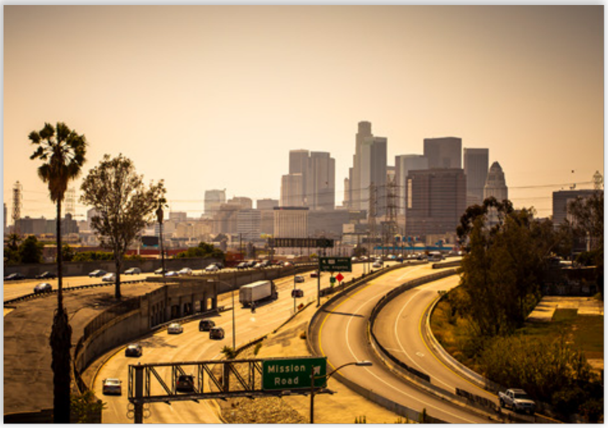
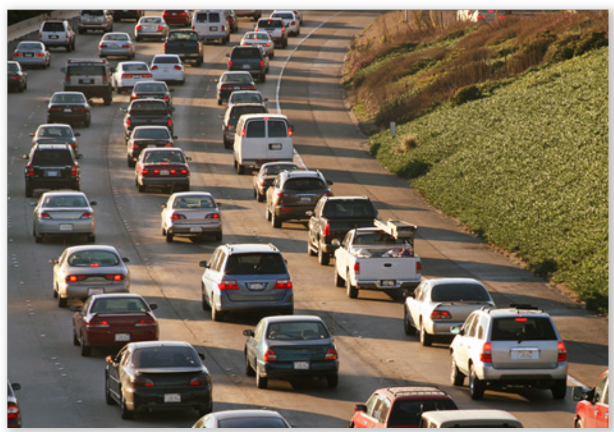
Effects of Roadside Barriers on Near-Road Pollutant Concentrations







Revised Final Report Prepared for

Washington State Department of Transportation
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December 2016 Revision

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Effects of Roadside Barriers on Near-Road Pollutant Concentrations

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Abstract

This work was completed as part of the Near-Road Air Quality Research Pooled Fund TPF-5(284), under the U.S. Federal Highway Administration Transportation Pooled Fund Program. The lead agency for TPF-5(284) is the Washington State Department of Transportation. Other TPF-5(284) participants include FHWA and the Arizona, California, Colorado, Ohio, Texas, and Virginia Departments of Transportation. Sonoma Technology, Inc., provides TPF-5(284) participants with technical, planning, facilitation, and website support.

Effects of Roadside Barriers on Near-Road Pollutant Concentrations

Background. Transportation projects that fail to meet federal, state, or local air quality goals may require mitigation measures to reduce project impacts. One strategy that has been identified to potentially mitigate project-level impacts is the use of a roadside barrier to block pollutant transport to receptors downwind. The objective of this study was to briefly summarize research to date on the effects of barriers on near-road air quality, and to assess the sensitivity of key parameters governing the effectiveness of roadside barriers, by generating a series of model scenarios and applying a line-source dispersion model developed by the U.S. Environmental Protection Agency (EPA).

Methods. Peer-reviewed literature examining the effects of roadside barriers on near-road concentrations was identified, acquired, and reviewed to determine the range of reductions in near-road concentrations that occur in the presence of a barrier. Based on the literature, we also identified key factors to examine via dispersion modeling and analyses, to gain a better understanding of how barrier effects might vary with changes in selected site parameters. Model scenarios were developed on the basis of literature review findings, and the EPA Research Line-Source (R-LINE) v2.0 dispersion model was applied to six scenarios identified as having a high potential for near-road pollution mitigation.

Results. The literature shows that barriers can effectively mitigate and dilute concentrations of mobile-source-emitted pollutants. The magnitude of the reductions depends on several factors but has been shown to be on the order of 20–60% within the first 100 meters of a road, assuming perpendicular wind conditions and a barrier of typical height (e.g., 6 m) set roughly at the edge of the road shoulder. The dispersion modeling analyses performed as part of this work indicate that concentrations downwind of a barrier are typically lower than they would be in the absence of a barrier and that barrier effectiveness increases with increasing barrier height, consistent with previous studies in the literature. The modeling work done here used a simplified site illustration and a tool under development by EPA. Further research is needed to more fully assess the ability of modeling tools to simulate barrier effects and to further examine how effects vary with site-specific conditions.

1. Introduction and Summary

Transportation projects that are at risk of failing transportation conformity tests or that fail to meet other state or local air quality goals may require mitigation measures to reduce project impacts and facilitate project approvals. Agencies have collectively identified a need to quantify the benefits of mitigation options for reducing near-road pollutant concentrations, summarize implementation lessons, and disseminate this information to inform future decision-making.

Over the past decade, interest in the effects of roadside structures, such as noise barriers and vegetation, on transportation-related pollutant concentrations near roadways has increased significantly. Through a variety of ambient monitoring, wind tunnel, and modeling studies, researchers estimate that roadside barriers may mitigate mobile source impacts near roadways in certain situations, depending on roadway and barrier configurations and meteorological conditions. Information that helps quantify the potential effects of barriers on near-road pollutant concentrations is needed to help transportation planners determine whether an existing roadside barrier or a new barrier feature could be used to help mitigate project-level air quality impacts.[1]

The intent of this work was to identify known near-road barrier effects on air quality, based on the literature, and to complete an initial assessment of dispersion modeled barrier effects using the latest applicable U.S. Environmental Protection Agency (EPA) modeling tools. This report summarizes pertinent research examining the effects of barriers on near-road air quality, including results from measurement, wind tunnel, and modeling studies; it also provides one illustration of modeled outcomes by presenting findings from a limited series of sensitivity analyses performed to model the effects of roadway and barrier configurations on near-road pollutant concentrations. These analyses used the EPA's R-LINE v2.0 dispersion model. The different model scenarios varied the barrier height, meteorological conditions, and vehicle emission release height. This study was conducted for research purposes and does not address model uncertainties or the potential for any unintended consequences associated with the placement of barriers near roadways. Near-road pollutant concentrations are a function of ambient background concentrations plus the added incremental impact of on-road mobile sources. The potential mitigation benefit of a barrier, as discussed in this report, applies to the on-road mobile source increment and not to ambient background concentrations.

Section 2 of this report summarizes the literature review findings. Section 3 summarizes dispersion model scenarios and presents results from the model runs. Section 4 documents conclusions and options for future work.

[1] For example, in May 2016, the Texas A&M Transportation Institute submitted a proposal in the annual American Association of State Highway and Transportation Officials (AASHTO) Call for Research Ideas to develop tools and procedures to model the effects of near-road barriers on near-road pollutant concentrations (http://environment.transportation.org/teri_database/idea_details.aspx?rid=1031).

2. Literature Review Findings

This section summarizes readily available findings from peer-reviewed scientific research, including measurement, wind tunnel, and modeling studies, examining the effects of barriers and roadway configurations on near-road pollutant concentrations. This summary identifies key factors, such as roadway configurations, barrier heights and placements, and meteorological conditions, that have a high potential for influencing near-road pollutant mitigation. This review was also used to inform the development of dispersion model scenarios.

2.1 Summary of Reviewed Literature

The presence of physical barriers, such as sound walls, vegetation, and/or buildings, as well as differences in a roadway's elevation in relation to the surrounding terrain, can alter pollutant concentrations in the near-road microenvironment. The effects of barriers and elevation differences have been studied in three ways: monitoring studies, wind tunnel tests, and computational modeling studies. Most existing studies focus on the scenario in which winds are perpendicular to the roadway direction. Under these crosswind conditions, studies show that a barrier or a difference in the elevation of a roadway in relation to the surrounding terrain (i.e., an above-grade or below-grade road) obstructs air flow, thereby decreasing concentrations on the leeward side (i.e., downwind) of the road for a distance that is dependent on the height of the barrier or grade, the wind speed, and proximity to the edge of the barrier.

STI examined near-roadway studies that evaluated pollutant concentration gradients in the vicinity of barriers or other elevated/depressed roadway configurations, regardless of pollutants measured or modeled. The existing body of literature includes few studies that measure particulate matter (PM) concentrations. Studies of ultrafine particles (UFP), black carbon (BC), carbon monoxide, or nitrogen oxides are more common. The biggest difference between these other pollutants and PM is that background concentrations of PM are much higher; therefore, the relative gradient in PM concentrations near the roadway is much smaller.

Tables 1 and 2, which are updated versions of a table initially developed by McCarthy et al. (2011) for the California Department of Transportation (Caltrans), show the studies that were reviewed. Table 1 summarizes studies that assess barrier-related reductions relative to a no-barrier control case; Table 2 summarizes results from studies that assess barrier-related reductions relative to the roadway.

Table 1. Summary of literature review findings on the effects of a barrier on near-road air quality. These studies all assess the percent reductions due to the barrier relative to a section of road without a barrier. Updated from McCarthy et al. (2011)

Pollutant	Type of Study	Barrier Height (m)	Wind Data (Duration, Direction, Speed)	Downwind Distance from Barrier (m)	% Reduction Relative to No-Barrier Control [c]	Reference
CO	Monitoring	6	Integrated, but directionally from road	15, 45, 95, 295	15−50%; not quantified by distance [c]	Baldauf et al. (2008b)
Particle counts (20 nm; 75 nm)	Monitoring	6	Integrated, but directionally from road	15, 45, 95, 295	15% for the first 100 m [c] for 20 nm; 15% for the first 40 m; −10% at 80-120 m [c] for 75 nm	Baldauf et al. (2008b)
NO_2, NO_x	Monitoring	4	>1 m/s, 1.5 years of data with wind direction ±60° from perpendicular	5, 10, 28	1%, 14%, 7% [c] for NO_2 27%, 20%, 13% [c] for NO_x	Dutch Air Quality Innovation Programme (2009)
PM_{10}	Monitoring	4	>1 m/s, 1.5 years of data with wind direction ±60° from perpendicular	5, 10	20%, 34% [c]	Dutch Air Quality Innovation Programme (2009)

Pollutant	Type of Study	Barrier Height (m)	Wind Data (Duration, Direction, Speed)	Downwind Distance from Barrier (m)	% Reduction Relative to No-Barrier Control [c]	Reference
Black carbon, particle counts >0.5 µm	Monitoring	~10	Integrated over 28 days	30 m	BC – 12.4% during downwind conditions [c] Particle counts – 0% during downwind conditions [c]	Brantley et al. (2014)
BC, CO, NO_2, UFP	Monitoring	~4.5	Integrated over one month	0-50, 50-150, 150-300	BC – [0–50 m] 43–48%; [150–300 m] 18–24% [c] NO_2 – [0–50 m] 34–37%; [150–300 m] 11–28% [c]	Baldauf et al. (2016)
Particle counts	Monitoring	3.7, 5.2	3.1 m/s 0.9 m/s	15 to 400	60% at 15 m, 0% at 100 m, 30% at 200 m [c] 55% at 15 m, 0% at 75 m, 50% at 150 m [c]	Ning et al. (2010)
BC, CO, NO_2	Monitoring	3.7, 5.2	3.1 m/s 0.9 m/s	15 to 400	22-60% at 15 m; -50 to -125% at 100 m; -38 to -105% at 200 m [c] 23-49% at 15 m; -67 to -122% at 60 m; -65 to -150% at 150 m [c]	Ning et al. (2010)
SF_6 (tracer)	Field experiment	6	1.4, 1.6, 3.6, 5.5 m/s	18 to 180	80% up to 120 m [c] 60–80% at 180 m [c] depending on wind speed	Finn et al. (2010)
Inert tracer	Wind tunnel	4	Not reported	Up to 110	60% reduction at 40 m [c]	Hölscher et al. (1993)
Inert tracer	Wind tunnel	6	4.97 m/s	Up to 240	>50% reduction at distances <60 m, converging to base case as distance increases [c]	Heist et al. (2009)
Inert tracer	Modeling	6	2.25 m/s	Up to 450	>90% reduction at distance <50 m, less than 50% reduction at distances greater than 50 m, slight increase at distances at 200–250 m [c]	Bowker et al. (2007)

Pollutant	Type of Study	Barrier Height (m)	Wind Data (Duration, Direction, Speed)	Downwind Distance from Barrier (m)	% Reduction Relative to No-Barrier Control [c]	Reference
Inert tracer	Modeling	6	3.6, 7.4, 1.65 m/s	Up to 180	Model reproduction of the Finn et al. (2010) field study using the Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model. Reductions of 80% up to 120 m [c]	Steffens et al. (2013)
Inert tracer	Modeling	3, 6, 9, 18	4 m/s	Up to 450	15−61% reduction at 20 m [c]	Hagler et al. (2011)
Inert tracer	Modeling	6	1.7, 3.6, 5.0, 7.4 m/s	Up to 240	Model reproduction of the Finn et al. (2010) field study and Heist et al. (2009) wind tunnel study using source shift and mixed-wake dispersion models. Reductions of 30-90% up to 120 m [c]: biased low under stable and high under unstable conditions.	Schulte et al. (2014)
Inert tracer	Modeling	3, 6, 9	2.5, 5, 10 m/s	Up to 360	Model reproduction of the Heist et al. (2009) wind tunnel study with additional simulation scenarios. Reductions in inert tracer concentrations between 10-70% within the first 90 m of the barrier [c]	Steffens et al. (2014)
Inert tracer	Modeling	2-20	12 m/s	Up to 250	Model simulation of double noise barrier as a function of the ratio of the height of the barrier to the width of the road. Characterizes different flow regimes as isolated roughness, wake interface, and skimming flow. Reductions of 20−90% [c]	Jeong (2014)
UFP	Modeling	6, 9, 10	1, 2, 4 m/s	100	Increased reductions in particle number counts when wide vegetative barriers or a combination of solid and vegetative barriers are implemented. UFP reductions up to 60% [c].	Tong et al. (2016)

Table 2. Summary of literature review findings on the effects of a barrier on near-road air quality. These studies all assess the percent reduction in concentration as a function of distance from the roadway relative to on-road concentrations; the effects of the barrier are not directly quantified. Updated from McCarthy et al. (2011)

Pollutant	Type of Study	Barrier Height (m)	Winds (Duration, Direction, Speed)	Downwind Distance from Barrier (m)	% Reduction Relative to Roadway [r]	Reference
CO	Monitoring	2.44	Integrated over 6 weeks	Not described	20% [r]	Nokes and Benson (1984)
$PM_{2.5}$, VOCs	Monitoring	1	Variable	2	65% [r] for $PM_{2.5}$; – 43% [r] for VOCs	McNabola et al. (2008)
NO_x	Monitoring	NA	>1 m/s under neutral atmospheric stability from road	5, 35, 70, 150 (variable)	15% at 65 m, 22% at 90 m relative to 30 m [r] 15% at 30 m, 38% at 55 m relative to 15 m [r]	Naser et al. (2009)
Particle counts	Monitoring	3.7, 5.2	3.1 m/s 0.9 m/s	15 to 400	60% at 15 m, 0% at 100 m, 30% at 200 m [r] 55% at 15 m, 0% at 75 m, 50% at 150 m [r]	Ning et al. (2010)
BC, CO, NO_2	Monitoring	3.7, 5.2	3.1 m/s 0.9 m/s	15 to 400	65−80% at 15 m; 30−40% at 100 m; 50−60% at 200 m [r] 65−75% at 15 m; 30−45% at 60 m; 50−55% at 150 m [r]	Ning et al. (2010)

The literature consistently shows a reduction in pollutant concentrations behind (downwind of) a solid barrier. Most modeling studies suggest that solid barriers loft pollution farther downwind behind the barrier; some of the measurement literature notes that the presence of a barrier may lead to increased concentrations farther downwind as the plume reattaches to the surface (Ning et al., 2010). However, the reattachment plume phenomenon has not been demonstrated conclusively across measurement studies. Additionally, the potential spatial scale of the reattachment plume depends on many variables, including the roadway configuration, barrier height, wind speed, and atmospheric stability.

Pollutant concentrations directly behind a barrier are lower than both on-road concentrations and roadways with no barrier. This finding is qualitatively consistent across monitoring, model, and wind tunnel exercises. The magnitude of the pollution reduction due to the presence of a barrier varies widely across the different monitoring studies and pollutants of interest, with some studies reporting reductions as small as a few percent (Brantley et al., 2014; Dutch Air Quality Innovation Programme, 2009) and others reporting reductions as high as 75% (Ning et al., 2010; Finn et al., 2010). A majority of previous studies show reductions of approximately 20−60% within the first 100 m, and approximately 25−65% within the first 50 m, downwind of a barrier (Nokes and Benson, 1984; Baldauf et al., 2016; 2008a; 2008b; Tong et al., 2016; Brantley et al., 2014; Hagler et al., 2012; 2010; 2009; Bowker et al., 2007; Jeong, 2014). Several studies indicate that dispersion models are able to reproduce the reduction in concentrations due to the presence of barriers in the near-road environment under relatively stable atmospheric conditions (Steffens et al., 2014; 2013; 2012; Schulte et al., 2014). Under unstable conditions, models are less effective at representing downwind concentrations (Schulte et al., 2014). Models may also be less effective at representing edge effects; however, few measurement studies are available to validate models under these conditions.

Elevated and depressed roadways are also effective at reducing downwind pollutant concentrations. Mitigation of near-road air quality impacts by a solid barrier or elevated/depressed roadway configuration occurs by isolating the on-road pollution. For elevated roadways, the on-road pollution is lofted to a plume height of approximately 1.5 times the height of the barrier/grade. This plume may reattach to the surface at a distance of approximately 15 times the height of the barrier/grade (Ning et al., 2010; Heist et al., 2009; Steffens et al., 2014) and may or may not lead to a slight increase in concentrations at the point of reattachment compared to similar conditions where no barrier is present. The surface concentrations behind the barrier are reduced, assuming there are no additional pollution sources leeward of the barrier such as frontage or access roads that can emit within the recirculation zone.

Dispersion modeling tools indicate that the location and spatial extent of a pollution plume is a function of barrier height, roadway grade, wind speed and direction, and vehicle-induced turbulence (a function of traffic counts, speed, and fleet mix). Given that meteorological and traffic characteristics change over short time scales, the spatial location of the reattachment plume (if any) is also likely to change over short time scales. The distance at which the plume reattaches to the surface has been estimated by Heist et al. (2009) to be 10 to 30 times the height of the barrier, and by Finn et al. (2010) to be more than 30 times the height of the barrier. A more recent modeling study estimates a distance of approximately 15 times the height of the barrier (Steffens et al., 2014). The variable nature of these findings suggests that the location of plume reattachment (if it occurs) is highly variable depending on a large number of meteorological and roadway configuration factors.

A key modeling study that covers the largest range of near-road configurations is a study by Steffens et al. (2014), which investigated the following sets of roadway configuration variables:

- Barrier height (no barrier, 3 m, 6 m, 9 m)
- Barrier configuration (no barrier, barrier on the upwind side, barrier on the downwind side, and barriers on both sides)
- Roadway configuration (at grade, elevated with angled slope, depressed with no slope, depressed with angled slope)
- Wind speed (2.5 m/s, 5 m/s, and 10 m/s)
- Additive effects (combining differences in barriers and roadway configuration)
- Edge effects (what happens near the edge of the noise barrier)

Steffens et al. (2014) found that a single barrier, on either side of the road, is almost as effective as a double barrier (a barrier on each side of the road). The initial displacement of air around the barrier disrupts the flow of air over the road, resulting in lower downwind concentrations in both cases.

In the modeling literature, barrier height and roadway grade have the largest effect on downwind concentrations when winds are perpendicular to the roadway. The barrier lofts the plume of on-road pollution, resulting in possible dilution of the plume and a reduction in concentrations at downwind receptors compared to the no-barrier case. The effect is stronger for higher barriers, but the flow regime changes if the ratio of the height of the barrier to the width of the road exceeds 0.15 (Jeong, 2014). In an early paper examining this effect, researchers found that a height-to-width ratio of less than 0.3 results in an isolated roughness flow regime (Oke, 1988). In these cases, the movement of air across the barrier produces vortices like those seen in urban canyons, which can result in increased concentrations in the on-road environment.

Studies indicate that edge effects are an important factor governing the effectiveness of barriers at reducing pollutant concentrations downwind. The “edge” in this instance refers to the vertical edge at the end of the barrier; for example, in the case of a half-mile-long sound wall, the edge refers to the sound wall terminus at either end of the half-mile wall. Steffens et al. (2014) found that relative pollutant concentrations increase more than 10% within 150 meters of the edge of the barrier on the downwind side, because air flow wraps around the edge of the barrier and transports higher on-road pollution to the back (downwind) side of the barrier.

Computational fluid dynamics (CFD) modeling and wind tunnel studies suggest that the largest reductions in downwind concentrations would be achieved by combining a below-grade roadway with a barrier at the top of the grade. This is predicted to result in greater reductions in downwind concentrations than those from an equivalently sized barrier in an at-grade road scenario (Steffens et al., 2014; Heist et al., 2009).

In addition to the literature just discussed, in July 2016, EPA published Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality (Baldauf, 2016). The guidance includes important considerations and recommendations for designing a roadside vegetative barrier to mitigate air quality impacts from the roadway, based on characteristics that have been shown to effectively reduce near-road air pollutant concentrations. The report also provides links to additional resources for siting, designing, and maintaining roadside vegetative barriers. Although the focus of the guidance is on design characteristics for vegetative barriers, many of the considerations are also applicable to solid barriers and can be used to optimize their mitigation potential, such as

- Use a higher barrier to achieve greater downwind reductions in pollutant concentrations,
- Minimize gaps in the barrier that can lead to increased pollutant concentrations downwind, and
- Ensure that the barrier end is not located near sensitive receptors.

Figure 1 highlights findings from the literature, and shows results from a controlled field experiment, wind tunnel studies, and three model studies. All of the studies used inert tracers or model equivalents to estimate the reductions in concentrations behind a barrier relative to a no-barrier case. Each study included an approximately 6 m high barrier and relatively high wind speeds perpendicular to the barrier. In each case, reductions are greatest directly behind the barrier, decreasing as a function of distance behind the barrier. In the controlled field experiment (which used hay bales to represent a barrier and a tracer gas to measure effects), the reduction was relatively constant as a function of distance from the barrier; in the wind tunnel and model studies, the reduction is largest close to the barrier and decreases rapidly over the first 100 m.

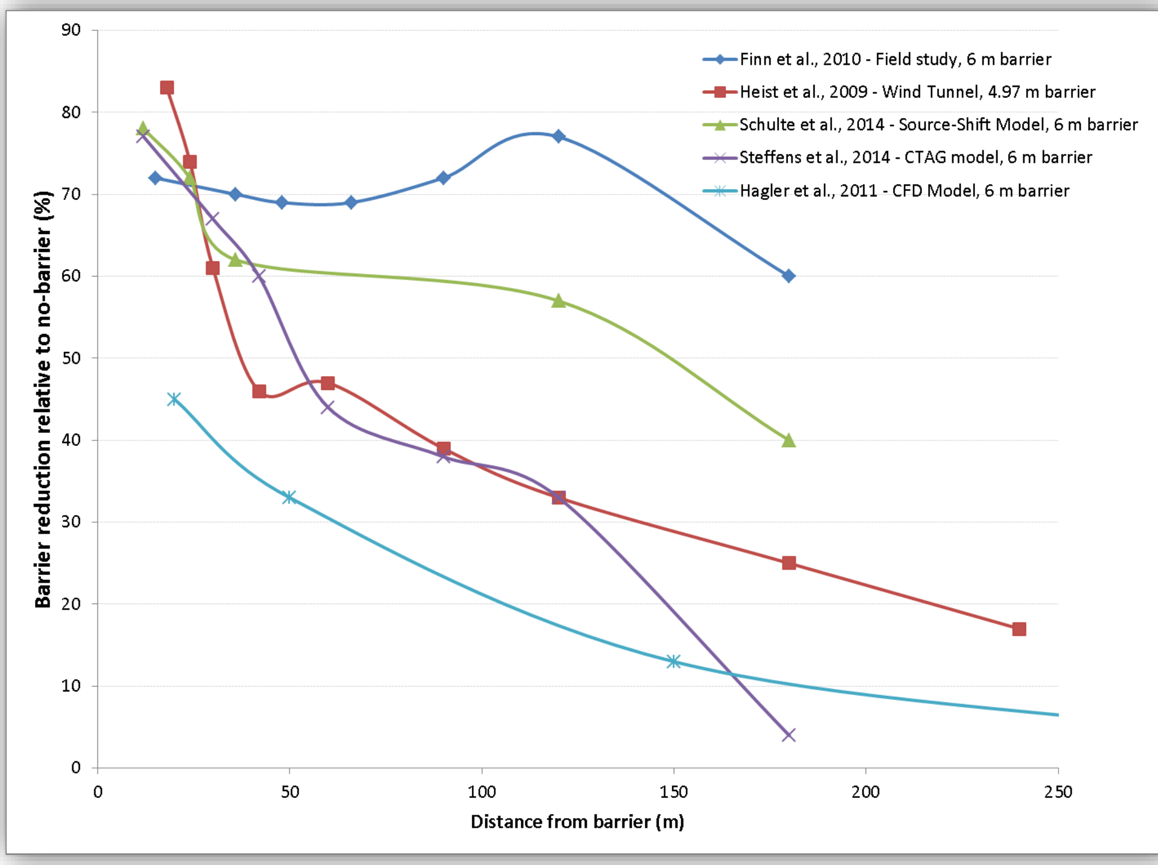

Figure 1. Results of previous controlled field, wind tunnel, and modeling studies, showing percent reduction in pollutant concentrations in the presence of a barrier (relative to no-barrier) versus distance from the barrier.

2.2 Key Factors Influencing Pollutant Concentrations Near Roadways

The key factors influencing concentrations in the near-road environment include:

- Source strength – number and type of vehicles and their emission rates
- Distance from the road to the receptor
- Meteorological conditions – wind speed, direction, and mixing height

The key parameters that have been examined regarding barriers' effectiveness in reducing near-road concentrations when winds are perpendicular to the road include:

- Barrier height
- Roadway configuration (above-grade, below-grade, at-grade)
- Barrier configuration (upwind, downwind, neither, or both; distance from road)

- Barrier length – edge effects
- Barrier type – solid or vegetative
- Meteorological conditions – primarily atmospheric stability/buoyancy, wind direction, and wind speed

On the scale of tens of meters to a few hundred meters from the roadway, studies suggest that barriers can effectively mitigate and dilute concentrations of mobile source-emitted pollutants. The magnitude of the reductions depends on the matrix of factors listed above. Both measurement and model studies indicate that the largest reductions occur within the first 50 m of the road, with the magnitude of the reduction typically decreasing by at least 20% after the first 50 m relative to the initial reduction. Within the first 100 m, typical modeled reductions are approximately 20-80%, with a majority of the reductions falling between 40-75%. Effects from the five measurement studies range from a 100% increase in concentrations to a 50% decrease in concentrations; a majority of the studies showed reductions between 0 and 40%. If we take the mid-points of the 0-40% range and the 40-75% range, we estimate reductions on the order of 20-60% within the first 100 meters of a road, assuming a barrier of typical height (e.g., 6 m) set roughly at the edge of the road shoulder, and assuming that winds are perpendicular to the roadway. Using a similar approach, we estimate reductions within the first 50 m to be on the order of 25-65%. Differences between modeling and measurement studies, as well as differences among findings from studies examining the same pollutant type, indicate there are substantial uncertainties in the quantitative effects of barriers. Furthermore, effects from an actual barrier will be a function of many site-specific factors.

3. Dispersion Modeling Results

This section describes model scenarios generated to assess the influence of roadside barriers on near-road pollutant concentrations, and summarizes effects on air quality and sensitivity to key parameters based on dispersion modeling results. This work provides one illustration of modeled outcomes and is not a formal model performance evaluation. Model scenarios were designed to enable assessment of effects free of other potentially confounding issues and do not replicate scenarios presented in the literature. The results provide an initial assessment of the comparability of modeled barrier effects using the latest applicable EPA modeling tools.

3.1 R-LINE Model v2.0

The R-LINE model is a research-grade dispersion model developed by the EPA Office of Research and Development (ORD) for assessing air quality impacts near roadways. R-LINE is based on a steady-state Gaussian formulation and is designed to simulate emissions from line-type sources (e.g., mobile sources along roadways) by numerical integration of point source emissions. R-LINE models the dispersion of pollutants released near the surface using vertical and lateral dispersion rates based on field and wind tunnel study measurements. The model uses surface meteorology developed using the AERMET meteorological data preprocessor. R-LINE is optimized for flat roadways; however, beta-option algorithms are available for simulating the effects of complex roadway configurations, such as roadside barriers and depressed roadways, in the publicly available version 1.2. The performance of the base version of the R-LINE model (without beta-option barrier or depressed roadway configurations selected) has been evaluated by comparison with other Gaussian dispersion models (AERMOD, CALINE) and with near-road concentrations from independent field studies (e.g., Heist et al., 2013; Snyder and Heist, 2013). R-LINE is not an EPA-approved model for PM hot-spot analyses.

At the time this work was performed, the publicly available version of R-LINE was version 1.2 (https://www.cmascenter.org/r-line/); however, version 2.0 was under active development and was expected to be released in 2016.[2] Model enhancements in Version 2.0 include

- The option to use hourly varying emission rates
- The option to model multiple pollutants
- Three optional NO_x chemistry algorithms
- An improved barrier algorithm to simulate increased mixing downwind of the barrier due to the change in flow patterns induced by the barrier, consistent with field study observations
- Updated input file formats
- Improved computational speed[3]

[2] Source: David Heist, Research Physical Scientist, U.S. Environmental Protection Agency; personal communication with Steven G. Brown, January 2016.

[3] Source: David Heist, Research Physical Scientist, U.S. Environmental Protection Agency; personal communication with Steven G. Brown, April 2016.

Given the expected improvement in barrier algorithm performance over Version 1.2, EPA recommended that we use Version 2.0 for our modeling.[4] Thus, Version 2.0 was used for the analyses described below. At the time this study was performed, the depressed roadway algorithm was not yet available in R-LINE v2.0.

The R-LINE barrier algorithms were derived from Schulte et al. (2014), and are based on the observation of increased mixing downwind of the barrier due to the change in flow patterns induced by the barrier. Barriers affect dispersion of roadway emissions by: (1) increasing vertical dispersion through turbulence generated in the wake of the barrier, (2) inducing vertical mixing behind the barrier in the cavity region, and (3) lofting the emissions plume above the barrier (Schulte et al., 2014). The effects of the barrier and changes to vertical lofting were expected to be largest during perpendicular wind conditions; therefore, the underlying formulation of R-LINE barrier algorithms was based on experimental data sets and wind tunnel studies that focused on wind directions close to perpendicular to the road (Schulte et al., 2014). Prior work supported by EPA found that R-LINE performance was superior when winds were ±40 degrees of perpendicular to the road (Snyder and Heist, 2013; Schulte et al., 2014). In this study, we limited our analysis to perpendicular wind directions within 40 degrees of perpendicular, as shown in Section 3.2.1, for consistency with previous work.

R-LINE Development Status

At the time this work was performed, the R-LINE model was still under development and was updated from Version 1.2 to Version 2.0 during the project. The design status of Version 2.0 used for this work somewhat restricted the analyses that could be completed. Some of the important design features of Version 2.0 that governed our sensitivity work include:

- Roadway configurations were limited to at-grade roads; depressed and elevated roadway configurations had not yet been implemented in R-LINE v2.0. However, algorithms for depressed configurations were under active development.
- Only a single noise barrier could be modeled. Algorithms for configurations with noise barriers on both sides of the road had not been implemented, although a placeholder had been reserved in R-LINE for development to allow for a second barrier (R-LINE User's Guide, v1.2).
- Results had been evaluated for winds only in a narrow sector perpendicular to the road. Parallel and upwind conditions had not been evaluated. If a barrier is upwind of the roadway, R-LINE ignores the barrier (R-LINE User's Guide, v1.2).
- Only solid barriers could be modeled at the time the analysis was performed. Options for vegetative barriers had not yet been implemented.

[4] Source: David Heist, Research Physical Scientist, U.S. Environmental Protection Agency; personal communication with Steven G. Brown, February 2016.

3.2 Model Scenario Development

3.2.1 Model Setup

Model scenarios were applied to a 10-lane highway, with five 3.6 m lanes in either direction. The modeled roadway was 1.1 miles long and was configured in the southwest to northeast direction such that the predominant wind patterns in the meteorological data were aligned perpendicular to the roadway. A five-year AERMET (version 15181) meteorological data set for 2010−2014 processed by the San Joaquin Valley Air Pollution Control District[5] for the Fresno, California, airport was used.

Figure 2 illustrates the roadway setup for modeling. Figure 3 shows the side view of the roadway and barrier configuration, along with the predominant wind direction. A single barrier was located downwind of the road 3.05 meters from the roadway edge. There was no barrier on the upwind side of the road. The wind rose in Figure 4 shows wind speeds and directions in the five-year Fresno AERMET meteorological data set. The perpendicular wind direction was set to 315 degrees because the winds originate from the northwest a majority of the time in the data set. We limited our analysis to conditions when wind directions were within 40 degrees of perpendicular to the roadway line source (i.e., an 80 degree arc from 275 to 355 degrees in the Fresno meteorological data set, see Figure 2 and discussion in Section 3.1).

For model scenarios including a barrier, a barrier the same length as the roadway (1.1 miles) was located 21.05 m southeast (downwind) of the roadway centerline, or 3.05 m from the edge of the road. This location was selected to represent an example of the minimum lateral clearance between a barrier and edge of the travel way allowable in state DOT sound wall design specifications, and therefore represents a practical implementation example (California Department of Transportation, 2006). A barrier extending the full length of the roadway was modeled to minimize potential influences from edge effects discussed in the literature (see Section 2).

Model receptors were located 1, 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 75, 100, 150, 200, 250, and 300 meters downwind of the barrier, extending out from the center of the road (Figure 2), at 1.8 meters in height to represent concentrations near ground level (U.S. Environmental Protection Agency, 2015). Hourly average concentrations for each receptor were modeled.

[5] http://www.valleyair.org/busind/pto/tox_resources/airqualitymonitoring.htm#met_data.

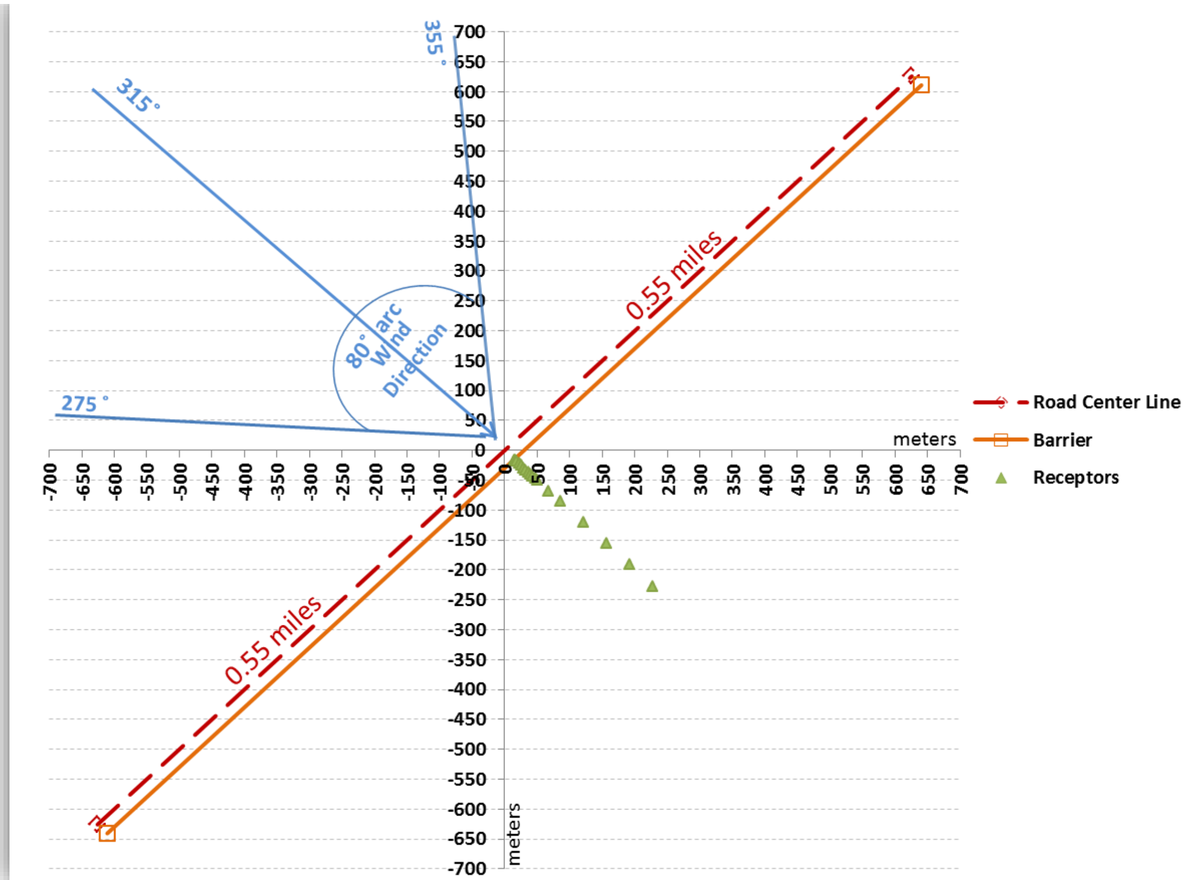

Figure 2. Aerial view illustrating the configuration of the modeled roadway and predominant wind direction relative to the barrier and receptors.

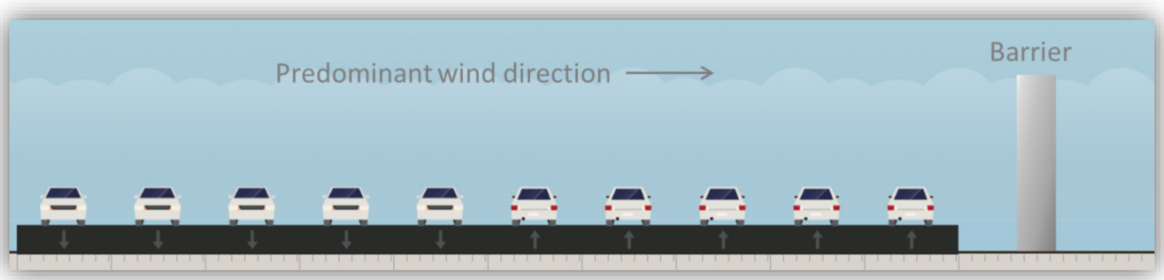

Figure 3. Side view illustrating the configuration of the modeled roadway and predominant wind direction relative to the barrier. Image created using STREETMIX (http://streetmix.net).

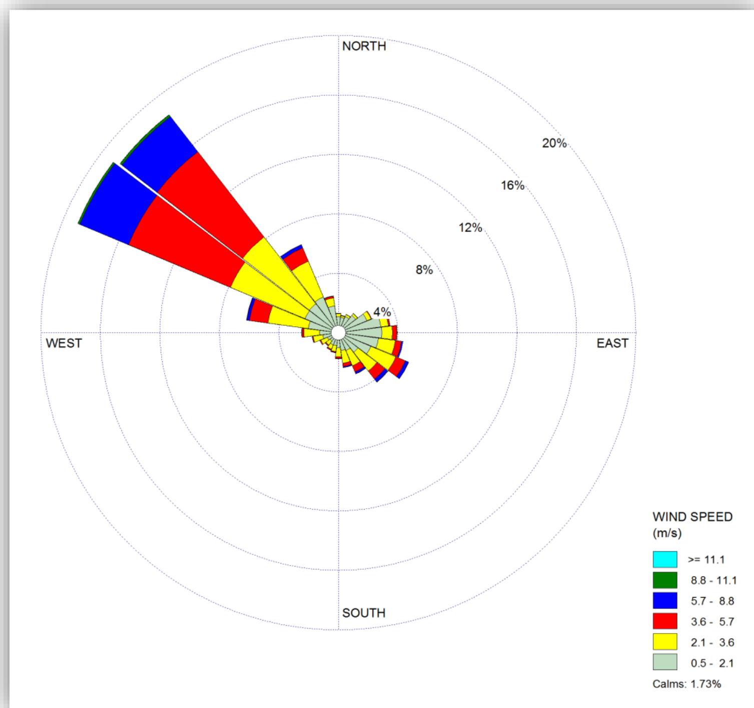

Figure 4. Wind rose illustrating predominant wind speeds and directions in the Fresno AERMET data set (2010–2014) used in this study.

The ratio of displacement height to roughness length (f-factor) was set to 7.7 using the average surface roughness in the AERMET file and the displacement height from Table 2 of the R-LINE v1.2 guidance document (Snyder and Heist, 2013). The numerical method option was employed for all scenarios, using the default total plume plus meander option. The average weighted vehicle height was based on 8% truck and 20% truck scenarios (1.73 m and 2.02 m respectively), based on the EPA 2015 Transportation Conformity Guidance for PM Hot-Spot Analyses, Appendix J (U.S. Environmental Protection Agency, 2015). Corresponding initial plume dispersion (sigma-z) parameters were 1.37 m for the 8% truck scenarios (Scenarios 0–3) and 1.60 m for the 20% truck scenarios (Scenarios 4 and 5). The scenarios are described in Section 3.2.2.

3.2.2 Model Scenarios

In light of the literature review summarized in Section 2, six model scenarios were developed to examine the effects of barrier height and average vehicle height on pollutant concentrations in the near-road environment. For each of these scenarios, the influences of meteorological conditions were also examined. Table 3 summarizes model scenarios generated for this study.

The base case scenario (Scenario 0) is a roadway consistent with an example of a project of air quality concern (POAQC) described in the final PM hot-spot analysis rule issued by the EPA in 2006 (U.S.

Environmental Protection Agency, 2006), with 125,000 AADT, 8% truck traffic, and no barrier. The emission rate associated with the base case is approximately 2.02 x 10^{-5} g m^{-1} s^{-1} $PM_{2.5}$, based on daily-average 2015 MOVES model $PM_{2.5}$ emissions (running exhaust, tire wear, and brake wear); this emission rate is held constant and is not varied diurnally.[6] While this study presents results for $PM_{2.5}$ as an example, the results presented in this report are applicable to the dispersion of other inert pollutants (e.g., CO) as well. Three scenarios (Scenarios 1, 2, and 3) that vary the barrier height relative to the base case were developed; barrier heights of 2.5 m, 5 m, and 7.5 m were modeled using the same traffic and fleet mix as the base case. These barrier heights fall within the range of heights commonly found in the literature (see Tables 1 and 2) and were selected to incrementally span a range of possible heights consistent with heights referenced by FHWA[7] and state departments of transportation. For example, the heights fall within the typical range of wall heights in Virginia, where noise walls are typically constructed to be 12 to 16 ft in height but can be up to 30 ft high;[8] similarly, the 2.5 m and 5 m heights fall within the acceptable range for sound wall heights specified in Caltrans' sound wall design specifications (California Department of Transportation, 2006).[9]

The final two scenarios (Scenarios 4 and 5) were modeled to examine the effects of varying the average vehicle height associated with a different fleet mix (e.g., fraction of trucks in the fleet) on downwind concentrations for the no-barrier and 5 m barrier cases. The increase in average vehicle height was based on a weighted average fleet mix of 20% truck traffic and 80% light-duty autos. The emission rate was not changed to represent a 20% truck fleet mix; the aim was to examine only the sensitivity of changing the average vehicle height, which changes the height of the initial dispersion of the plume emitted from the line source. The roadway elevation and surrounding terrain were held constant in all scenarios.

[6] An equivalent EMFAC-based 2015 emission rate for the base case scenario is 1.71 x 10^{-5} g m^{-1} s^{-1} $PM_{2.5}$.
[7] http://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/keepdown.cfm.
[8] Source: Chris Voigt, Virginia Department of Transportation; personal communication with Ashley R. Graham, May 2016.
[9] Caltrans' sound wall design specifications state that the minimum allowable height of a barrier is six feet. The maximum allowable height is 14 feet if the barrier is less than 15 feet from the edge of the roadway, and 16 feet if the barrier is more than 15 feet from the edge of the roadway.

Table 3. Model scenarios examined in this work.

Scenario	Modeling Factor	Barrier Height (m)	Average Vehicle Height (m)[a]
0	Base Case	No barrier	1.73
1	Barrier Height	2.5	1.73
2		5	1.73
3		7.5	1.73
4	Average Vehicle Height (Fleet Mix)	No barrier	2.02
5		5	2.02

[a]Average vehicle height of 1.73 m represents a fleet mix of 8% trucks and 92% cars. Average vehicle height of 2.02 m represents a fleet mix of 20% trucks and 80% cars.

3.3 Model Results – Air Quality Outcomes

In this section, dispersion modeling results are presented by barrier height, meteorology, and vehicle height. As discussed earlier, published work to date indicates that R-LINE performance is superior when winds are ±40 degrees of perpendicular to the road. In this case, therefore, modeling was performed for ±40 degrees of perpendicular (275 to 355 degrees) to the barrier. Thus, all results here are for the 80-degree arc where the barrier is downwind of the roadway; these conditions existed for a total of 23,412 hours over the five years of hourly meteorological data (about half of the total time). As noted later (Section 4), additional measurement and model development work could better characterize barrier effects for a range of meteorological conditions.

3.3.1 Barrier Height

Figure 5 shows the average normalized pollutant concentrations as a function of distance from the barrier when winds are within 40 degrees of perpendicular of the roadway with (1) no barrier, (2) a 2.5 m barrier, (3) a 5 m barrier, and (4) a 7.5 m barrier (Scenarios 0 through 3). Concentrations are normalized by the concentration for the no-barrier scenario at 1 m from the barrier location. Concentration gradients are shown at a 1.8 m receptor height, which EPA uses to represent a typical breathing height for an adult human. In the absence of a barrier, pollutant concentrations originating from the roadway decrease by 50% within the first 100 m of the road. The model predicts that the presence of a barrier reduces the maximum concentrations downwind of the roadway; the taller the barrier, the larger the reduction. In the presence of a 2.5 m barrier, concentrations are estimated to be reduced by approximately 17−24% relative to the no-barrier case.

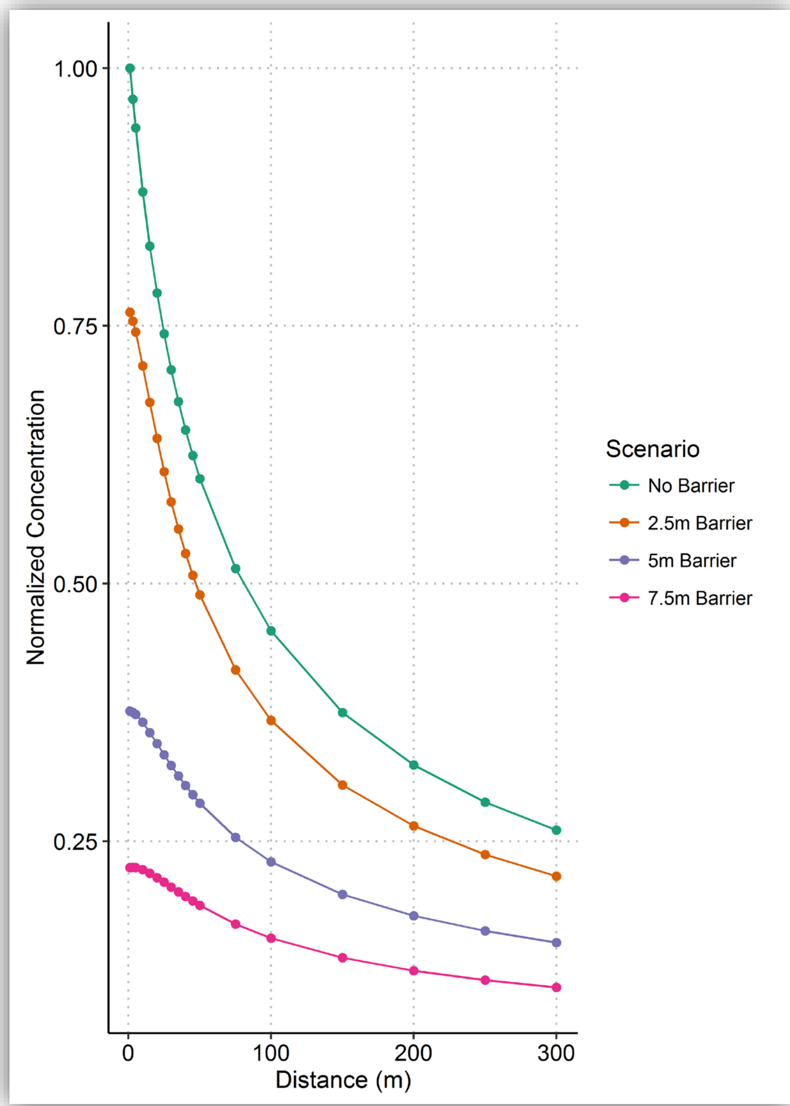

Figure 5. Average normalized concentration by receptor distance from the barrier for model scenarios with no barrier and with a 2.5 m, 5 m, and 7.5 m barrier, for winds within 40 degrees of perpendicular to the barrier (275 to 355 degrees). All concentrations are normalized relative to the modeled concentration for the no-barrier scenario at 1 meter from the barrier location. Distances are measured from the barrier's location at 3.05 m from the road edge.

Figure 6 shows the ratio of concentrations for each scenario with a barrier to concentrations for the no-barrier scenario (i.e., the decrease in modeled concentrations when a barrier is next to the roadway compared to when there is no barrier). Table 4 summarizes the modeled average percent concentration reduction by barrier height and distance from the barrier, compared to the no-barrier scenario. Concentrations at 1 m from the barrier are reduced by 24% for a 2.5 m barrier, by 62% for a 5 m barrier, and by 78% for a 7.5 m barrier, compared to the no-barrier case. For the 2.5 m barrier, the concentration reduction relative to the no-barrier case is greatest in the wake of the barrier, decreasing with increasing distance to approximately 25 meters, and then increasing by a few percent out to approximately 100 m before leveling off at a reduction of approximately 19%. The 5 m and 7.5 m barriers exhibit steeper percent reduction gradients for the first 50 m and then shift towards a more gradual slope of reduction relative to the no-barrier case.

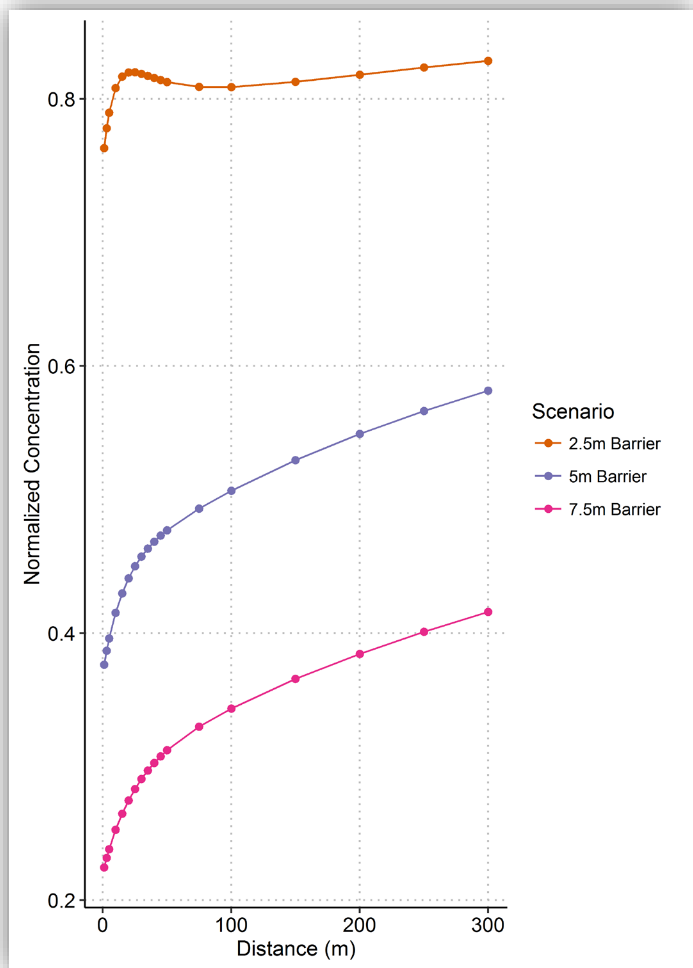

Figure 6. Ratio of modeled concentrations in the presence of a 2.5 m, 5 m, and 7.5 m barrier relative to the no-barrier case by receptor distance from the barrier, with winds within 40 degrees of perpendicular to the barrier (275 to 355 degrees).

Table 4. Modeled average percent reduction in concentrations at receptors due to a barrier relative to the no-barrier case, with winds within 40 degrees of perpendicular to the barrier (275–355 degrees).

Receptor Distance (m)	% Reduction Relative to No-Barrier Scenario		
	2.5 m Barrier	5 m Barrier	7.5 m Barrier
1	24	62	78
3	22	61	77
5	21	60	76
10	19	58	75
15	18	57	74
20	18	56	73
25	18	55	72
30	18	54	71
35	18	54	70
40	18	53	70
45	19	53	69
50	19	52	69
75	19	51	67
100	19	49	66
150	19	47	63
200	18	45	62
250	18	43	60
300	17	42	58

3.3.2 Meteorology

The figures in the previous section summarize results for all meteorological conditions when the receptors are downwind (±40 degrees) of the roadway. However, the effectiveness of the barrier at mitigating pollutant concentrations varies with wind speed, wind direction, and other meteorological parameters. In this section, we compare modeled concentrations between the 5 m scenario and no-barrier scenario by wind speed and wind direction. In the following figures, ratios of less than one indicate that concentrations behind the 5 m barrier are lower than those in the no-barrier scenario, while ratios above one indicate that the concentrations are higher for the barrier case. The box whisker plots show the median ratio as the central notch in the box plot, with the interquartile range (25^{th} to 75^{th} percentile) indicated by the range of the box.

Figure 7 shows the ratio of concentrations between the 5 m barrier scenario and the no-barrier scenario, grouped by wind speed and wind direction for all receptors. At low wind speeds (<2 m/s), the barrier reduces concentrations by 60−70% on average, but at wind speeds greater than 3 m/s, the barrier reduces concentrations by only 30%. This is inconsistent with the modeling results presented by Steffens et al. (2014), which showed a modest relationship between wind speed and concentration reductions behind a barrier; they attributed most of the difference to on-road turbulence. However, in Steffens et al. (2014), the lowest wind speeds were 2.5 m/s, higher than the wind speeds under which the greatest differences are observed in this study. A previous study examining the effects of vegetative barriers found a stronger influence of wind speed, but attributed it to deposition effects (Steffens et al., 2012). In the Fresno meteorological data set used in this work, a majority of low wind speed conditions occur at night, when there is no convective mixing, resulting in more plume stratification. Although the highest pollutant concentrations are likely to occur at low wind speeds, most model and measurement studies report results for wind speeds greater than 2 m/s.

Figure 8 shows the variation of the barrier to no-barrier ratio as a function of wind direction in the sector perpendicular to the roadway. For the 5 m barrier scenario, a greater reduction in modeled concentrations was observed for winds originating from 335−355 degrees than for winds originating from 270−335 degrees. This is primarily because the meteorology (i.e., wind speed, atmospheric stability) varies by wind direction within the 80 degree downwind arc. The 335−355 degree wind directions occurred relatively more often at night, while the other wind directions occurred primarily during the daytime, typically at higher wind speeds. At night, atmospheric stability is typically higher and wind speeds are lower, resulting in a stronger reduction of pollution from the barrier under these conditions. This is reflected in the diurnal profile of the concentration ratio comparing the 5 m barrier scenario to the no-barrier scenario (Figure 9). During daytime, there is greater atmospheric mixing and more dispersion, resulting in an average reduction in pollution of about 31% across all receptors during daytime hours; at night, however, this reduction averages 43%. AERMET meteorological data used by R-LINE includes two different types of mixing: mechanical mixing and convective mixing. Mechanical mixing occurs at all hours, whereas convective mixing occurs only during daytime hours when there is incoming radiation, surface heating, and turbulence in the lower atmosphere. Convective mixing reduces the relative effects of the barrier because roadway emissions are initially more dispersed and diluted during unstable convective conditions.

For the simplified illustration used here, modeled concentrations in the presence of a barrier were higher than the modeled concentrations in the absence of a barrier during some hours (ratios greater than one in Figures 5-7). This was true only during the daytime, for all downwind wind directions, when wind speeds were less than 3 m/s. Of the 23,412 model-hours analyzed, modeled increases in concentrations in the presence of a barrier (compared to the no-barrier scenario) occurred in 248 hours, or 1.1% of the time.

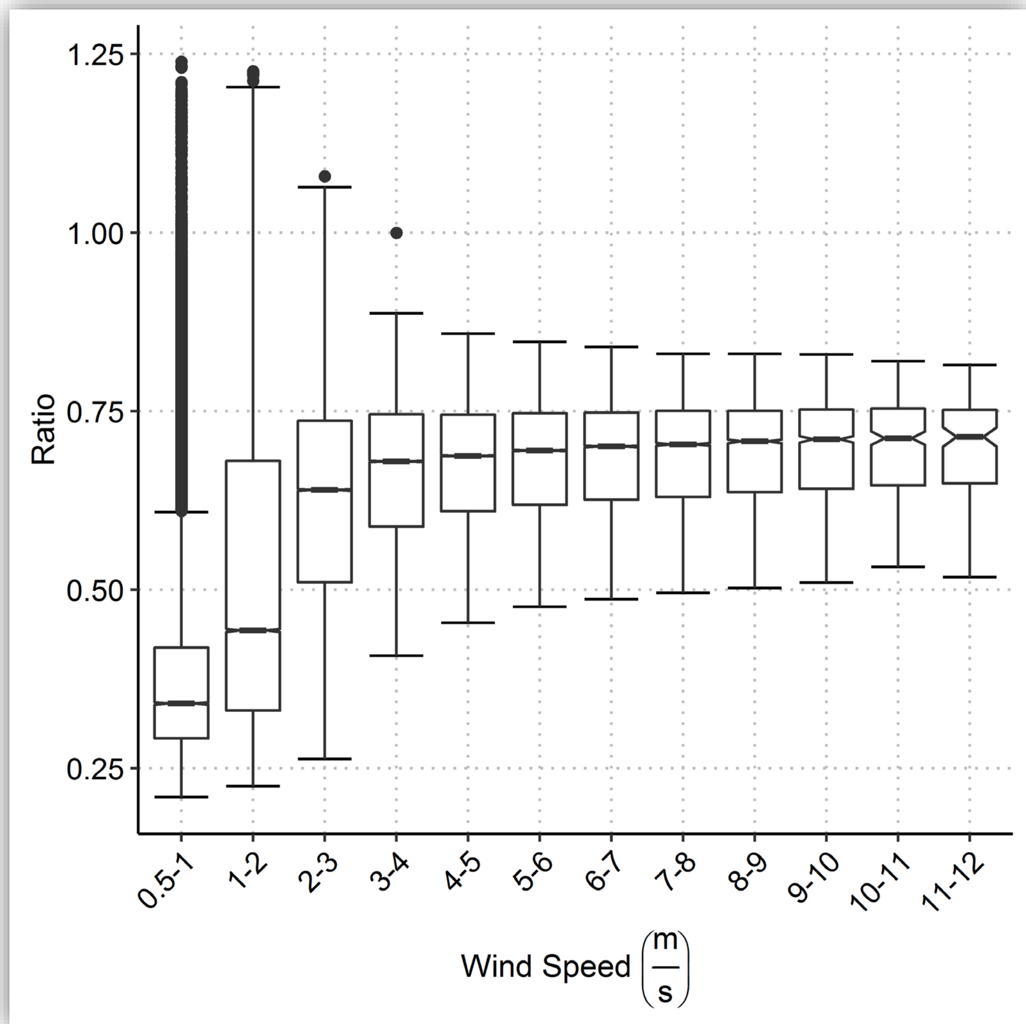

Figure 7. Ratio of concentrations for the 5 m barrier scenario relative to no barrier for all receptors, versus wind speed for winds near-perpendicular to the barrier (275 to 355 degrees).

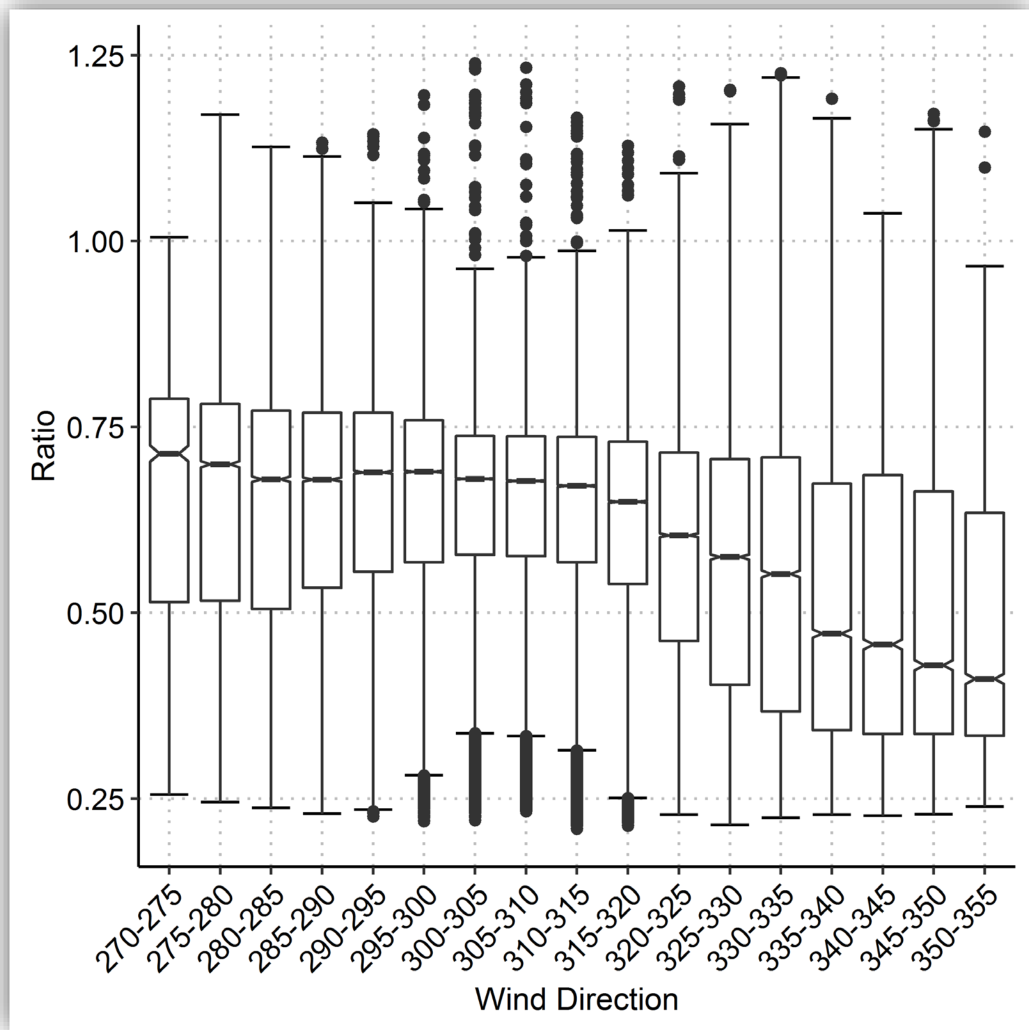

Figure 8. Ratio of concentrations for the 5 m barrier scenario relative to no barrier for all receptors, versus wind direction.

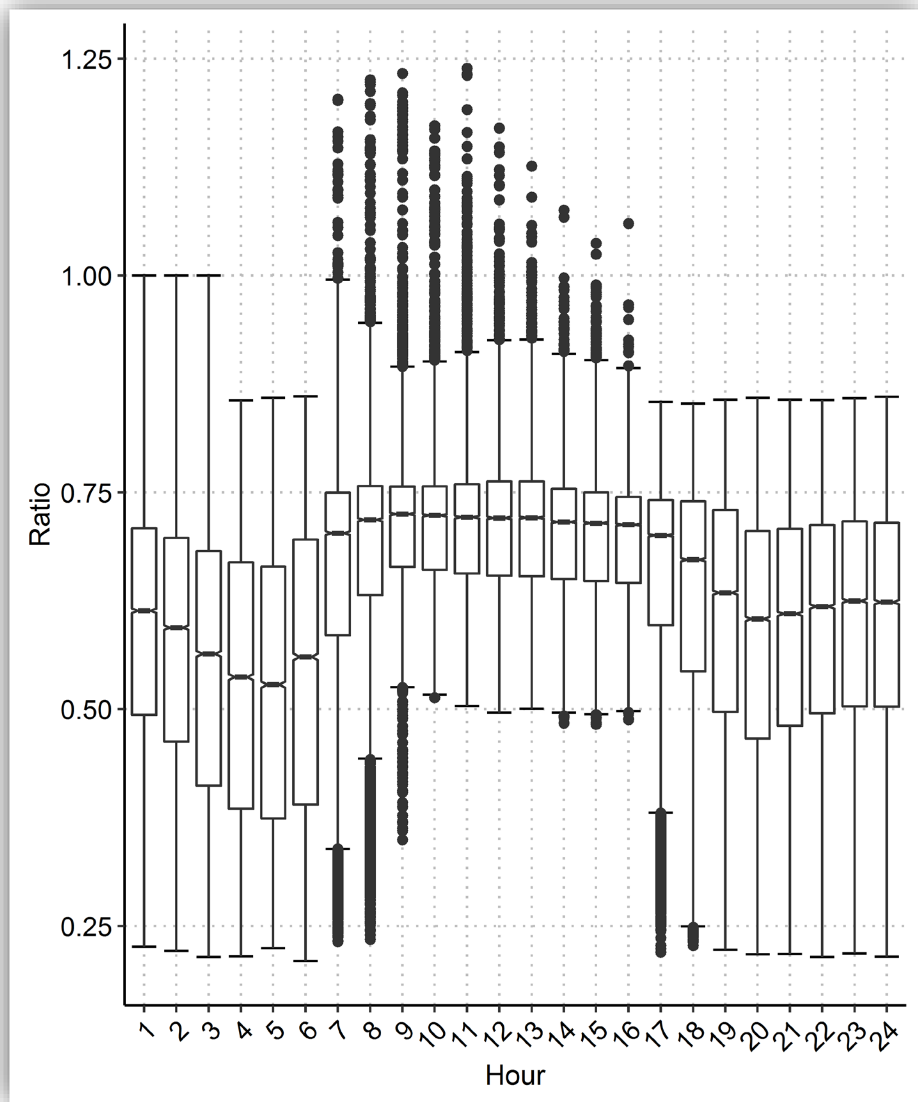

Figure 9. Ratio of concentrations for the 5 m barrier scenario relative to no barrier for all receptors, versus hour of the day.

3.3.3 Average Vehicle Height

Figure 10 shows the ratio of results for a 1.73 m average vehicle height versus a 2.02 m average vehicle height, for the no-barrier and 5 m barrier cases (a ratio of less than one indicates lower concentrations for a 2.02 m vehicle height). On average, modeled concentrations for the 1.73 m and 2.02 m scenarios are very similar. Concentrations for the 2.02 m vehicle height were from 3% (5 m barrier) to 5% (no barrier) lower at 1 m from the roadway than concentrations for the 1.73 m average vehicle height. By 300 m from the road, the average difference in concentrations between the 2.02 m and 1.73 m vehicle heights is approximately 2% for both the no-barrier and 5 m barrier cases.

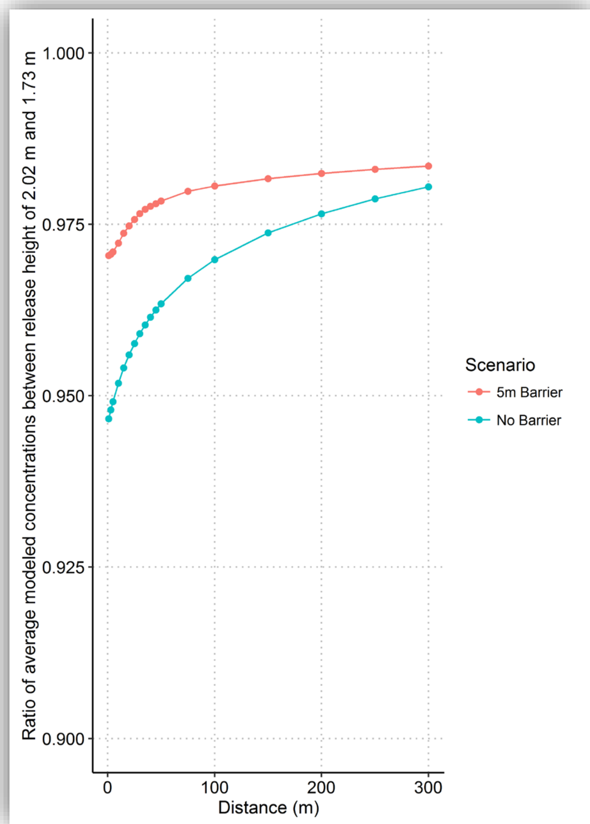

Figure 10. Ratio of average modeled concentrations for average vehicle heights of 2.02 m and 1.73 m by receptor distance for the no-barrier and 5 m barrier cases.

3.3.4 Summary of Results Compared with Literature

Figure 11 includes the results from previous controlled field experiment, wind tunnel, and modeling studies that were shown earlier in Figure 1, and also presents the modeling results from this study for the 2.5 m, 5 m, and 7.5 m barrier cases. The 5 m results from this study fall within the range of barrier reductions relative to no-barrier reported in the literature for similar barrier heights, at distances from the barrier ranging from approximately 25 m to 150 m. Modeled reductions for a 5 m barrier within approximately 25 m of the barrier were lower in this study (~55-60%) than in a majority of previous modeling studies (~75-80%), whereas modeled reductions at 200-250 m from this study were higher (~45%) than those from previous modeling studies (~10-20%).

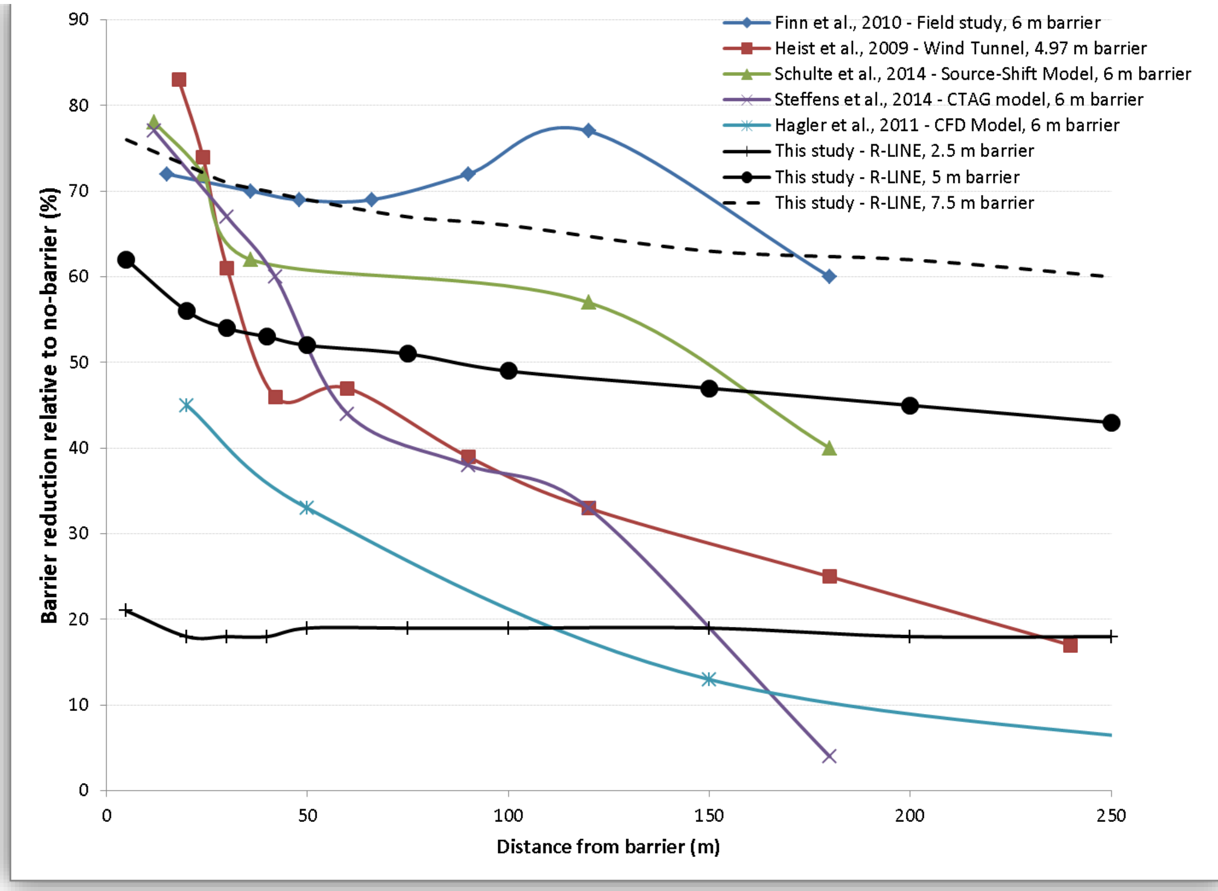

Figure 11. Percent reduction in pollutant concentrations in the presence of a barrier (relative to no-barrier) versus distance from the barrier. Results shown are from previous controlled field, wind tunnel, and modeling studies (shown in Figure 1), plus the 2.5 m, 5 m, and 7.5 m barrier height model results from this study.

4. Conclusions and Options for Future Work

4.1 Summary of Results and Discussion

This study involved (1) assessing the status of the science regarding pollutant measurements and modeling in the presence of roadside barriers; (2) generating scenarios to test the sensitivity of dispersion model predictions of pollutant concentrations to barrier height, meteorological conditions, and emission release height; and (3) applying a dispersion model to the scenarios to examine, for a simplified case study illustration, the potential effects of solid barriers on near-road pollutant concentrations. The simplified modeling scenarios described here were designed to exclude potentially confounding issues such as roadway geometry. Future work could examine more complex cases and test how well the latest versions of dispersion modeling tools replicate measurement and other modeling studies from the literature.

The base case for the modeling was a roadway consistent with a POAQC example described in the final PM hot-spot analysis rule issued by the EPA (U.S. Environmental Protection Agency, 2006). The EPA-based example involves a highway with 125,000 AADT and 8% diesel truck traffic (i.e., 10,000 trucks per day). The project team compared concentrations from the base case scenario with no barrier and an average vehicle height consistent with the POAQC example to three scenarios with varying barrier height and the same traffic conditions. Two additional scenarios were also developed that modeled an average vehicle height consistent with 125,000 AADT and 20% diesel truck traffic (i.e., 25,000 trucks per day). The effects of meteorological conditions on modeled concentrations were examined for all six scenarios.

The near-road barrier literature consistently shows that the presence of physical barriers, such as sound walls, can substantially alter pollutant concentrations in the near-road environment. Overall, the literature shows that pollutant concentrations downwind of a barrier are lower than both on-road concentrations and concentrations in the absence of a barrier, although study results varied widely and a limited number of studies indicated that barriers could increase downwind concentrations at some locations. Studies indicate that the effectiveness of a barrier at mitigating pollutant concentrations depends on many barrier, road configuration, and meteorological factors. Although there is variability within the literature, an approximation of typical barrier effects can be derived by qualitatively focusing on the more consistent findings across the literature, and identifying a mid-point for the range of effects in the measurement and modeling findings published to date. These findings indicate that barriers typically reduce pollutant concentrations on the order of 20−60% within the first 100 m and approximately 25−65% within the first 50 m downwind of a 6 m barrier, although actual effects will be a function of many site-specific factors.

Dispersion modeling analyses performed as part of this work indicate that concentrations downwind of a barrier are typically lower than they would be in the absence of a barrier, that barrier effects are greatest close to the barrier, and that barrier effects increase with increasing barrier height, consistent with previous studies in the literature. In addition, the modeling analyses found, on average, the effectiveness of a barrier at mitigating near-road pollutant concentrations is inversely proportional to wind speed and is also sensitive to atmospheric stability. The findings from the simplified illustration modeled here are consistent with the overall literature findings that the use of a roadside barrier can help mitigate near-road air quality impacts.

As of this writing, the 2015 proposed revisions to 40 CFR Part 51 Appendix W, *Guideline on Air Quality Models*, specify AERMOD as the regulatory option for near-road dispersion modeling. AERMOD does not currently include the option to model the effects of roadside barriers; however, given the emerging body of literature demonstrating near-road barrier effects, it would be beneficial for a future version of AERMOD, or another tool approved by EPA for use in hot-spot analyses, to incorporate the ability to assess the effects of roadside barrier features. Through the development of the R-LINE model, EPA is developing the ability to quantify the effects of new or existing barriers on pollutant concentrations downwind of a roadway. However, at the time this work was performed, R-LINE was under active development. To assist with conformity hot-spot analyses, EPA-approvable analysis methods are needed to quantitatively assess barrier effects and to post-process AERMOD or other hot-spot modeling results. Until EPA-approved modeling tools become available, interim approaches are needed.

The information presented in this report could be used as a starting point to engage in interagency discussion regarding the possibility of developing conservative adjustment factors to represent barrier effects. For example, assume a very simplified case where a 6 m barrier was installed adjacent to an at-grade straight road in simplified terrain. As noted earlier, the literature indicates pollutant reductions are typically on the order of 25−65% within the first 50 m downwind of a barrier approximately 6 m in height. One way to conservatively apply the findings from this work to such a simplified case would be to assume that the barrier would reduce pollutant concentrations by 25% within the first 50 m of the road under conditions when the roadway is downwind of the barrier (i.e., use the lower end of the typical range of effects indicated by the literature). Using this example in a hot-spot analysis context, concentrations could be modeled for a no-barrier scenario, and then, to represent a “build barrier” scenario, a 25% reduction could be applied to the concentration estimates corresponding to the downwind conditions supported by the literature. Of course, in a real-world case, many factors will govern barrier effects including barrier type, barrier and roadway configuration, barrier length, pollutant type, and meteorological conditions such as wind speed and atmospheric stability. More work is therefore needed to establish a detailed methodology for calculating and adjusting estimated barrier effects based on predominant wind patterns or other factors. As shown in this report, the modeling and measurement literature indicates there are substantial uncertainties in quantitative effects of barriers, and outcomes might include zero or negative reductions under some circumstances. However, in concept, the findings documented here could be used to support interagency consultation on expected barrier effects, and to develop step-by-step analysis methods that could be used to represent typical, lower-bound (conservative) barrier effects under selected site conditions.

4.2 Options for Future Work

Given the substantial interest in and potential benefits of the use of barriers to reduce near-road air pollutant concentrations, this section presents several examples of studies that could be performed to build upon this work and improve the quantitative estimates of near-road barrier effects.

Option 1: Develop a Case Study and Literature-Based Methods for Estimating Barrier Effects

To support the development of an approach to quantify barrier effects on near-road concentrations, one option is to complete a pilot study that (1) selects a real-world project scenario and links that project's site-specific conditions to barrier effects factors supported by the literature, (2) provides a step-by-step analysis methodology to estimate barrier effects by appropriately considering and applying the literature-based findings to a specific case, (3) shares the proposed methodology with the appropriate interagency stakeholders if the project involves interagency consultation, and (4) adjusts the methodology, as needed, to reflect interagency feedback, and applies the adjusted methodology to the project to estimate "with-barrier" pollutant concentrations. The findings can be presented as a range of expected barrier effects, with the lower end of the range suitable for use if interagency consultation favors a conservative estimate of barrier effects. Alternatively, a hypothetical project rooted in real-world data could be used, such as the case study described in the Near-Road Pooled Fund Task Order 2 (Scoping Study to Identify Potential Project Types and Situations That Will Not Create PM Hot Spots); that case study was based on an EPA-created case and is consistent with EPA hot-spot analysis training materials. A study using a hypothetical case could illustrate the range of expected barrier effects based on the literature, and provide an approach for how one might select a conservative representation of those outcomes for a particular project. At the appropriate time, these findings could be shared with EPA and/or other potentially interested stakeholders to solicit their feedback, address comments, and identify future analyses needed to address concerns and update the methodology for use with real-world projects.

Option 2: Perform a Field Study to Examine Edge Effects

As discussed in this report, many factors influence barrier effects on near-road pollutant concentrations. In particular, results from previous modeling studies suggest that edge effects are an important factor governing barrier effects; however, there are limited data from measurement studies available to quantify edge effects or to support development and validation of modeling algorithms. A field study could be designed and implemented to further examine and quantify edge effects. The study would examine the area spatially affected by the barrier edge to better define how far a barrier would need to extend to minimize the influence of edge effects on downwind receptors and thereby safeguard against unintended pollutant concentration consequences from barrier use. The study could be conducted in three separate phases: (1) design and deploy the field study; (2) analyze field study measurements to assess barrier effects (including edge effects) on near-road concentrations; and (3) leverage the measurement data to conduct a model-versus-measurement comparison assessing how well selected modeling tools, such as R-LINE, can represent near-road concentrations near the edge of a barrier, and to develop recommended modeling improvements as needed.

Option 3: Perform a Field Study to Examine Meteorological Conditions and Plume Reattachment

Meteorological Conditions

As discussed earlier, dispersion modeling results show that the effectiveness of a barrier at reducing pollutant concentrations downwind varies with meteorological parameters, including wind speed, wind direction, and atmospheric stability. While the scenarios modeled in this study did not replicate those in previous studies, important differences between the results presented in this study and those presented in other modeling and measurement studies are largely related to atmospheric stability. Using meteorological data from nighttime conditions, when wind speeds were low (<2 m/s), this work found that the presence of a barrier resulted in larger reductions in concentrations compared to daytime conditions when convective wind currents were stronger and the atmosphere was less stable. However, few measurement or modeling studies have characterized the low wind speed and nighttime conditions we modeled as having the greatest barrier effects. As a result, it is unclear how well the dispersion modeling results generated from this study represent real-world outcomes. Dispersion model performance (AERMOD, for example) is known to have limitations when modeled wind speeds are less than 1 m/s (for example, where the friction velocity (u*) is under-predicted during stable conditions; see: Paine et al., 2012). In addition, as noted earlier, studies indicate that dispersion models are better able to reproduce the reduction in concentrations due to the presence of barriers in the near-road environment under relatively stable atmospheric conditions (Steffens et al., 2014; Steffens et al., 2013; Steffens et al., 2012; Schulte et al., 2014). Under unstable conditions, models are less effective at representing downwind concentrations (Schulte et al., 2014).

Measurement and modeling studies under stable, low-wind-speed, nighttime conditions are important for accurately characterizing 24-hr pollutant concentrations near roadways, particularly since low wind speeds tend to be associated with higher near-road pollutant concentrations. More field study measurement work is needed to assess how well dispersion models represent barrier effects under low-wind-speed (i.e., calm) meteorological conditions.

Furthermore, this study and a majority of studies documented in the literature assessed the effects of barriers when winds originate from directions within 40 degrees of perpendicular to the roadway and barrier. Additional field study and modeling data that can be used to assess the effects of barriers for all wind directions are needed to more fully characterize the quantitative effects of barriers and the associated uncertainties.

Reattachment Plume Location and Resulting Concentrations

A limited subset of the literature suggests that, in some situations, the presence of solid barriers may enhance pollutant concentrations, relative to a "no barrier" case, at some distance downwind of the barrier as the plume reattaches to the surface. As discussed in this report, higher "with barrier" concentrations at plume reattachment locations have not been demonstrated conclusively across studies. Furthermore, the spatial scale of the reattachment plume likely varies with roadway configuration, barrier height, wind speed, and atmospheric stability.

Also, as shown in Figures 5 through 7, modeling performed as part of this study found in a small fraction (1.1%) of cases that barriers resulted in higher concentrations at some locations under some circumstances. Although this study focused on a limited number of dispersion modeling scenarios and did not replicate scenarios presented in the literature, these concentration enhancements appear to be inconsistent with the broad findings available to date in the literature. More field measurement work is needed to assess the location of plume reattachment downwind of a barrier, and to investigate whether and under what conditions the plume, once reattached to the ground, is substantively higher in concentration than in a no-barrier case. The goal of such work would be to help assess whether higher "with barrier" concentrations are largely a modeling artifact or are reflective of real-world outcomes under certain conditions.

Option 4: Perform Additional Model Sensitivity Analyses

The number of modeling scenarios that could be examined as part of this study was limited because the R-LINE model was still under active development. Additional modeling scenarios and sensitivity analyses could be completed to compare modeled outcomes with previous measurement, wind tunnel, and other modeling studies. Such analyses would enhance understanding of model performance and the potential effects of roadside barriers on downwind concentrations. Of particular interest are the effects of depressed or elevated roadway configurations. Previous modeling and wind tunnel studies have shown that a scenario combining a below-grade roadway with a barrier at the top of the grade produces greater reductions in downwind concentrations than a scenario that places an equivalently sized barrier at the same grade as the roadway (Steffens et al., 2014; Heist et al., 2009). At the time this work was performed, the depressed roadway beta-algorithm in R-LINE v2.0 was still under active development by EPA. Given the potential indicated by previous studies for a mitigation enhancement associated with a depressed roadway configuration, future modeling could be performed to assess the effects of varying roadway depression depth.

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