA standards	Average PM_{10} improvement: **Daytime in-leaf season among 13 US cities:** 0.64% **100% tree cover short-term (1 hour):** 8.3%
(QUARG 1996)	A review and analysis of the sources of particulate matter and the factors influencing its atmospheric behavior	• Smallest particles (0.001µm in diameter) last for about 10 minutes in the atmosphere and then agglomerate to form accumulation size particles (0.05-2.0µm in diameter) • A portion of particles enter the troposphere and are widely dispersed, with residence times approaching one year	
(Ruijgrok, Tieben et al. 1997)	A comparison of model and experimental results of dry deposition of particles to a forest canopy	• Turbulent transport affected by surface roughness and canopy height • Canopy wind profile affected by leaf area density	

Summary of Key Literature			
Key Literature	**Summary**	**Key Findings**	**Air Quality Benefit**
		• Interception efficiency affected by collector dimensions in canopy • Impaction efficiency affected by vegetation created drag • Brownian diffusion affected by dimension of large collectors and vegetation drag	
(Gallagher, Beswick et al. 1997)	Measurements of sub-micron aerosol deposition to a forest and their implications	• Deposition of particulate matter governed by efficiency of transport across boundary layers • Efficiency of transport across boundary layers a strong function of particle diameter • Brownian diffusion dominates for particles less than 0.2µm diameter • Inertial mechanisms (impaction, interception) begin to dominate in 0.2-0.5µm • Sedimentation dominates large particles (greater than several microns) • Sub-micron particle deposition increases strongly with increasing wind speed fluctuations • Deposition of small particles influenced by canopy that is complex enough to allow for significant in-canopy flow	
(Nowak and Crane 1998)	The effects of urban trees on air quality	• Air quality improves with increased percent tree cover and decreased boundary-layer heights • Strategies to improve air quality: increase number of healthy trees, sustain existing tree cover, use low VOC emitting trees, sustain large long-lived trees that require low maintenance, supply ample water to trees, avoid pollutant sensitive species, plant evergreen trees for PM reduction	New York average PM10 improvement: **Daytime in-leaf season:** 0.47% **100% tree cover short-term (1 hour):** 13%
(Cahill 2008)	A wind tunnel vegetation study for redwood, deodar, and live oak	• Diesel exhaust mass almost entirely below 0.25µm in diameter, with many of the most toxic polycyclic aromatic hydrocarbons below 0.10µm in diameter • Diffusion to surfaces efficient for very fine and ultra fine particle diameter range • Vegetation able to remove 30-80% of very fine particles at wind velocities below about 1.0m/s • Effectiveness of PM removal greatest at low wind speeds and when trees are very close to the pollutant source • Vegetation with high surface area adequate to slow, but not stop, wind will maximize particle removal rates since diffusion scales by the amount of time the particles are close to a surface • Redwood and deodar were the most effective at PM removal	79-99% removal for particles 0.17µm to 0.015µm in diameter by redwood vegetation
(Belot 1994)	A wind tunnel study to determine the deposition	• Leaf deposition rates are nearly independent of particle diameter for particles in the range	

Summary of Key Literature			
Key Literature	**Summary**	**Key Findings**	**Air Quality Benefit**
	of particles on evergreen species: Norway spruce, Scots pine, and Holm oak	0.2μm-1.0μm • A dense plantation decreases wind speed and deposition rate • For particles greater than 1μm in diameter, the deposition rate increases rapidly with particle size and wind speed	
(McDonald, Bealey et al. 2007)	An estimation of the potential of urban tree plantings for the mitigation of PM_{10} concentrations	• As efficiency of impaction increases, deposition velocity increases • Forested areas have higher deposition velocities • West Midlands PM_{10} removal rate of 4.6 g/m^2 • Glasgow PM_{10} removal rate of 4.4 g/m^2 • Must consider BVOC emissions, pollen release, and accumulation of contaminates in soil below tree in benefit assessment of trees • Single trees and edge trees collect particles more efficiently than canopy trees • Trees with the largest surface area have the greatest potential to remove PM	**West Midlands:** A 25% planting area would result in a 19% increase in deposition and an average total PM_{10} concentration reduction of 3% **Glasgow:** A 25% planting area would result in an average total PM_{10} concentration reduction of 0.4%
(Beckett, Freer-Smith et al. 1998)	A review of the role of vegetation and urban woodlands in reducing particulate pollution	• Forest canopies more effective than other vegetation types at capturing particles due to turbulence created by greater surface roughness • Effectiveness of particle uptake is increased by rough or sticky surfaces • Increased stickiness facilitates greater coarse particle capture • Increased roughness facilitates greater fine particle capture • Most effective use of trees as particulate filters is in plantings as close as possible to the source	

Appendix B: Case Study Results and Discussion of Key Dry Deposition Model Parameters

Example PM_{10} Removal Estimates for the Willett School Case Study

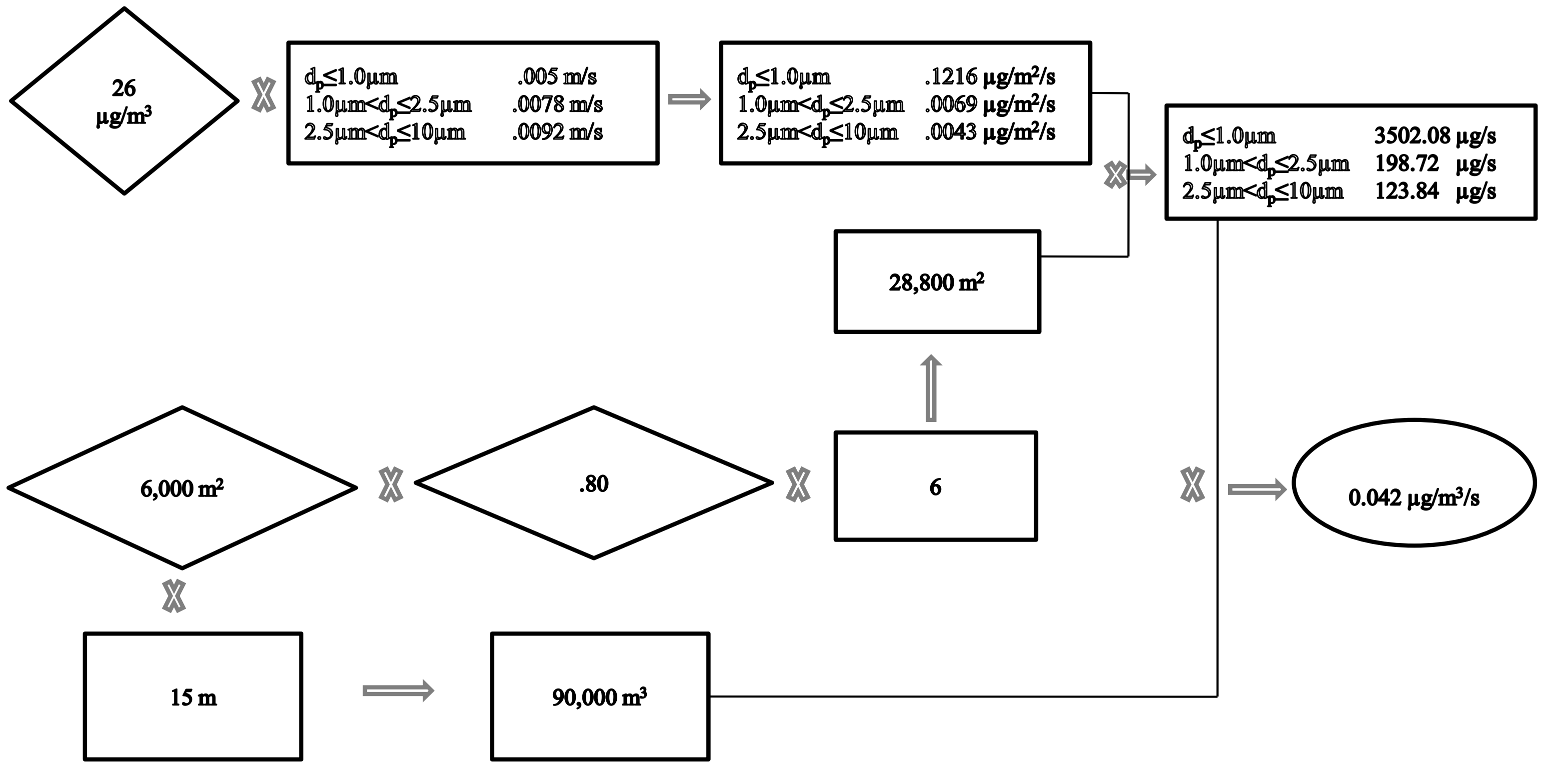
Following the methodology described in the paper along with the inputs and data shown in **Figure B.1,** the Willett Elementary School plot could be expected to remove 0.042 µg/m^3 per second or 120.65 kg/year for an estimated PM concentration reduction of approximately 0.16% per second and 4.6% per hour. In interpreting the meaning of the percent concentration reduction, it is necessary to consider the appropriate box size (volume of air). **Table B.1** summarizes the effect of box size on concentration reduction for the Willett School example. It should be noted that the appropriate relative reduction for the Willett School application is 4.6% since it takes into account the proper mixing height (the mixing height is the height to which the air near the earth's surface is well mixed due to turbulence caused by the interaction between the surface and the atmosphere) and land area.

TABLE B.1
EFFECT OF BOX SIZE ON RELATIVE REDUCTION

Box Area	Time Period	Box Size (volume of air)	Mixing Height	PM_{10} Reduction
Tree Planting	1 second	90,000 m^3	15 m	0.16 %
Tree Planting	1 hour	90,000 m^3	15 m	85 %
Willet Elementary School (School + Planting)	1 hour	11,000,000 m^3	250 m	4.6 %

Note: The 4.6% reduction is based on the dry deposition model, which accounts for the vertical particulate flux; further work is needed to establish PM removal rates for near-road environments.

The 0.16% reduction is based on a box size of 90,000 m^3 that was assumed to be confined to the immediate edges of the plot area and height and did not consider the air beyond or above. For the Willett School example, the concentration reduction per hour would be 85% (box size equal to 90,000 m^3); however, it is important to note that the 85% reduction should not be directly applied to the Willett School example as the box size used in both cases would require that the school be located within the tree planting to attain the air quality improvement benefits. To gauge the air quality effect of the planting on the school, the air volume of the original box (90,000 m^3) was expanded to incorporate the air volume around the school and to take account of the mixing height above the planting. The length of the school property was assumed to be equal to the length of the planting (200 m), the height was taken as the minimum day mixing height (250 m) used by Nowak et al. (2006) in the peer-reviewed i-Tree application UFORE, and the width was estimated to be 220 m (from the edge of roadway on Highway 113 to the edge of roadway on Sycamore Lane). Taking account of mixing height and school area, the adjusted box or volume of air would be 11,000,000 m^3 and the one hour concentration reduction would be 4.6%.



The effectiveness of PM removal via tree plantings depends on characteristics of the species chosen (e.g., foliage surface, canopy structure, and life span) and varies by particulate size. The case study shows that vegetation at the Willett Elementary School plot could be expected to remove approximately 120 kg/year of PM (about 0.042 μg/m3 per second), which represents an estimated PM concentration reduction of approximately 4.6 percent per hour given an assumed mixing height of 250 m and volume of 11,000,000 m^3.

FIGURE B.1: CASE STUDY RESULTS

Note that this PM_{10} reduction is assumed to result from the mixing of the air mass within the total volume of the box, inclusive of the vegetative screen. The estimated pollutant reductions are therefore analogous to what the literature reports in the context of regional mixing and dry deposition on vegetation, rather than the horizontal movement of an air mass through and/or over a vegetative screen, which is what would be expected to occur in the near-road environment.

Nowak et al. (2006) reported that in some U.S. cities the one hour PM reduction reached 8% in areas with 100% tree coverage. Our estimation of a 4.6% reduction generally agrees with Nowak et al. (2006).

While the percent reduction would not change under different concentration assumptions, the PM mass removal would change. It should be pointed out that the concentration used in Figure B.1 is an annual mean value of the ambient background concentration. To accurately estimate PM mass removal for areas in close proximity to medium or high volume roads, concentration values must either be estimated or physically measured at the proposed project site. If concentration values from neighborhood (regional background) ambient air quality monitoring stations are used, the resulting PM removal estimations will not reflect roadway-specific concentration gradients and the near-road impact of vegetative screens.

Discussion of Key Model Parameters

The dry deposition model described in this paper may be applied to small scale or localized applications where the pollutant source is in close proximity to the planting. The model tends to underestimate PM removal when compared with real-world measurements and so estimates obtained by this methodology should be considered conservative (Peters and Eiden 1992; Gallagher, Beswick et al. 1997; Ruijgrok, Tieben et al. 1997; Gallagher, Nemitz et al. 2002). These conservative estimates provide a first order approximation that can be used by agencies interested in exploring the option of using vegetation as a filtration mechanism to reduce PM exposure at near-road land uses.

Leaf Area Index

A key consideration in the dry deposition model is the leaf area index. The leaf area index, as previously noted, is a dimensionless ratio of leaf area to canopy projection area (the amount of ground covered by the canopy). 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 (the value used in the i-Tree program), 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 dry deposition model represents a conservative estimate for pines, which can range from an LAI of 6 to 12 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. **Table B.2** summarizes the effects of LAI on PM pollutant removal for the Willet Elementary School scenario.

TABLE B.2
EFFECT OF LAI ON PM REMOVAL

Vegetation Type	LAI**	PM Removal (kg/yr)	Change from Willett School Assumption (LAI=6)*
Deciduous (90%) & Coniferous (10%) Mix	6	120.65	-
All Biomes	5.32	106.98	-11.3%
Temperate evergreen broad-leaved forests	5.82	117.03	-3%
Temperate evergreen needle-leaved forests	6.70	134.72	11.7%
Plantations (managed forests)	8.72	175.34	45.3%
Lorenz and Murphy (1988) Maximum	12	241.30	100%

Notes:
*The percent change is relative to the PM removal with a LAI value of 6; for example, for a LAI of 8.72, the PM removal would be 45.3% greater than the PM removal for LAI=6.
**LAI values, other than the reference value of 6, taken from Scurlock et al. (2001)

As shown in **Table B.2**, an LAI of 6 produces a conservative PM removal estimate and is in agreement with real-world LAI measurements. Of the 1,008 records compiled by Scurlock et al. (2001), 86 percent contain LAI values below 8; therefore, unless site and species-specific information is available, the use of LAIs greater than 8 may lead to overestimation of PM removal and is not generally recommended. If an assumption of LAI ≥ 8 were appropriate for a *Pinus Sabiniana* planting at the Willett Elementary School site, the reported PM removal would be increased by at least 33.3% to 160.87 kg/yr.

Dry Deposition Rate and Wind Speed

Another key consideration in the dry deposition model is the dry deposition rate. Dry deposition rates vary throughout the literature and are inherently dependent on wind speed, canopy and foliage characteristics (such as density and leaf shape), species, particle diameter, and other environmental factors (such as temperature). In addition, dry deposition rate can be defined in relation to ground area, stem deposition, gravitational sedimentation, leaf impaction, and diffusion. Accordingly, only deposition rates related to leaf impaction and diffusion were considered. We gave prime consideration to the choice of a deposition rate for particles in the range $d_p \leq 1.0$ µm since 93.5% of the mass distribution in our model is categorized in this range. Lovett (1994) reported a deposition rate of generally less than 0.005 m/s for $d_p \leq 1.0$µm; Lorenz and Murphy (1989) reported an average deposition rate of 0.0043 m/s for 0.5µm ≤ $d_p \leq 1.0$µm; Peters and Eiden (1992) reported a deposition rate range of 0.004 m/s to 0.042 m/s for $d_p = 0.01$µm; and, Cahill (2008) measured a deposition rate of 0.005 m/s for $d_p = 0.01$µm. Considering the values from the literature, the assumed deposition rate of 0.005 m/s for $PM_{1.0}$ is generally appropriate and likely conservative given that it reflects generally stable meteorological conditions (wind speed approximately 2 m/s or less). Meteorological conditions have a measureable effect on deposition rate and can vary with the time of day, season, and location. While the approach presented in this paper attempts to account for deposition rates in relation to particle diameter and their respective deposition mechanism (diffusion, impaction, sedimentation), it does not fully account for wind speed as it assumes relatively stable conditions (wind speed approximately 2 m/s or less). Approaches that directly consider wind speed (such as the i-Tree methodology) introduce additional complexity that requires detailed data (data that can vary by species, location, and season) about the vegetation and that is not readily available. Accordingly, total PM removal may be underestimated. **Table B.3** summarizes the effect of wind speed on total PM removal for the Willet Elementary School example.

TABLE B.3
EFFECT OF WIND SPEED ON PM REMOVAL

Wind Speed (m/s)	Deposition Rate (m/s) for $d_p = 0.01\mu m$	PM Removal (kg/yr)	Change from Willet School Assumption
≤ 2.0	0.005	120.65	-
0.5	0.002	54.37	-55%
2	.01	231.12	92%
5	.042	938.12	678%

Note: Wind speeds (0.5, 2, 5) and corresponding deposition rates taken from Peters and Eiden (1992)

As is evident from **Table B.3**, wind speed has a significant effect on total PM removal. However, absent site-specific data, the model employed in this paper generally produces a conservative estimate of PM removal. Care should be exercised when choosing deposition rates for wind speeds much greater than 5 m/s because re-suspension and bounce-off effects must be considered. Under moderate wind speed conditions (generally less than 5 m/s) these effects can be ignored (Peters and Eiden 1992). While horizontal wind speed plays an important role in PM removal, vertical wind velocity within the tree canopy can also play a role depending on particle diameter. For particle deposition where the governing mechanism is diffusion, neglecting wind direction is appropriate since air flow near the leaf surface is assumed to be parallel to the surface, regardless of the direction of the wind vector (Peters and Eiden 1992). Accordingly, our model assumes that the vertical wind velocity is zero since the deposition of 93.5% of the concentration is governed by diffusion. Our assumption of a uniformly distributed particulate concentration (for $PM_{1.0}$) in the plot area is supported by measurements showing that concentrations of particulates with $0.01\mu m \leq d_p \leq 3.0\mu m$ are approximately equal above and below the canopy (Peters and Eiden 1992). While in-canopy concentration is important, a more overriding consideration is the effect of near-road concentrations on diffusion.

Planting Location

An important variable that is not explicitly factored into the dry deposition model is the proximity of the planting to the pollution source. As shown throughout the literature, pollutant concentration decreases as distance from the roadway increases. Therefore, the closer a planting is to the roadway, the higher the concentration exposure. A higher pollutant concentration exposure is important because the lower pollutant concentration created within the planting results in a concentration gradient: the larger the gradient, the higher the diffusion rate. In other words, if the PM concentration outside of the planting is very high relative to the concentration inside the planting, the rate of diffusion will be high. As the distance from the roadway increases, the PM concentration and the concentration gradient both decrease. To maximize the effectiveness of diffusion to a near-road tree plot, the plot should maximize surface area. This can be achieved by maximizing coverage area and by choosing species with a high LAI. Cahill (2008) hypothesized that "…vegetation near very fine particle sources can be effective in removing some of the most toxic particles in the air before they get mixed into the regional air mass." This hypothesis is supported by the theory of diffusion and by the results of the wind tunnel experiments conducted by Cahill (2008) and presented in **Table 2.1**. As noted by QUARG (1996) and referenced in **Table 1.1**, proximity to pollutant source is especially important for the smallest particles ($d_p = 0.001$) since their atmospheric residence time is limited. After about 10 minutes, these particles agglomerate to form accumulation size particles ($0.05\ \mu m \leq d_p \leq 2.0 \mu m$) where diffusion is not necessarily the governing deposition mechanism. To take advantage of the diffusion deposition mechanism, the plot should be located close enough to the pollutant source as to prevent agglomeration of the smallest particles to accumulation mode.