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United States
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# Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality

**Office of Research and Development**
National Risk Management Research Laboratory, Air Pollution Prevention and Control Division

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# Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality

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# 1.0 Introduction

Public health concerns related to near-road air quality is an important environmental issue because there are an increasing number of health studies linking adverse health effects to populations spending significant amounts of time near high-traffic roads (HEI, 2010). These effects may be attributed to increased exposure to particulate matter, gaseous criteria pollutants, and air toxics emitted by vehicle activity on the road. 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 to directly reduce air pollutants emitted to the air from transportation sources are vital components of air quality management, these programs often take a long time to fully implement. Thus, other mitigation options, including the preservation and planting of roadside vegetation and the construction of roadside structures such as noise barriers, are 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.

Several studies have investigated the role of vegetation on pollutant concentrations in urban areas employing modeling, wind tunnel, and field measurements (Baldauf et al., 2008; Brode et al., 2008; Hagler et al., 2012; Nowak, 2005; Nowak et al., 2000; Stone and Norman, 2006; Tong et al., 2015). Roadside vegetation has been shown to reduce a population's exposure to air pollution through the interception of airborne particles or through the uptake of gaseous air pollution via leaf stomata on the plant surface (Petroff et al., 2009) in addition to affecting pollutant transport and dispersion. Noise barriers combined with mature vegetation have also been found to result in lower ultrafine particle concentrations along a highway transect compared to an open field or a noise barrier alone (Baldauf et al., 2008; Bowker et al., 2007). Pollution removal ($O_3$, $PM_{10}$, $NO_2$, $SO_2$, CO) by urban trees in the United States (US) has been estimated across the continental United States using the U.S. Forest Service's i-Tree model (Nowak et al., 2014).

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.

Trees can also act as barriers between sources and populations, although vegetation is inherently more complex to study than solid structures and the effectiveness of vegetative barriers at reducing ultrafine particle (UFP) concentration has been shown to be variable (Hagler et al., 2012). 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 (Nowak et al., 2000; Wania et al., 2012) or in enhanced dispersion due to increased air turbulence and mixing. 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). 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 (Buccolieri et al., 2009; Buccolieri et al., 2011; Gromke et al., 2008).

In addition to air quality 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, the benefits and potential unintended consequences of roadside vegetation need to be considered for any application.

This guidance 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. This guidance is written for general considerations applicable to multiple scenarios, so does not address specific siting or permitting requirements that might be required in certain circumstances, such as planting in a highway right-of-way or within a city park.

# 2.0 Physical Design Recommendations

## Barrier Physical Characteristics

Generally, a higher and thicker vegetation barrier will result in greater reductions in downwind pollutant concentrations. While studies evaluating varying heights of vegetation barriers have been minimal, several studies have investigated the effect of height on pollutant reductions for solid noise barriers. Figure 1 shows results of Computational Fluid Dynamic (CFD) modeling of solid noise barriers of varying heights, indicating that higher barriers require additional plume transport and dispersion above the structure, resulting in greater downwind pollutant reductions.

While the porosity of vegetation will allow some air movement through the barrier, the height of the structure will still force some air flow up and over the vegetation, increasing dispersion. The porosity and thickness of the vegetation will affect the amount of air flow allowed through the structure compared with flow forced up and over. Generally, the lower the porosity 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. However, vegetation barrier design should allow some air flow through the vegetation in order to enhance particulate removal. Previous studies suggest porosities between 0.5 and 0.9 to be most effective (see Tong et al., 2016 for summary).

The integrity of the vegetation barrier must be maintained in order to allow for pollutant reductions downwind. Studies have shown that gaps in vegetation barriers 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; in addition, the highly porous vegetation can cause winds to stagnate also leading to higher downwind concentrations. Figure 2 provides examples of a) effective barriers that have full coverage from ground to top of canopy and b) ineffective vegetation barriers due to gaps that may result in higher pollutant concentrations.

In order to achieve sufficient physical characteristics of a vegetation barrier, multiple rows and types of vegetation may be most feasible. For example, a barrier could consist of a row of bushy plants and shrubs 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.

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 facility (e.g. school, daycare, elderly care facility) or neighborhood, 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., 2016). If extending the barrier laterally is not feasible, extending the barrier perpendicular to the road, wrapping around the area of interest, has been shown to be effective as well (Brantley et al., 2014).

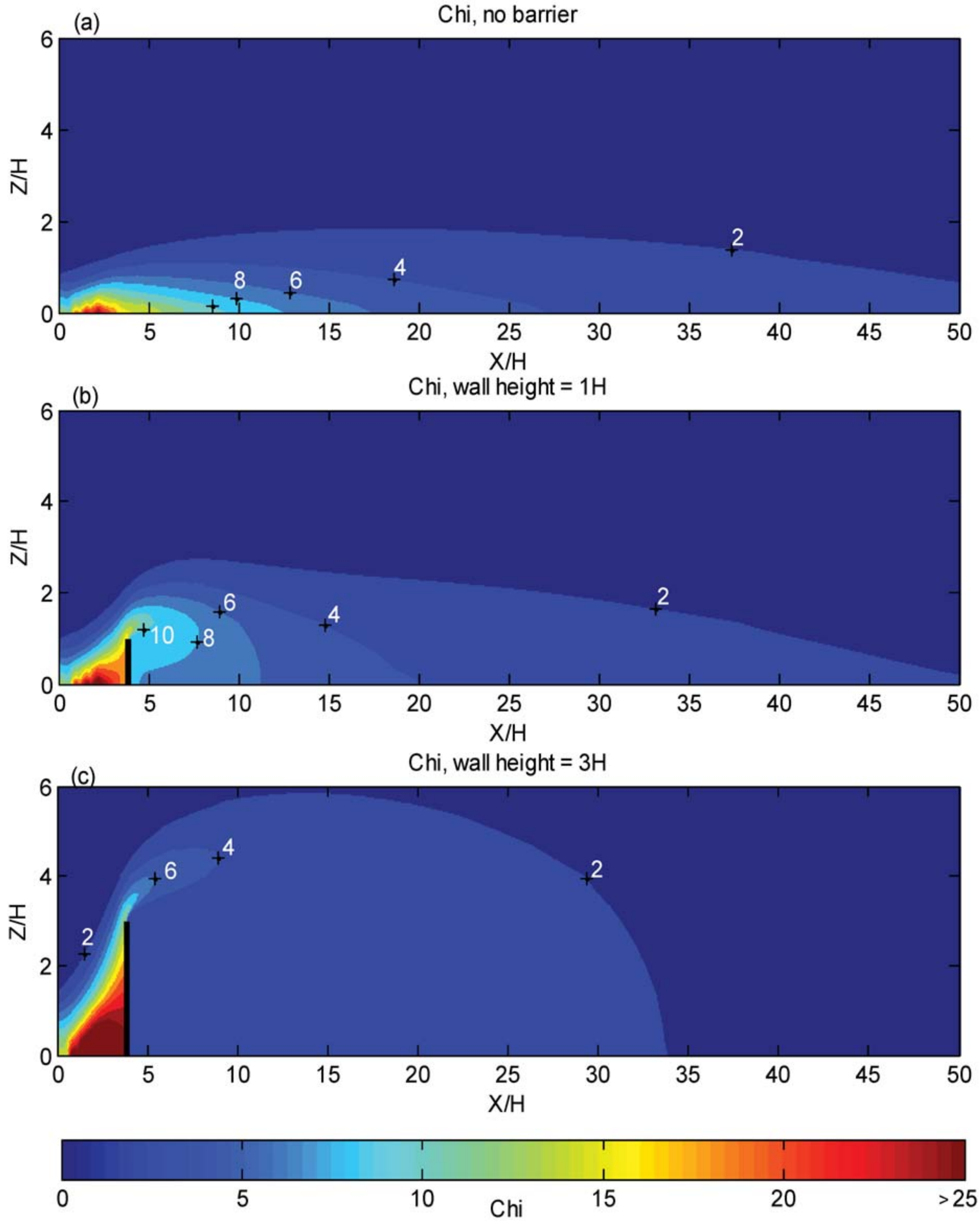


Figure 1. CFD modeling analysis of varying solid noise barrier heights. For the figure above, the top panel shows no barrier, the middle panel a barrier of height, H, and the bottom panel a barrier of height 3H. The distances downwind are also relative to the barrier height. As an example, for H=6 meters, the middle panel would represent a 6 meter tall barrier and the bottom panel an 18 meter tall barrier, and the x-axis distance values would also be multiplied by 6 meters. For this figure, Z represents the vertical height above ground and X the distance from the nearest travel lane on the road (Hagler et al, 2012).

(a) (b)

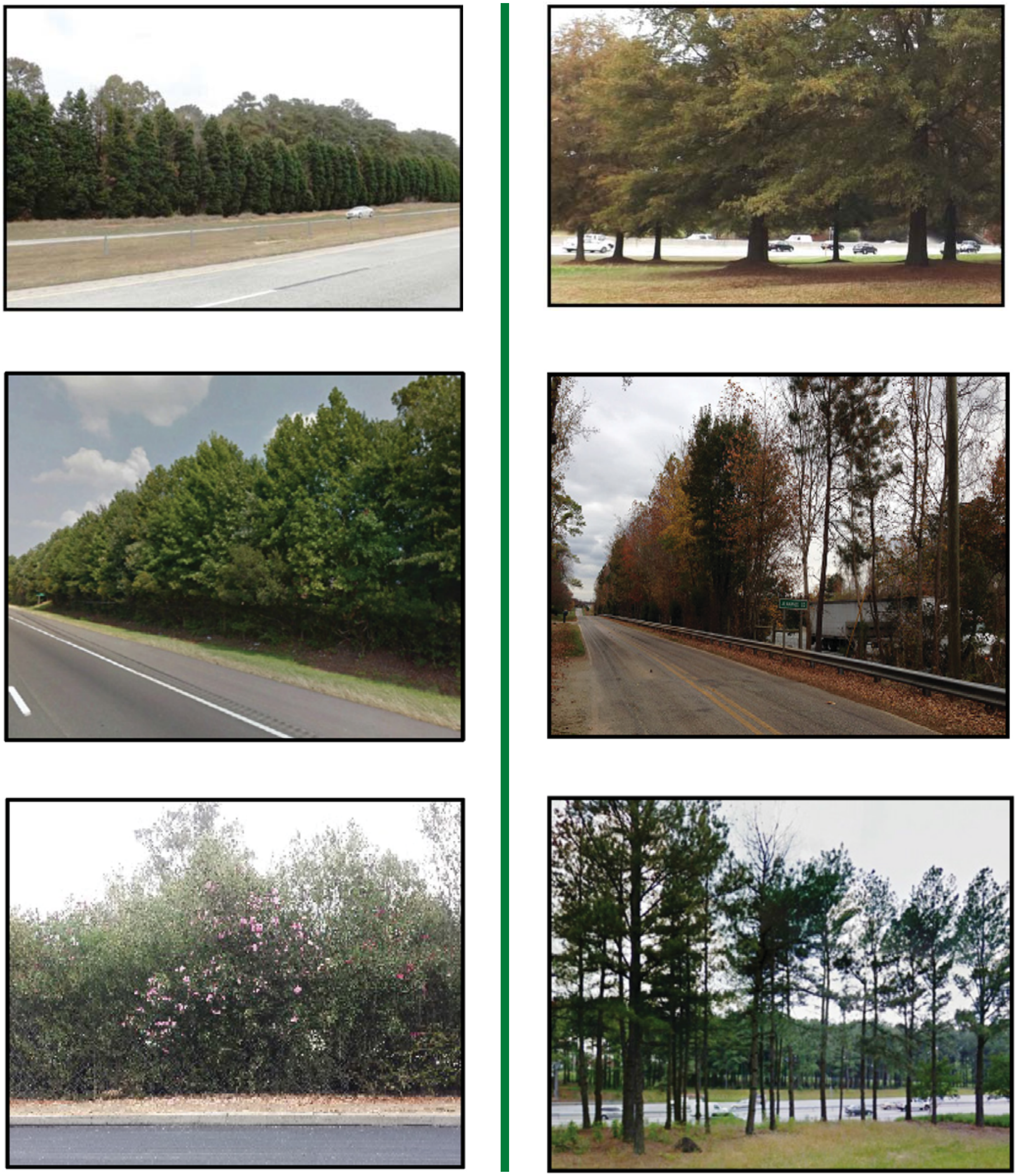

Figure 2. Examples of effective (a) and ineffective (b) roadside barriers.

## Vegetation Characteristics

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 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. The U.S. Forest Service's i-Tree model (https://www.itreetools.org) can provide a list of potential species that best meet the factors listed below, although users need to identify whether particular vegetation types can survive and prosper in a particular area of interest.

### *Seasonal Effects:*

The vegetation chosen for a barrier should not be subject to significant changes in characteristics and integrity during changing seasons. Therefore, deciduous trees that lose leaves during the cold season should not be considered for a barrier to mitigate air quality impacts. 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 (Tong et al., 2016). Figure 3 provides some example leaf surfaces.

### *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 can 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.

### *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, NOx, and particulates; materials from brake and tire wear; re-entrained road dust; and salt and sand used for road surface treatment during winter weather conditions.

(a)


(b)


Figure 3. Example leaf characteristics including a) waxy pine needles and b) hairy leaf surfaces.

### *Other 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.

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 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.

Non-invasive species – Vegetation barriers should 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 – For roadside vegetation barriers located near sensitive populations, the vegetation should not be poisonous or have the potential to cause harm in other ways. However, when the barrier can be isolated, this factor may not be a concern.

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 compatibility of the chosen vegetation species with existing species, and not obstructing outdoor advertising.

# 3.0 Vegetation with Noise Barriers

Although limited, some research suggests that combining vegetation with a solid noise barrier can lead to further downwind pollutant reductions than either vegetation or a solid noise barrier alone (see 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 noise barrier by a sufficient height in order to allow air flow through and over the plants to enhance pollutant removal and air mixing.

Solid barriers can vary in height; research on air pollution reductions from these structures has been conducted for heights between 4.5 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. 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 4 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 plants 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 improve local air quality; however, no air quality measurement studies have been conducted to confirm or negate these model results.

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 no empirical evidence exists to confirm this assumption.

(a)

(b)

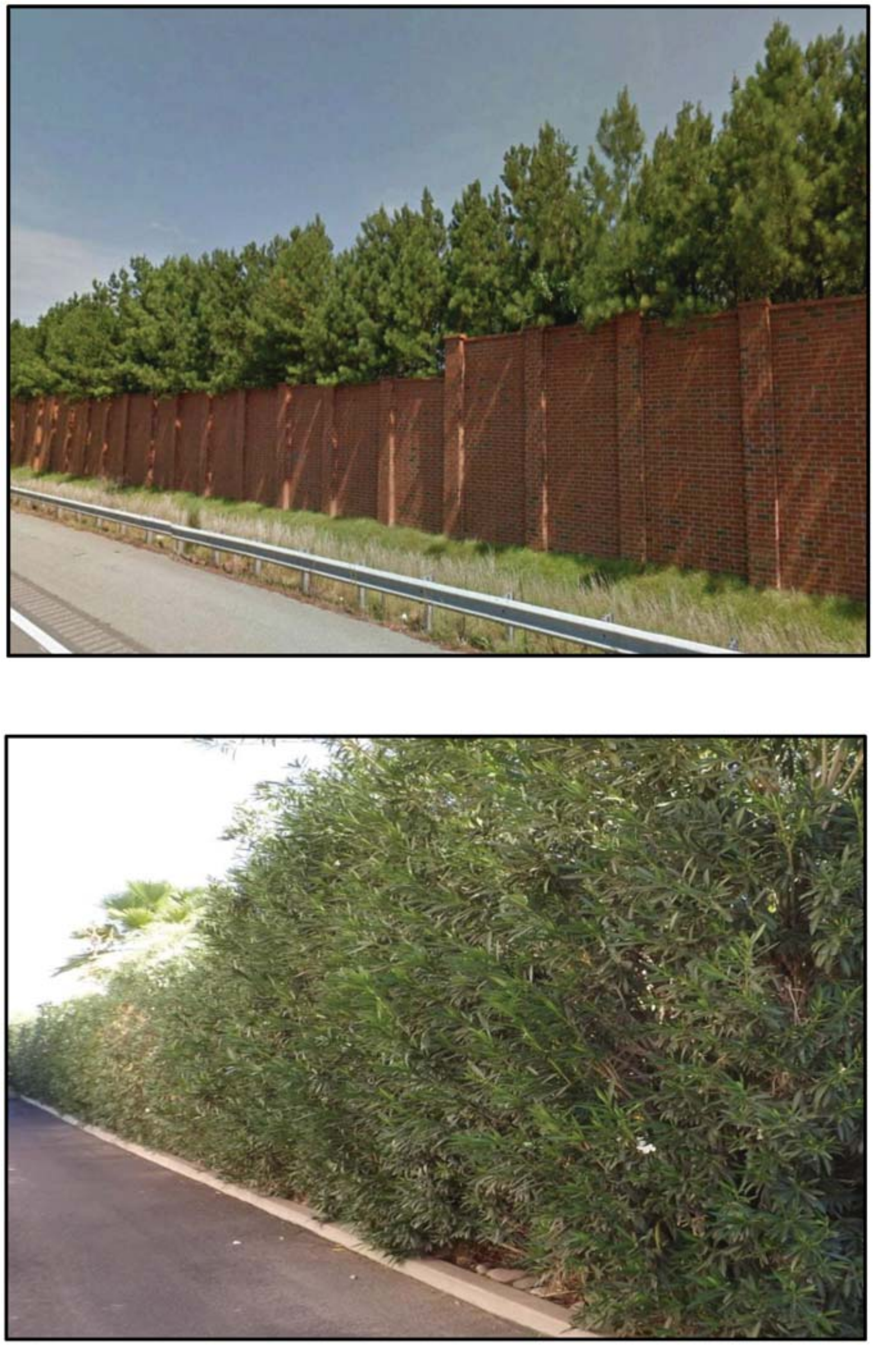

Figure 4.  Examples of effective combinations of vegetation with solid noise barriers. Panel (a) shows vegetation behind the barrier (as studied in Baldauf et al., 2008) while panel (b) shows bushy vegetation in front of the barrier (no empirical evidence available).

# 4.0
# Summary

Research shows that roadside vegetation affects nearby air quality. If properly designed, vegetation barriers can be used to reduce near-road air pollution, either alone or in combination with solid noise barriers. The important factors to consider for effective roadside vegetative barriers are included in the summary table at the end of this document.

## Additional Resources

Many resources exist which can aid in the siting, design and maintenance of roadside vegetation barriers to provide air quality and other benefits to local communities. Just a few examples include:

- USDA Forest Service i-Tree program (**www.iTreetools.org**)
- State and local extension services
- EPA Stormwater Calculator (**https://www.epa.gov/water-research/national-stormwater-calculator**)
- EPA EnviroAtlas (**https://www.epa.gov/enviroatlas**)

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# References


Baldauf RW, Isakov V, Deshmukh PJ, Venkatram A, Yang B., Zhang KM. 2016. Influence of solid noise barriers on near-road and on-road air quality. Atmospheric Environment. Vol 129: pp. 265–276.

Baldauf RW, Thoma E, Khlystov A, Isakov V, Bowker G, Long T. 2008. Impacts of noise barriers on near-road air quality. Atmospheric Environment. Vol 42: pp. 7502-7507.

Bowker GE, Baldauf RW, Isakov V, Khlystov A, Petersen W. 2007. The effects of roadside structures on the transport and dispersion of ultrafine particles from highways. Atmospheric Environment. Vol 41: pp. 8128-8139.

Brantley HL, Hagler GSW, Deshmukh PJ, Baldauf RW. 2014. Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. Science of The Total Environment. Vol 468-469: pp. 120–129.

Brode R, Wesson K, Thurman J. 2008. AERMOD sensitivity to the choice of surface characteristics. 101st Annual Conference of the Air & Waste Management Association, Portland, OR.

Buccolieria R, Salimb SM, Leoa LS, Di Sabatinoa S, Chanb A, Ielpoc P, Gennarod G, Gromke C. 2011. Analysis of local scale tree–atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. Atmospheric Environment. Vol 45: pp. 1702–1713.

Buccolieria R, Gromke C, Di Sabatinoa S, Ruck B. 2009. Aerodynamic effects of trees on pollutant concentration in street canyons. Science of The Total Environment. Vol 407: pp. 5247–5256.

Detto, M, Katul GG, Siqueira M, Juang, J-Y, Stoy P. 2008. The Structure of Turbulence Near a Tall Forest Edge: The Backward-Facing Step Flow Analogy Revisited. Ecological Applications, Vol 18: pp. 1420–1435.

Frank, C, Ruck B. 2008. Numerical study of the airflow over forest clearings. Forestry. Vol 81: pp. 259-277.

Gromke C, Buccolieria R, Di Sabatinoa S, Ruck B. 2008. Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations – Evaluation of CFD data with experimental data. Atmospheric Environment, Vol 42: pp. 8640–8650.

Hagler GSW, Lin M-Y, Khlystov A, Baldauf RW, Isakov V, Faircloth J. 2012. Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. Science of The Total Environment. Vol 419: pp. 7-15.

Health Effects Institute (HEI). 2010. Traffic-related air pollution: a critical review of the literature on emissions, exposure, and health effects. HEI Special Report 17. Health Effects Institute, Boston, MA.

Nowak DJ, Hirabayashi S, Bodine A, Greenfield E. 2014. Tree and forest effects on air quality and human health in the United States. Environmental Pollution. Vol 193: pp. 119-129.

Nowak DJ. 2005. Strategic tree planting as an EPA encouraged pollutant reduction strategy: how urban trees can obtain credit in state implementation plans. Sylvan Communities: pp. 23-27.

Nowak DJ, Civerolo KL, Trivikrama Rao S, Gopal S, Luley CJ, E. Crane D. 2000. A modeling study of the impact of urban trees on ozone. Atmospheric Environment. Vol 34: pp. 1601-1613.

Petroff A, Zhang L, Pryor SC, Belot Y. 2009. An extended dry deposition model for aerosols onto broadleaf canopies. Journal of Aerosol Science. Vol 40: pp. 218-240.

Steffens JT, Wang YJ, Zhang KM. 2012. Exploration of effects of a vegetation barrier on particle size distributions in a near-road environment. Atmospheric Environment. Vol 50: pp. 120-128.

Stone B, Norman JM. 2006. Land use planning and surface heat island formation: A parcel-based radiation flux approach. Atmospheric Environment. Vol 40: pp. 3561-3573.

Tong, Z.; Baldauf RW, Isakov V, Deshmukh P, Zhang KM. 2016. Roadside vegetation barrier designs to mitigate near-road air pollution impacts. Science of The Total Environment. Vol 541, pp. 920-927.

Wania, A., Brse M, Blond N, Weber C. 2012. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. Journal of Environmental Management. Vol 94, pp. 91–101.

# Summary Table

| Barrier Characteristic | Recommendation | Description |
|---|---|---|
| ***Physical Characteristics*** | | |
| 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. |
| ***Vegetation Characteristics*** | | |
| 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 |

# Summary Table

| Barrier Characteristic | Recommendation | Description |
|---|---|---|
| ***Other Considerations*** | | |
| 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 non-invasive species | The use of non-invasive species will ensure effective pollutant reductions without potential unintended consequences from invasive species adversely effecting 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) to preserve sight-lines and vegetation compatibility while avoiding potential wildlife/auto accidents and obstruction of outdoor advertising. |

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