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Roadside Vegetation Design to Improve Local, Near-Road Air Quality

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Abstract

As public health concerns have increased due to the rising number of studies linking adverse health effects with exposures to traffic-related pollution near large roadways, interest in methods to mitigate these exposures have also increased. Several studies have investigated the use of roadside features in reducing near-road air pollution concentrations since this method is often one of the few short-term options available to reduce near-road air pollution. Since roadside vegetation has other potential benefits, the impact of this feature has been of particular interest. The literature has been mixed on whether roadside vegetation reduces nearby pollutant concentrations or whether this feature has no effect or even potentially increases downwind pollutant concentrations. However, these differences in study results highlight key characteristics of the vegetative barrier that can result in pollutant reductions or increase local pollutant levels. This paper describes the characteristics of roadside vegetation that previous research shows can result in improved local air quality, as well as identify characteristics that should be avoided in order to protect from unintended increases in nearby concentrations. These design conditions include height, thickness, coverage, porosity/density, and species characteristics that promote improved air quality. These design considerations can inform highway departments, urban and transportation planners, and developers in understanding how best to preserve existing roadside vegetation or plant vegetative barriers in order to reduce air pollution impacts near transportation facilities.

Keywords

Air pollution; traffic; vegetation; particulate matter; highway landscape design

Introduction

Numerous health studies have linked adverse health effects with spending significant amounts of time near high-traffic roads with elevated air pollution levels of particulate matter, gaseous pollutants, and air toxics emitted by nearby motor vehicle activity (e.g. HEI, 2010). The significant impact of traffic emissions on urban populations all over the world has motivated research on methods to reduce exposure to these pollutants. While vehicle emission control techniques and programs directly reduce air pollutants emitted to the air from transportation sources, these programs often take a long time to fully implement and may be offset by increases in vehicle activity. Thus, other mitigation options will also be needed to fully and comprehensively reduce air pollution exposures for these urban populations.

Recent studies have investigated how roadside vegetation may provide an opportunity to reduce near-road pollutant concentrations in urban areas. This roadside vegetation can include the preservation of existing trees and bushes, as well as planting vegetation, which may be some of the few near-term mitigation strategies available for urban developers and facilities already subject to high pollution levels near roads. These mitigation methods, if successful, can complement existing pollution control programs and regulations, as well as provide measures to reduce impacts from sources that are difficult to control such as brake and tire wear and re-entrained road dust (EPA, 2016).

In general, vegetation and green infrastructure has been shown to have overall health benefits including increased physical activity, lower obesity, improved mental health, overall improved birth outcomes, lower adverse cardiovascular illness, and decreased mortality (James et al, 2016; James et al, 2015). Davdand et al., (2015) found an improvement in school children's cognitive development associated with an increase in surrounding greenness, particularly at schools. The authors partly attributed this association to reductions in nearby air pollution.

In addition to air quality and general health benefits, roadside vegetation can improve aesthetics, increase property values, reduce heat, control surface water runoff, and reduce noise pollution (with dense, thick and tall stands). However, vegetation can also affect driver sight lines, protrude into clear zones along highway right-of-ways, contribute to debris on roads, present fire hazards, and be pathways for pests and invasive species. Thus, all of the benefits and potential unintended consequences of roadside vegetation need to be considered for any application.

This paper provides insight into roadside vegetation design characteristics that have been shown to most effectively reduce near-road air pollutant levels downwind of major highways in order to implement this feature as an air pollution mitigation strategy. The recommendations focus on general considerations applicable to multiple development types and scenarios, and do not address site-specific siting or permitting requirements that might be required in certain locations such as planting along a particular highway right-of-way or within a city park.

Vegetation Effects on Air Quality

Trees and other vegetation have been shown to reduce regional air pollution levels through the interception of airborne particles or through the uptake of gaseous air pollution through leaf stomata on the plant surface (see reviews by Janhall, 2015; Gallagher et al., 2015). Pollution removal (O_3 , PM_{10} , NO_2 , SO_2 , CO) by urban trees has been estimated across the continental United States (US) using the US Forest Service's i-Tree model (Nowak et al., 2014). This study suggested that nationwide vegetation can reduce air pollution levels by approximately one percent (equating to over 10 million tons removed).

Removal of gaseous pollutants by trees can be permanent, while trees typically serve as a temporary retention site for particles. The removed particles can be re-suspended to the atmosphere during turbulent winds, washed off by precipitation, or dropped to the ground with leaf and twig fall (Nowak et al., 2000). These removal mechanisms can impact local air,

water and soil pollution; thus, careful consideration of the land uses that surround roadside vegetation are needed when choosing species.

At the local level, trees can also act as barriers between sources and populations, although vegetation is inherently more complex to study than solid structures. For example, the effectiveness of vegetative barriers at reducing ultrafine particle (UFP) concentration has been shown to be variable (Janhall et al., 2015; Tong et al., 2015; Hagler et al., 2012; Pataki et al., 2011). This variability is likely due to a number of confounding factors. The complex and porous structure of trees and bushes can modify near-road concentrations via pollutant capture or through altering air flow, which can result in either reduced dispersion through the reduction of wind speed and boundary layer heights (Wania et al., 2012; Vos et al., 2012; Nowak et al., 2000) or in enhanced dispersion due to increased air turbulence and mixing as the pollutant plume is lofted up and over the vegetation (Bowker et al., 2007). Recirculation zones have also been observed immediately downwind of forested areas with a flow structure consistent with an intermittent recirculation pattern (Detto et al., 2008; Frank and Ruck, 2008). Janhall (2015) summarized that low vegetation like hedges, can filter out PM when located close to an emission source such as a road, while high vegetation like trees can reduce mixing and turbulence and result in increased concentration levels. Thus, vegetation type, height, and thickness can all influence the extent of mixing and pollutant deposition experienced at the site. The built environment also matters greatly - air flow and impacts of trees are substantially different for a street canyon environment than an open highway environment (Gromke et al., 2016; Li et al., 2016; Pugh et al., 2012; Buccolieri et al., 2011; Buccolieri et al., 2009; Gromke et al., 2008).

Several studies have shown significant reductions in air pollution concentrations behind roadside vegetation barriers (Tong et al., 2016; Al-Dabbous et al., 2014; Brantley et al., 2014; Steffens et al., 2012). Each of these studies compared air quality concentrations near a large roadway with and without the presence of roadside vegetation. For all of these studies, the roadside vegetation was dense and a mixture of trees and bushes, with full coverage from the ground to the top of the canopy, although the heights, thickness and species varied. Two recent studies demonstrated through field measurements and modeling that hedgerows can improve air quality in street canyons if the bushes provide full coverage with no openings or gaps (Gromke et al., 2016; Li et al., 2016).

Roadside Vegetation Barrier Physical Design Characteristics

The seemingly contradictory results of previous field studies investigating how roadside vegetation affects near-road air quality actually provide useful insights on the characteristics needed for such a barrier to improve local air quality. The following sections review how height, thickness and the porosity of the vegetation interact to either provide an effective barrier against air pollution impacts or potentially have no or even a negative effect. These recommendations and characteristics focus on the presence of vegetation along highways and motorways that carry large volumes of traffic but are not located in urban street canyons. Although there are similarities in results from street canyon studies to this type of application, other recent publications provide more detailed information on designs for street canyons (Gallagher et al, 2015; Gromke et al, 2016; Li et al, 2016).

Generally, a vegetation barrier along a high-volume highway should be tall, thick, and dense to achieve greater reductions in downwind pollutant concentrations. Each of these factors is discussed below with an emphasis on roadside vegetation characteristics that promote improved near-road air quality

Vegetation Barrier Height: Studies evaluating varying heights of vegetation barriers have been minimal. Near-road vegetation barrier studies in non-street canyon settings that measured air pollution reductions behind the vegetation typically had heights ranging from 4 meters or higher (Steffens et al, 2012; Al-Dabbous et al, 2014; Brantley et al, 2013). At these heights, the barrier will be above the exhaust release height of motor vehicles operating on the adjacent roads, forcing the pollutant plume to loft above and over or pass through the vegetation. Heights lower than approximately 4 meters may allow for the pollutant emissions to proceed downwind of the low barrier unimpeded. Barriers of these height will only be effective if there's full coverage from the ground to top of the canopy. Ornamental trees with large openings under the canopy can result in higher downwind concentrations by allowing the plume to pass through while also reducing wind speeds as in the example of Tong et al. (2015). Thus, the vegetation barrier should be similar to a solid noise barrier by impeding the entire plume air flow from the highway. Solid noise barrier studies also suggest walls 4 meters or taller provide a sufficient height for air quality improvement (for example Baldauf et al., 2014; Heist et al, 2009). As discussed in Gallagher et al (2015) and Li et al (2016), vegetation heights for barriers in street canyons may be effective at lower heights due to the increased complexity of air flow.

Vegetation Barrier Thickness: The thickness of the barrier will provide the residence time to allow for particulate removal by impaction or diffusion, as well as reduce turbulence and wind speed, increasing the amount of air flow blocking. The vegetation thickness also forces air flow over the barrier for a longer distance, as well as provides increased distance from the air pollution source to the downwind receptors. The thickness of the barrier needed for effective air pollution mitigation will vary depending on the porosity/density of the vegetation. In general, studies reporting decreased near-road pollutant concentrations with vegetation were a minimum of approximately 5 meters thick, with most approaching 10 meters or more (Neft et al., 2016).

Vegetation Porosity/Density: The porosity or density of the vegetation comprising the barrier will determine air movement through the barrier. Generally, the lower the porosity (or higher the density) and thicker the barrier, the more air flow forced over the structure. At extremely low porosities, the vegetation will affect pollutant transport and dispersion in a similar manner as a solid noise barrier. At higher porosity, the vegetation can reduce wind speeds, allowing pollutants to stagnate within or behind the vegetation, potentially leading to higher pollutant concentrations. Thus, the vegetation porosity should be high enough that the combination of particle loss within the vegetation and the particle removal mechanisms dominate the lowering wind speed and stagnation effect, leading to reduced concentrations behind the barrier. Since the measurement of porosity and/or density along the lateral plane of air flow from a highway is very difficult, a quantitative technique in the field has not been implemented. Modeling and wind tunnel analyses have used Leaf Area Index (LAI) and

Leaf Area Density (LAD) to estimate the porosity/density of vegetation (Lin and Khlystov, 2012; Steffens et al, 2012; Tong et al. 2016; Neft et al, 2016). These studies suggest thicker and denser vegetation promotes increased pollution reductions, although none provide a quantitative relationship that has been shown effective in the field. Figure 1 shows examples of effective and not-effective vegetation barriers that provides a qualitative understanding of the porosity and density needed for pollution reductions.

Vegetation Barrier Coverage: As described, gaps in vegetation barriers, whether from high porosity, missing or dead trees, or space under ornamental trees, can lead to increased pollutant concentrations downwind, sometimes higher than concentrations would be if no barrier were present. These increases can occur because pollutant emissions from the road funnel through the gaps or cause winds to stagnate. Thus, the vegetation should provide full coverage from the ground to the top of the canopy as shown in Figure 2. This characteristic is important in planning the barrier design as well as maintaining existing or planted roadside vegetation. In order to achieve sufficient coverage, multiple rows and types of vegetation may be most feasible. For example, a barrier could consist of a row of bushy plants and hedges followed by a row of trees to enable a barrier with full coverage from the ground to top of canopy at the initial planting, yet achieve higher canopy heights than feasible by bushy plants alone. In addition, rows of multiple vegetation types may allow for sufficient downwind pollutant removal while the vegetation grows over time after first planting. This approach will ensure sufficient density for pollutant removal at the initial planting, while allowing for increased pollutant removal as the vegetation matures. This process will also limit concerns of promoting plant monocultures.

Vegetation Barrier Length: In addition to passing through gaps, pollutants can also meander around the edges of a roadside vegetative barrier. Thus, if a vegetative barrier will be constructed for a specific neighborhood or facility (e.g. school, daycare, elderly care facility), it should extend sufficiently beyond the area of concern. Research on solid noise barriers suggests that the barrier should extend at least 50 meters laterally beyond the area of concern in order to maximize reductions in downwind concentrations (Baldauf et al., 2008; Baldauf et al., 2016). If extending the barrier laterally is not feasible, extending it perpendicularly from the road, wrapping around the area of interest, has been shown to be effective as well (Brantley et al., 2014; Li et al, 2016).

Roadside Vegetation Species Considerations

Certain types and species of vegetation will provide more air quality benefits compared to other types of vegetation. When considering the design and construction of a vegetation barrier, optimal species' physical characteristics should be favored to the extent feasible. However, given the vast number of vegetation species, and the regional differences in the feasibility and effectiveness of specific species for a roadside barrier, specific recommendations cannot be made in this document. The U.S. Forest Service's i-Tree model (see Nowak et al, 2014) can provide a list of potential species that best meet the factors listed below in the United States. In addition, users need to identify whether particular vegetation types can survive and prosper in a particular area of interest. Key factors to consider include:

Seasonal Effects: The vegetation chosen for a barrier should not be subject to significant changes in characteristics and integrity during changing seasons. Deciduous trees that lose leaves during the cold season should not be considered for a barrier to mitigate air quality impacts year round. Instead, trees that are not subject to significant seasonal changes, such as coniferous plants, should be considered. Other shrubs and bushes that are not subject to seasonal changes can also be considered as part of a roadside barrier.

Leaf Surface Characteristics: Leaf surfaces can also enhance particulate removal through diffusion and interception. Trees and bushes with waxy and/or hairy surfaces have been shown to preferentially remove particulates compared to smooth leaf surfaces. In addition, vegetation with leaf and branch structures that provide increased surface area for particle diffusion are preferred (Petroff et al., 2009; Tong et al., 2016).

Vegetation Air Emissions: When selecting vegetation for a roadside barrier, especially at locations where sensitive populations may be spending significant amounts of time, care must be taken to choose species that do not emit compounds which increase air pollution or allergic responses. Compounds that can be emitted by vegetation include volatile organic compounds (VOCs), which can enhance the formation of ozone, and high-allergy pollens. Both can exacerbate respiratory effects and should be avoided for roadside barriers, especially in areas where sensitive populations may be present, such as children and the elderly.

Resistant to air pollution and other environmental stressors: Vegetation implemented in a roadside barrier must also be resistant to air pollution and other traffic stressors since concentration levels will be high. If the vegetation is not resistant and cannot maintain its integrity, gaps will form in the barrier, potentially leading to increased pollutant concentrations downwind as discussed previously. Air pollutants emitted by traffic can include the typical tailpipe emissions like CO, NO_x, and particulates; materials from brake and tire wear; re-suspended road dust; and salt and sand used for road surface treatment during winter weather conditions

Other Vegetation Barrier Considerations:

In addition to air quality considerations, other potentially beneficial and adverse aspects of vegetation need to be considered in the construction and use of a roadside barrier. These considerations include general physical and species-specific factors. While location-specific factors will need to be addressed on an individual basis, some general considerations include:

Vegetation Maintenance: The roadside vegetation will need to be maintained in order to provide a protective barrier from air pollution exposures yet not lead to safety concerns from reduced visibility or falling debris. Maintenance requirements will depend on vegetation type and species, so a plan should be in place when selecting and constructing the barrier for optimal long-term performance. These requirements include watering and fertilization needs, trimming and other pruning requirements, and overall plant care. Maintenance should also include vegetation replacement due to die-off, disease, or damage from accidents.

Properly designed roadside vegetation may also minimize the need for extensive mowing and trimming, saving money and reducing air pollution emissions.

Water runoff control: An additional benefit of a roadside vegetation barrier can be the control and containment of surface water runoff from the impervious road and supporting infrastructure. Roadside barriers constructed to provide water runoff control can prevent localized flooding as well as improve water quality in the area. For certain regions of the country, drought resistant vegetation that can also resist high-water events may be most appropriate.

Native and Non-invasive species: Whenever feasible, native species should be considered for implementing the roadside barrier. Native species may more likely be robust and resistant to local climatic conditions. The vegetation barriers should also not be constructed from invasive species that may not be contained within the project area of interest, and may create problems at other locations or at the roadside. Non-poisonous species should also be used, especially if present near children or in locations that have the potential to cause harm in other ways.

Roadway Safety: Planting on or near a highway right-of-way (ROW) requires consideration of potential safety issues. In most cases, the applicable highway department will require approvals for planting near roads due to these issues. Concerns may include creating undesirable wildlife habitat near roadways (e.g. deer and other animals that can exacerbate auto accidents), preserving safe lines-of-sight and viewshed standards for drivers on the road, maintaining clear zones and horizontal clearance for driver safety, ensuring compatibility of the chosen vegetation species with existing species, and not obstructing outdoor advertising.

Vegetation with Noise Barriers

Noise barriers combined with mature vegetation have also been found to result in lower ultrafine particle concentrations along and away from a highway compared to an open field or a solid noise barrier alone (Bowker et al., 2007; Baldauf et al., 2008). For vegetation planted with a solid noise barrier, the overall considerations should be the same as for vegetation alone. However, for the vegetation to have an additive effect for pollutant reductions, the vegetation should exceed the top of the solid barrier by a sufficient height in order to allow air flow through and over the plants to enhance pollutant removal and air mixing. Vegetation in combination with a solid noise barrier will also likely be effective at higher porosities than for vegetation alone since the addition of the vegetation mainly enhances particulate removal through diffusion or impaction since the solid barrier has already enhanced turbulence and mixing of the traffic plume.

Solid barriers can vary in height; research on air pollution reductions from these structures has been conducted for heights between 4 and 6 meters. A vegetation barrier should extend at least 1 meter above the barrier, although the higher and thicker the plants, the greater the downwind reduction as suggested by Hagler et al (2011). For shorter solid barriers, vegetation should extend above the barrier to a height of at least 6 meters to maximize the

potential for downwind pollutant reductions. Figure 2 provides examples of combinations of vegetation with solid noise barriers that could lead to increased reductions in downwind air pollutant concentrations.

Previous research is based on vegetation planted behind the noise barrier (opposite side from the road), although bushes or trees in front could provide an added reduction if sufficiently away from the solid barrier to allow air to flow through. Some modeling studies suggest that “green walls” such as ivy or other climbing vegetation on solid noise barriers may also improve local air quality (Pugh et al, 2014); however, as noted above, air flow through the vegetation would be needed to enhance particulate diffusion and impaction.

No research has been done on whether gaps or spaces in vegetation along solid walls can lead to increased downwind concentrations. Since solid noise barriers alone can reduce downwind pollutant concentrations, gaps in accompanying vegetation would likely not have the same detrimental effects as with vegetation alone, although the gaps would likely limit the added benefit of particulate removal from the adjacent vegetation.

Summary

Research shows that roadside vegetation affects nearby air quality, both in a positive and negative way. If properly designed, vegetation barriers can be used to improve near-road air quality, either alone or in combination with solid noise barriers. Many factors must be considered in designing effective roadside vegetative barriers that are applicable for use by transportation departments, urban planners and local developers as summarized in Table 1.

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Figure 1.
Examples of (a) effective vegetation barriers that are dense with full coverage from the ground to the top of canopy and (b) ineffective roadside barriers due to gaps and high porosity.

Figure 2.

Examples of effective combinations of vegetation with solid noise barriers. Panel (a) shows vegetation behind the barrier (as studied in Baldauf et al., 2008) while panel (b) shows bushy vegetation in front of the barrier (no empirical evidence available).

Table 1.

Factors affecting the effectiveness of roadside barriers in mitigating near-road air pollution impacts

Barrier Characteristic	Recommendation	Description
<i>Physical Characteristics</i>		
Height	5 meters or higher (or extend 1+ meter above an existing solid barrier)	The higher the vegetative barrier, the greater the pollutant reductions. A minimum of 5 meters should provide enough height to be above typical emission elevations for vehicles on the road. However, heights of 10 meters or more would likely provide additional pollutant reductions
Thickness	10 meters or more	The thicker the vegetative barrier, the greater the pollutant reductions. A minimum thickness of 10 meters should provide enough of a barrier to remove particulate and enhance dispersion. However, gaps in the barrier should be avoided. Multiple rows of different types of vegetation (e.g. bushes, shrubs, trees) should be considered for maximum coverage and pollutant removal during all stages of the barrier
Porosity	0.5 to 0.9	Porosity should not be too high to allow pollutants to easily pass through the barrier or cause wind stagnation. As the porosity gets lower, the vegetation barrier will perform similarly to a solid barrier, which may limit the amount of particulate removal since air is forced up and around the plants
Length	50 meters or more beyond area of concern	Extending the barrier beyond the area of concern protects against pollutant meandering around edges. May also consider constructing the barrier perpendicular from the road depending on land availability
<i>Vegetation Characteristics</i>		
Seasonal Effects	Vegetation not subject to change by season	Vegetative barrier characteristics must be consistent throughout all seasons and climatic conditions in order to ensure effective pollutant reductions
Leaf Surface	Complex waxy and/or hairy surfaces with high surface area	Leaf surfaces with complex and large surface areas will capture and contain more particulate pollutants as air passes through the structure
Air Emissions	Vegetation with low or no air emissions	Vegetation used for roadside barriers should not be sources of air pollution, either at the local or regional scale
Pollution and Stress Resistant	Resistant to effects of air pollution and other stressors	Vegetation must be able to survive and maintain its integrity under the high pollution levels and stress that can occur near roads in order to provide effective pollution reductions from traffic emissions. In addition to air pollution, other stressors can include salt and sand for winter road conditioning and noise impacts
<i>Other Considerations</i>		
Maintenance	Plan must be in place to properly maintain vegetative barrier	Proper vegetation maintenance must be provided in order for the barrier to survive and maintain its integrity to provide effective pollution reductions from traffic emissions
Water Runoff	Contain surface water runoff and improve water quality	Roadside vegetative barriers constructed appropriately can provide an added benefit of controlling and containing surface water runoff from the road, which can also improve local water quality
Drought Resistant	Choose species resistant to drought and flooding	Many regions face climatic conditions of extended drought followed by localized flooding. Vegetative barrier must maintain its integrity under these conditions in order to provide effective pollution reductions
Native Species	Choose native species	Native species will be more robust and resistant to climatic conditions in the area of interest; thus, maintaining its integrity under these conditions in order to provide effective pollution reductions
Non-invasive	Choose noninvasive species	The use of non-invasive species will ensure effective pollutant reductions without potential unintended consequences from invasive species adversely affecting nearby land uses
Non-poisonous	Choose non- poisonous species if sensitive populations will be nearby	Non-poisonous species are strongly encouraged and should be used if the barrier will be at a location with sensitive populations, such as elementary schools, parks, and recreation fields where small children may be active and in close contact
Roadway Safety	Maintains safety for drivers on the road; conforms to local safety and permit requirements	Prior to planting, ensure vegetation plan will meet all safety and other local permit requirements (e.g. local highway department, city planning department)

Barrier Characteristic	Recommendation	Description
		to preserve sight-lines and vegetation compatibility while avoiding potential wildlife/auto accidents and obstruction of outdoor advertising