
Cornell University

# Modeling the effects of roadside structures on near-road air pollution

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Cornell University

# Acknowledgement


- Gayle Hagler and Rich Baldauf at USEPA
- Wei Tang and Matt Freeman, Lockheed-Martin
- Tom Whitlow and EERL CFD modelers, Yan Wang, Bo Yang and Andy Hall at Cornell University

# Outline

- Summary of available models
- Findings from existing modeling studies
  - Noise barriers
  - Selected European studies.
  - Preliminary results from EERL
- Limitations of existing studies
- Knowledge gaps
- Implications

# Related Studies

- There are numerous modeling studies on the effects of vegetation canopy on boundary layer turbulence.
- Street canyon studies provide good background on micro-scale modeling.

# Vegetation model

Sink term on momentum equation:

$$S_d = -c_d \cdot a \cdot |U| \cdot u_i$$

Source term on turbulent kinetic energy (*k) transport equation:*

$$S_k = c_d a\left(\beta_p |U|^3 - \beta_d |U| k\right)$$

Source term on turbulent kinetic energy dissipation (□ ) transport equation:

$$S_\varepsilon = c_d a\left(c_\varepsilon \beta_p |U|^3 \frac{\varepsilon}{k} - c_\varepsilon \beta_d |U| \varepsilon\right)$$

# Computational Fluid Dynamics (CFD) models

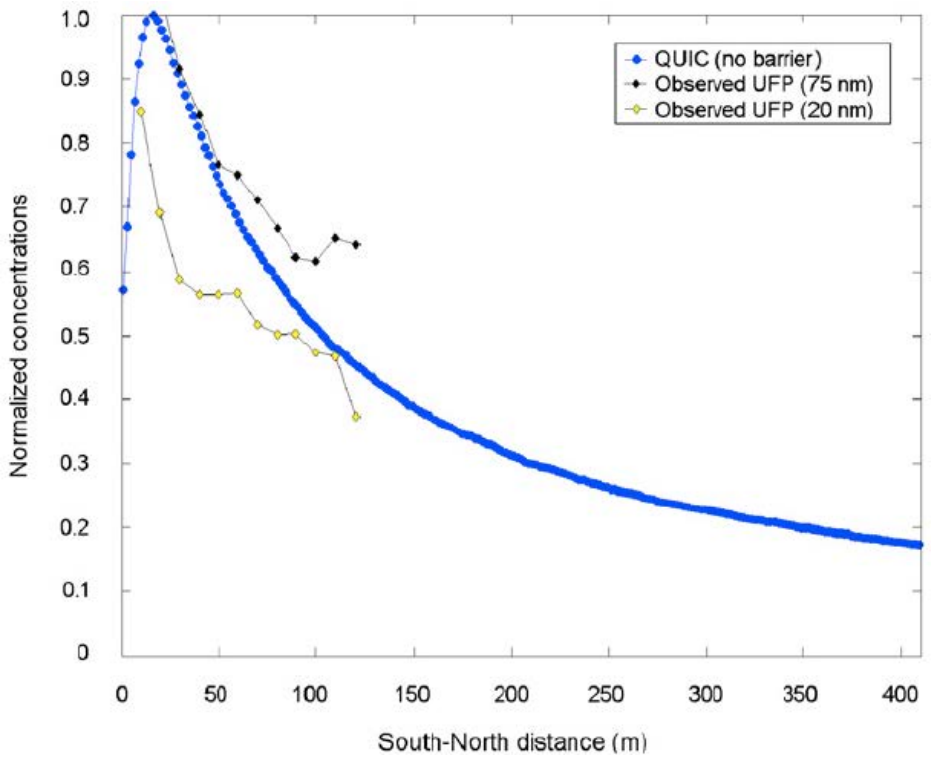
- Solving Navier-Stokes equations using finite difference and finite volume methods in two or three dimensions.
- Turbulence is modeled using different formulations, e.g., *Reynolds-averaged Navier–Stokes approach (k–ε model, RNG k–ε model, Realizable k–ε model), and Large-Eddy Simulation (LES) approach.*
- Computational cost depending on resolution
- Widely used in street canyon simulations
- Recently used in modeling air quality near large roads
- CFD capable of simulating vegetation effects: URVE, ENVI-MET, M2UE, …

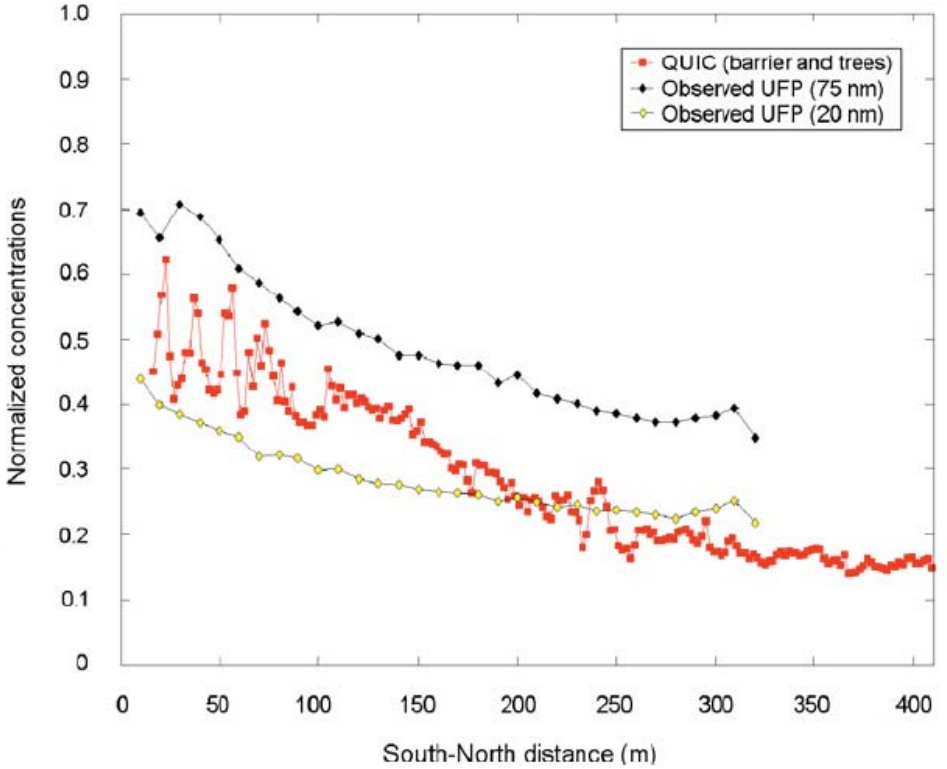
# QUIC (Quick urban & Industrial complex)

- Does not solve Navier-Stokes equations
- The buildings and stands of trees treated as solid, non-porous, rectangular blocks
- Use empirical formulation of flow around blocks to predict the flow patterns in the entire domain
- Relatively computationally inexpensive
- Employed in several studies on noise and vegetation barriers (Bowker et al., 2006; Bowker et al., 2007)

Bowker, G.E., Gillette, D.A., et al. (2006). Modeling flow patterns in a small vegetated area in the northern Chihuahuan Desert using QUIC (Quick Urban & Industrial Complex). Environmental Fluid Mechanics 6, 359–384.
Bowker, G. E., R. Baldauf, et al. (2007). "The effects of roadside structures on the transport and dispersion of ultrafine particles from highways." Atmospheric Environment 41(37): 8128-8139.

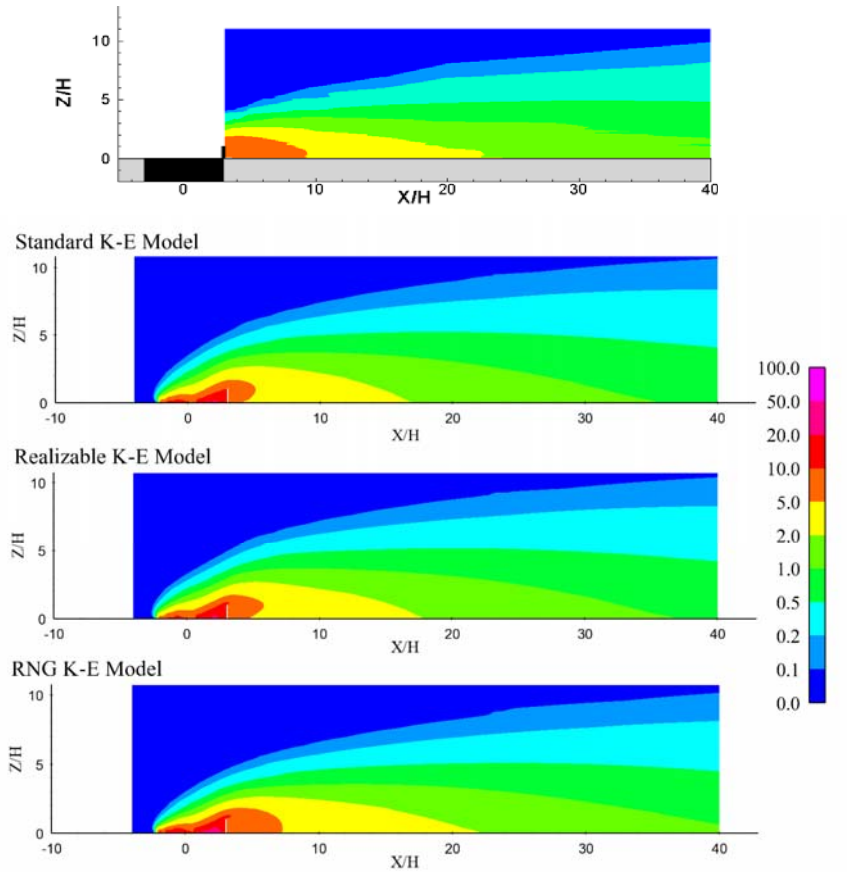
# QUIC Results

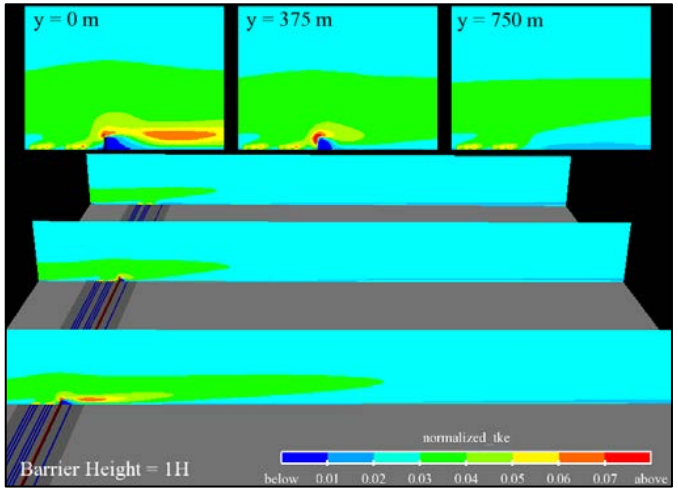


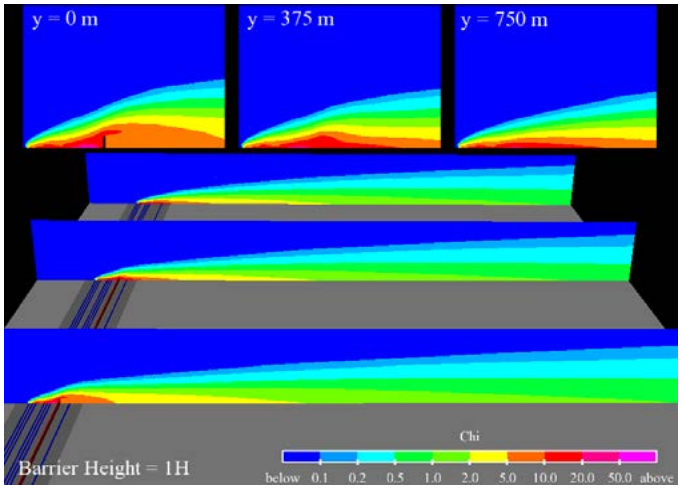




Bowker, G. E., R. Baldauf, et al. (2007). Atmospheric Environment 41(37): 8128-8139

# Noise Barriers: Simulations of wind tunnel data



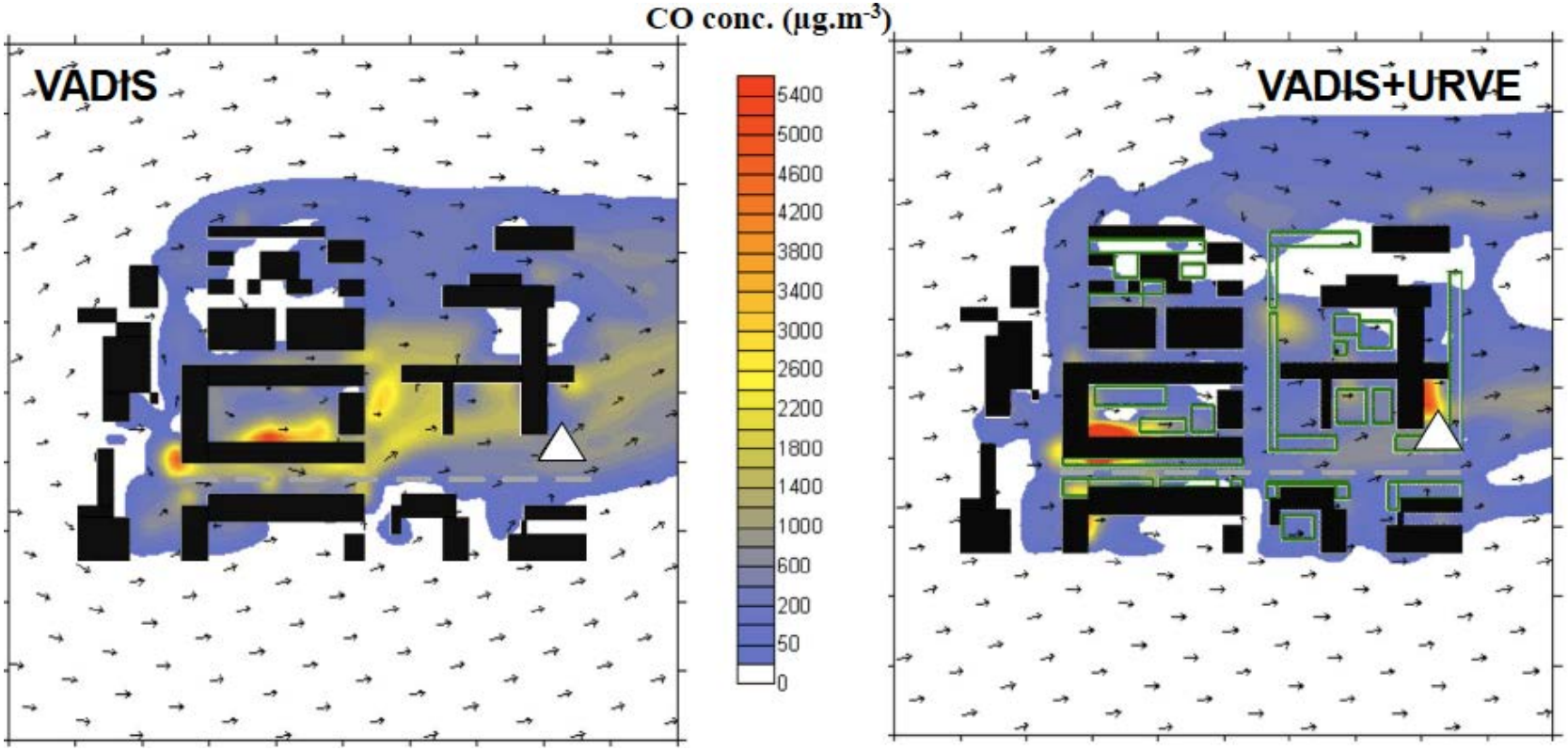




Hagler et al., Computational fluid dynamics modeling to assess the impact of roadside barriers on near-road air quality. CWE2010

Heist, D. K., S. G. Perry, et al. (2009) Atmospheric Environment 43(32): 5101-5111

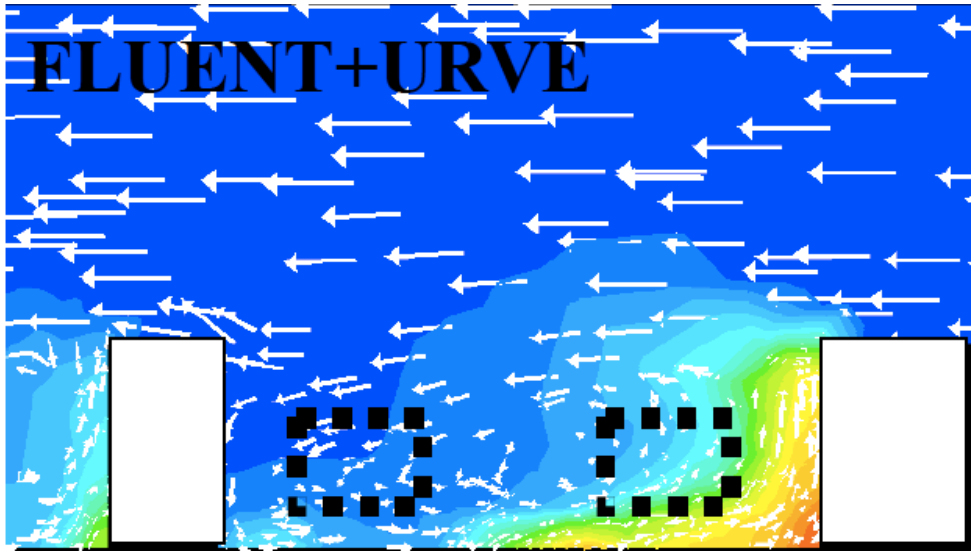
# URban VEgetation module (URVE) - 1



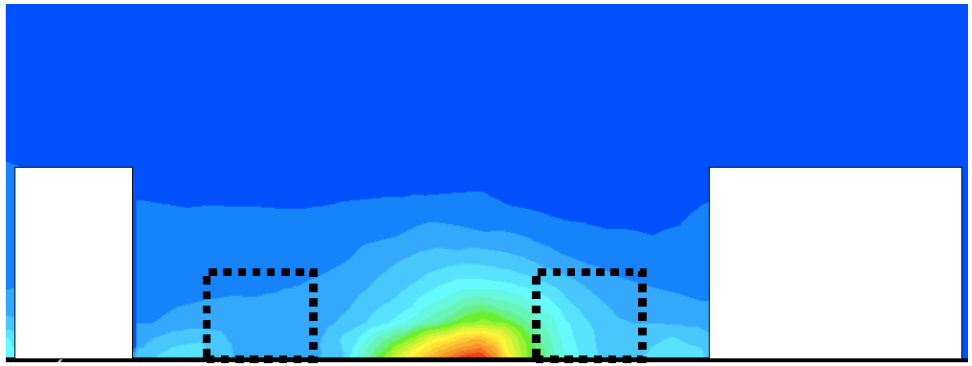

The alignment of the trees with the incoming wind increases the ventilation and efficiency of the CO removal. However, in specific areas the trees induce the rearrangement of vortices that lead to the formation of additional hot-spots.

Amorim et al., (2010) CLIMAQS conference

# URban VEgetation module (URVE) - 2



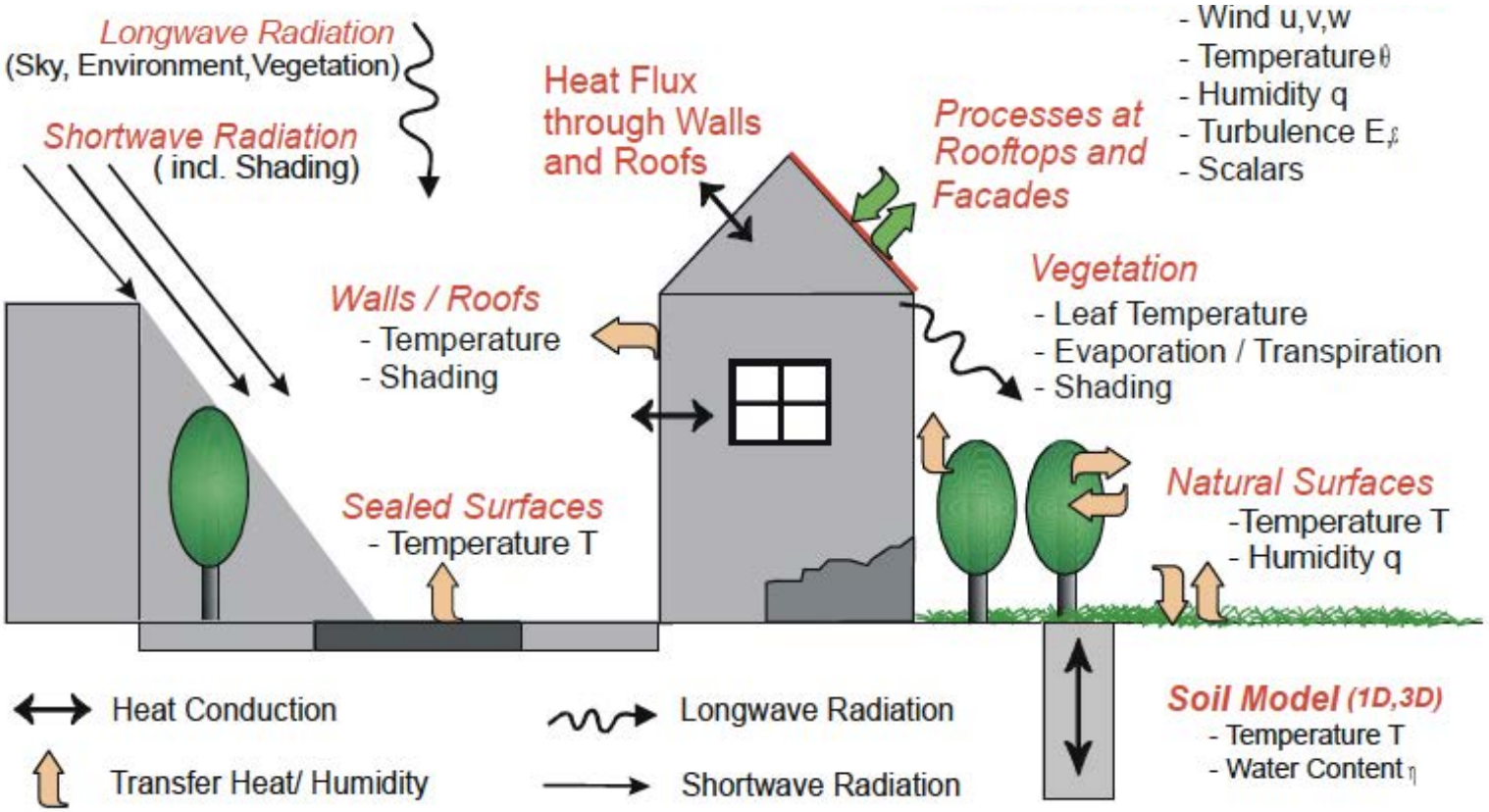

The oblique roof-level incoming winds induce a counter-clockwise swirling flow inside the avenue. This spiral airflow transports the pollutant emitted near ground level by traffic towards the leeward side of the street-canyon through the open space under the foliage.



With no space available in the trunk region, the canopy would trap the pollutants within the lateral boundaries of the Avenue, sheltering the buildings from the direct impact of traffic emissions.

Amorim et al., (2010) CLIMAQS conference

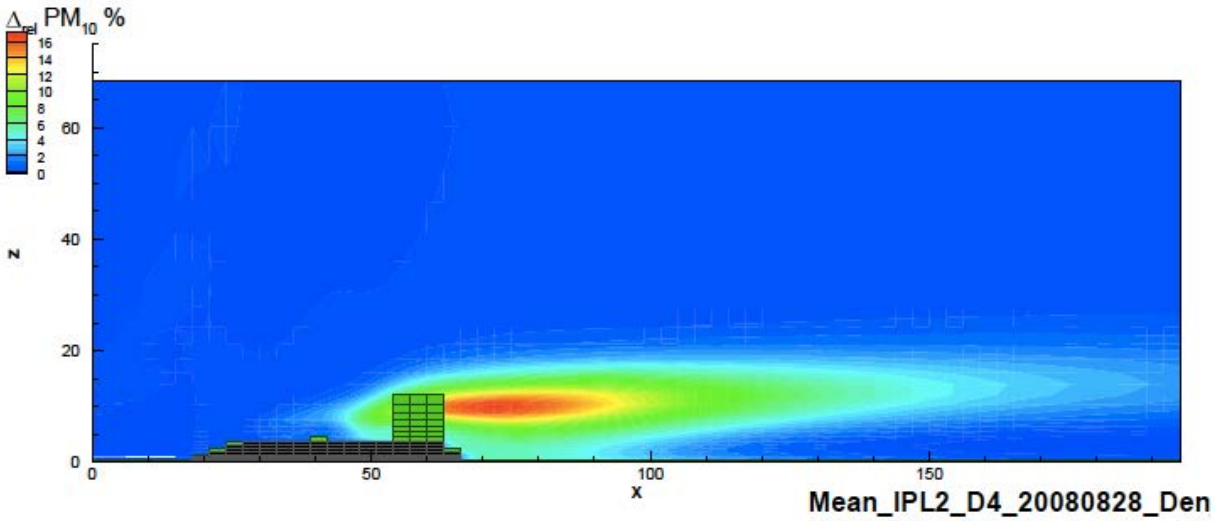
# ENVI-met

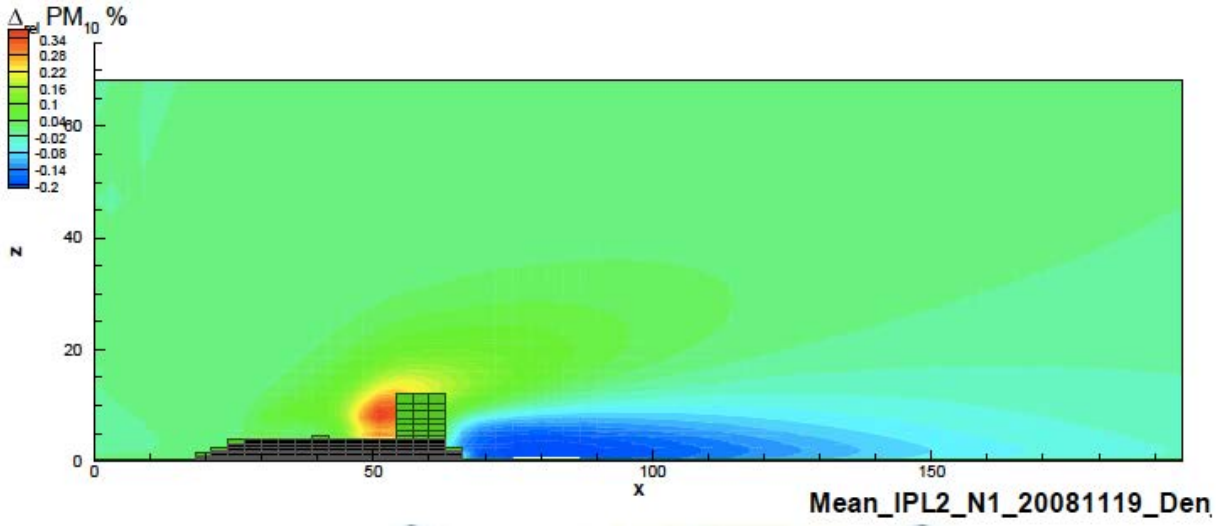



A compressive microclimate model. But it is NOT an open source model.

M. Bruse et al., Univ. of Mainz

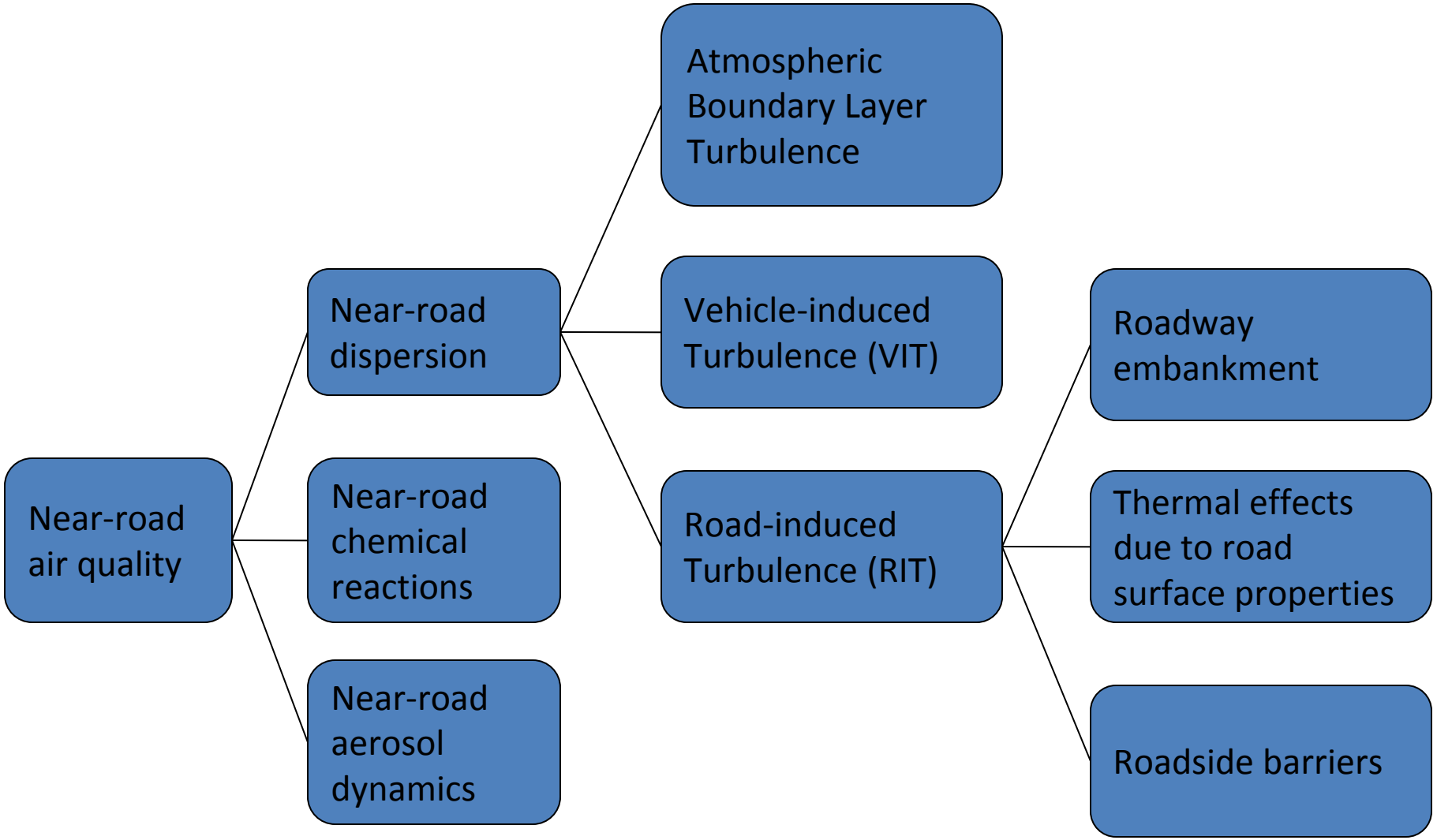
# ENVI-met analysis



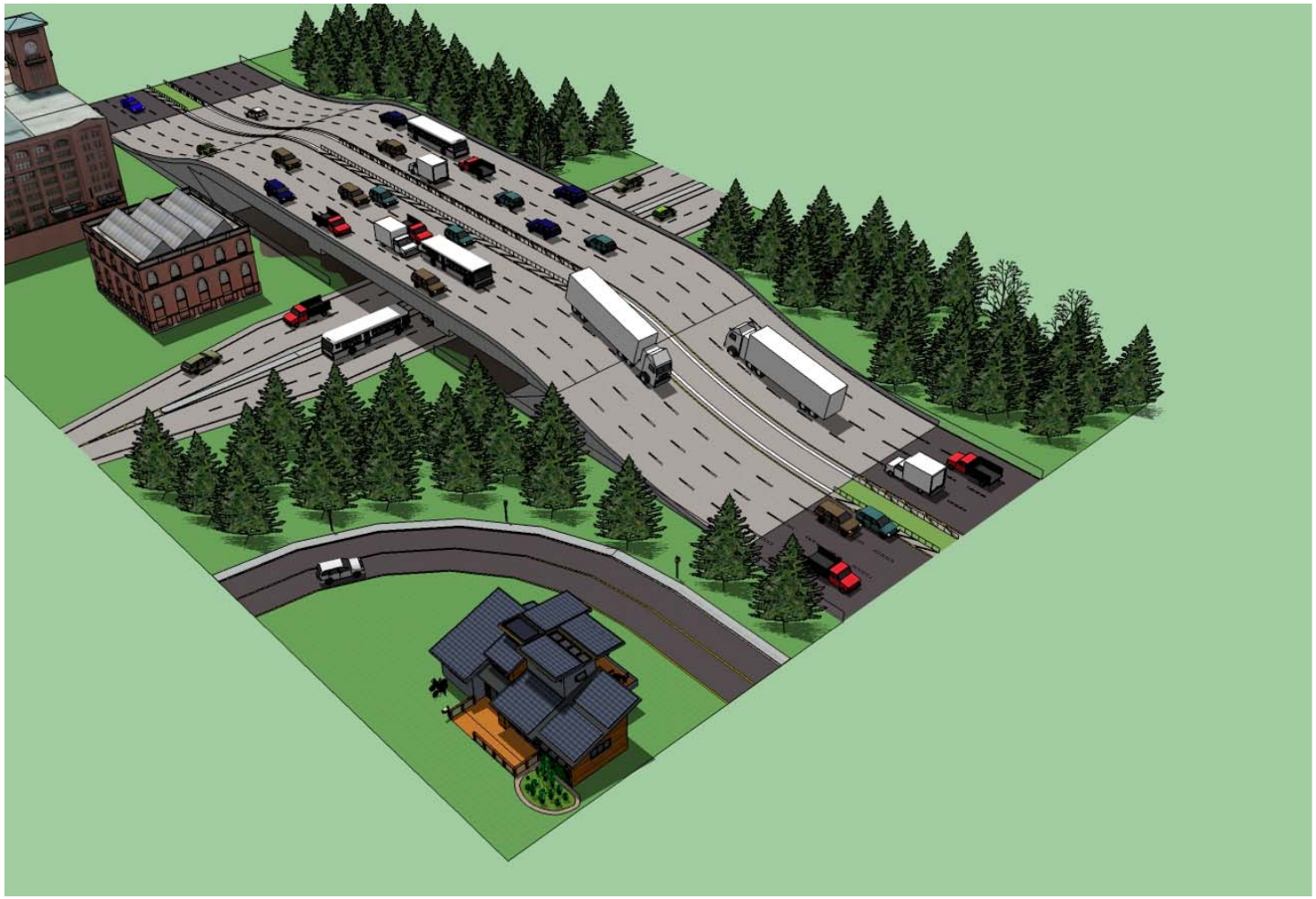




Vegetatie voor een betere luchtkwaliteit: Perceel II – A50 Valburg; Stadsregio Arnhem Nijmegen – KEMA – WUR – Alterra – Integralis PP BV – VITO, DVS-2009-019, Augustus 2009.

# CFD-VIT-RIT, a micro-environmental air quality model

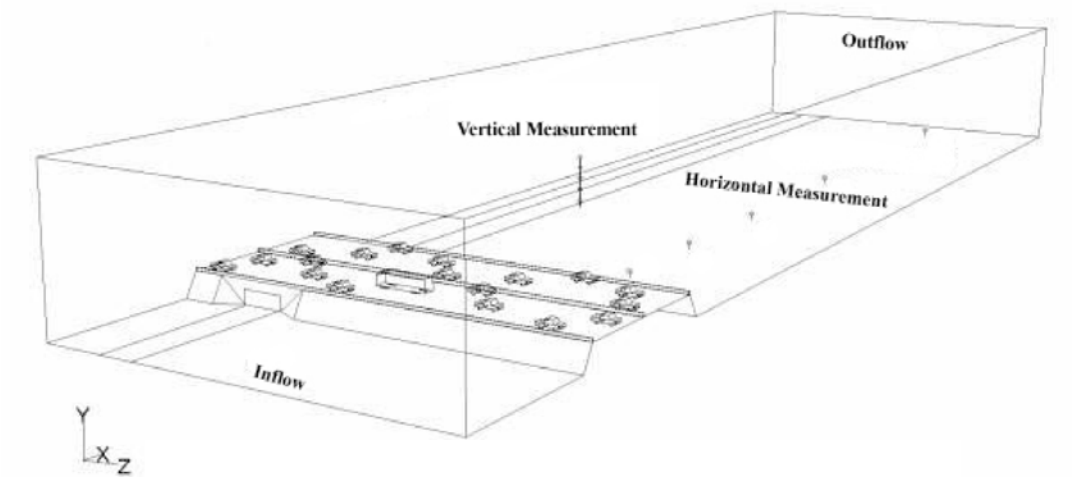


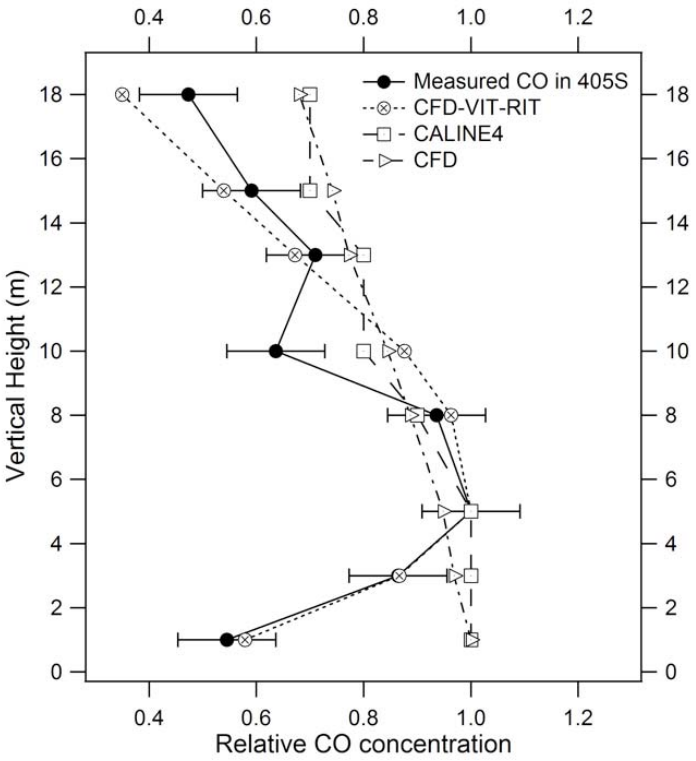
# CFD-VIT-RIT: Micro-environment

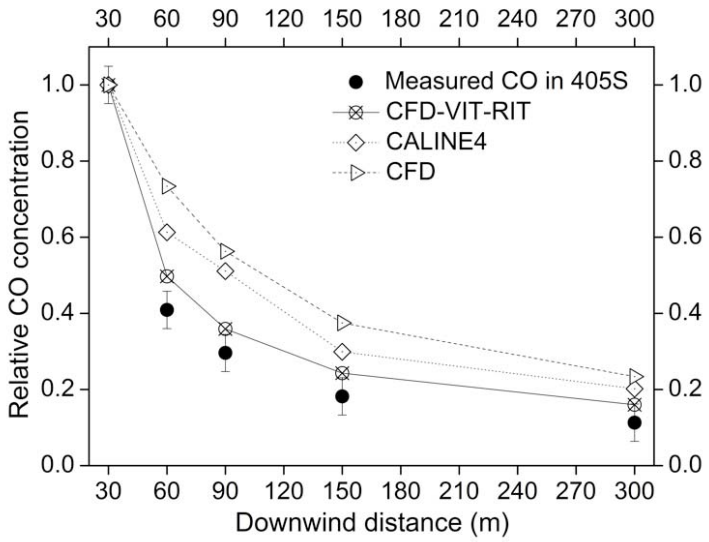


A complex exposure environment

# CFD-VIT-RIT: Roadway configurations

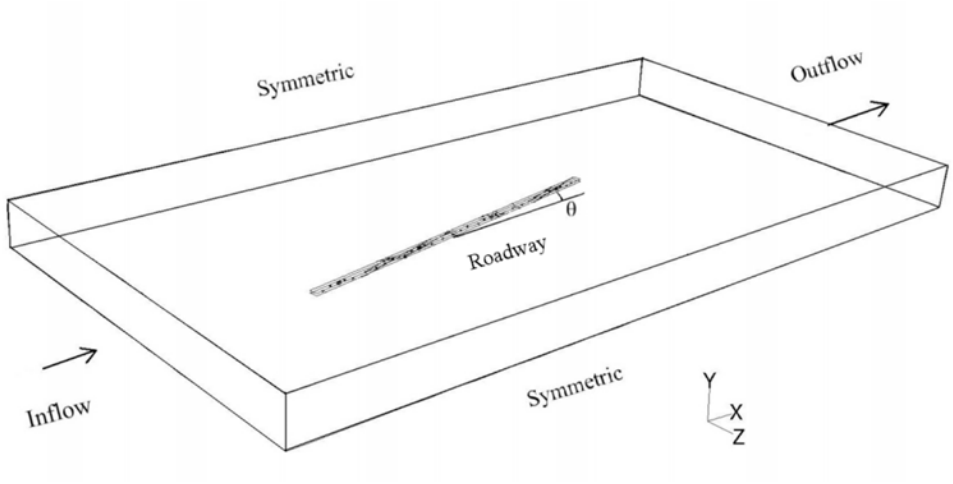


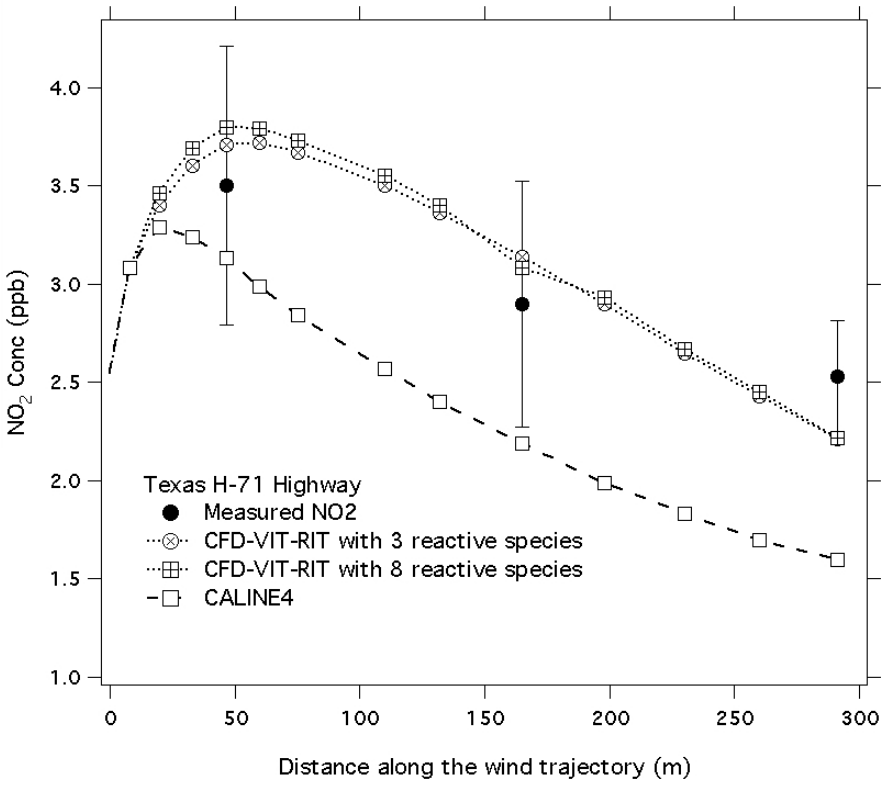




Wang, Y. and K. M. Zhang (2009). Environmental Science & Technology **43(20): 7778-7783.**

# CFD-VIT-RIT: NOx chemistry near roadways

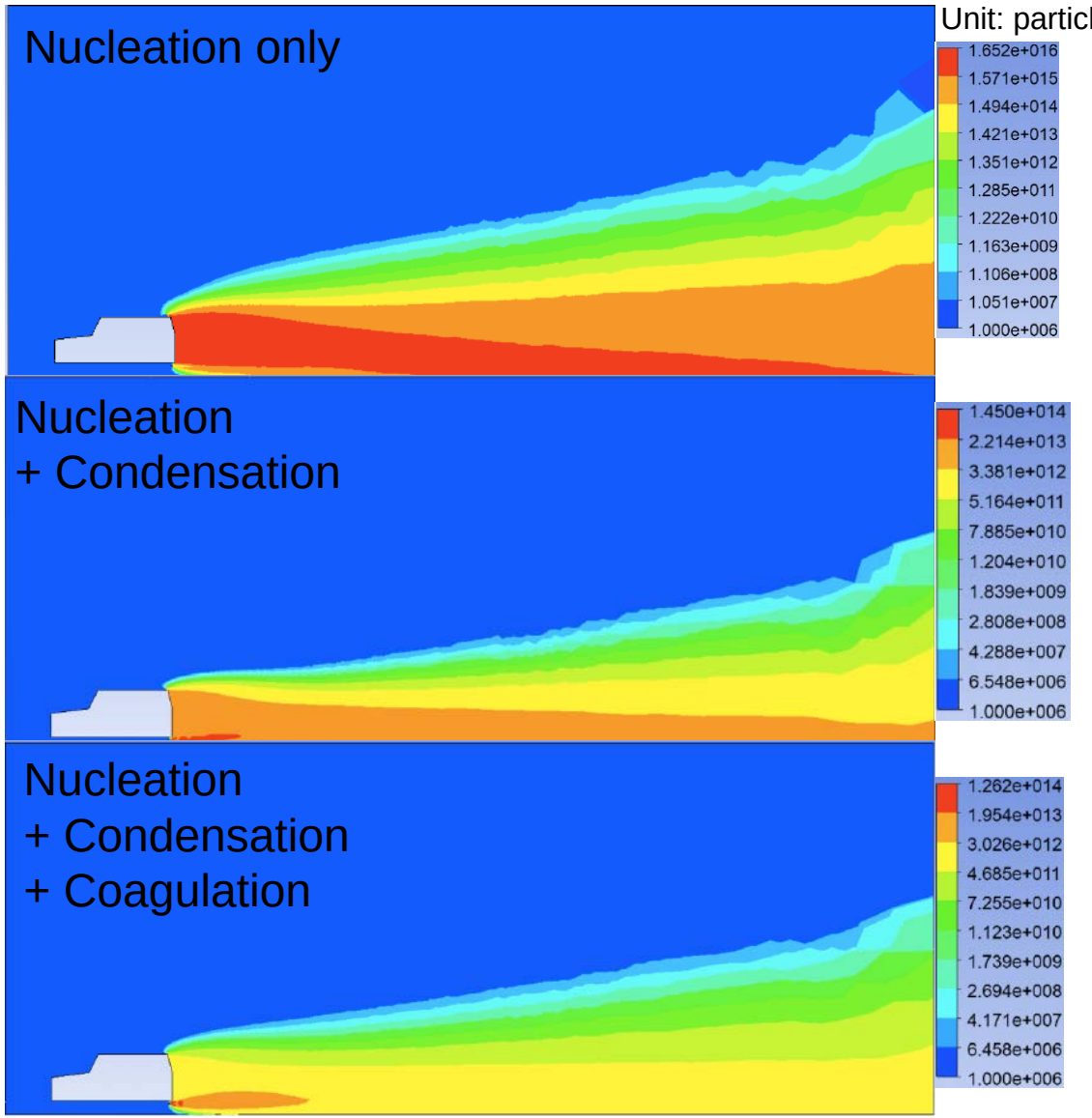



We applied CFD-VIT-RIT to investigate the chemical evolution of $NO_X$ near roadways. CFD-VIT-RIT is shown to be capable of predicting both NOx and $NO_2$ profiles downwind. CALINE4 constituently underpredicts $NO_2$ concentrations.

Wang et al. (2010). To be submitted to Atmospheric Environment

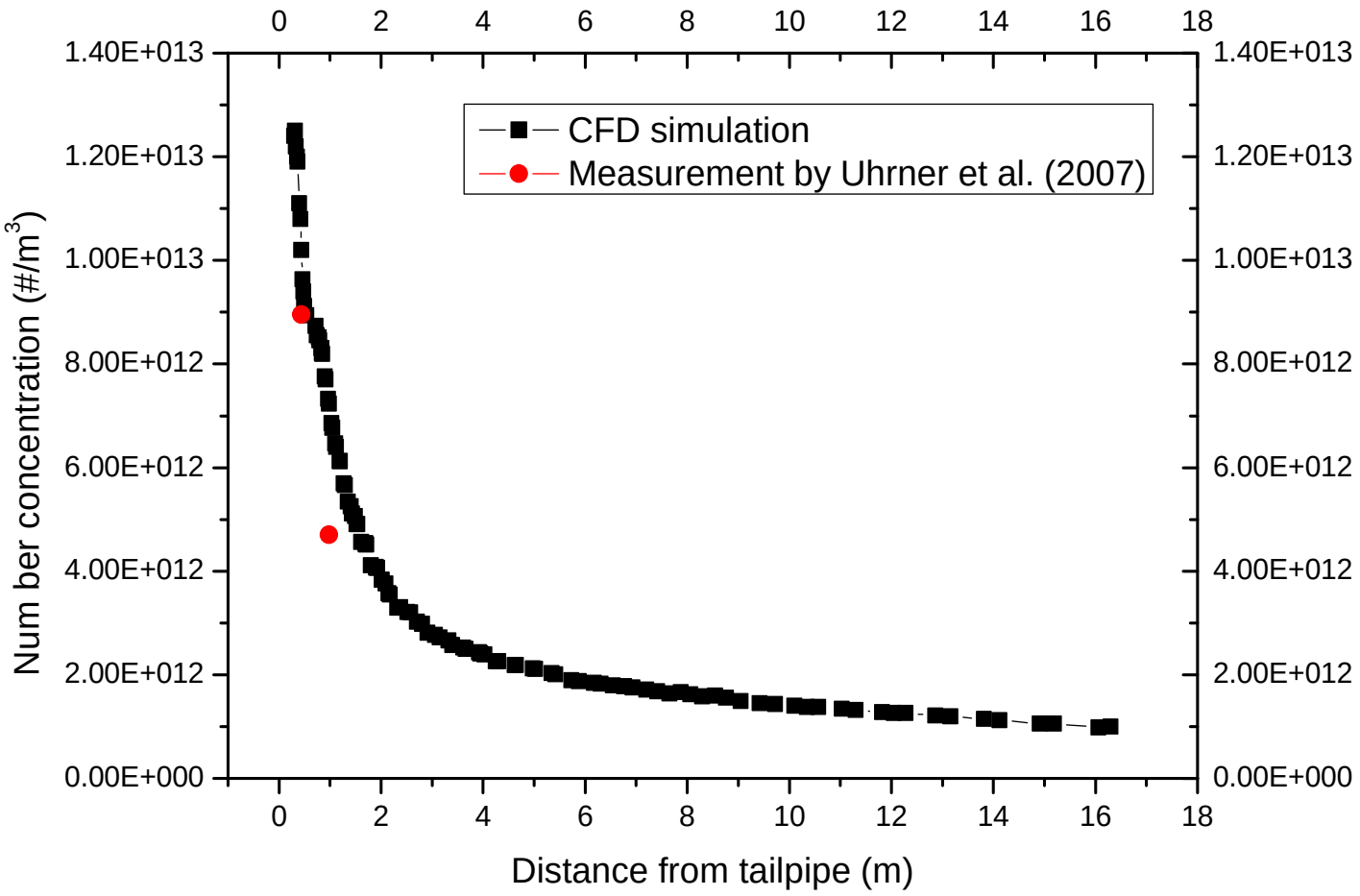
# CFD-VIT-RIT: Aerosol dynamics




We incorporated a sectional, aerosol dynamics module into the CFD-VIT-RIT framework to simulate the on-road and near-road evolution of particle size distribution.

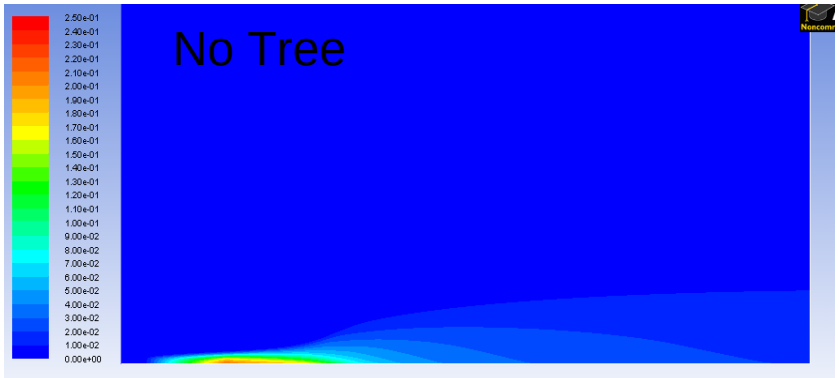
Wang, Y and K. M. Zhang, Unpublished

# CFD-VIT-RIT: Aerosol dynamics

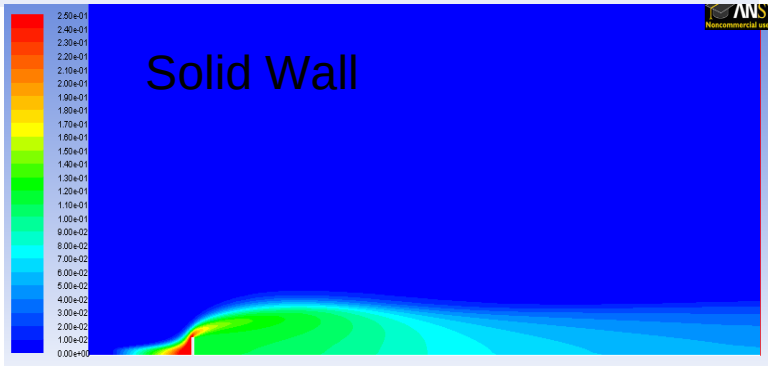


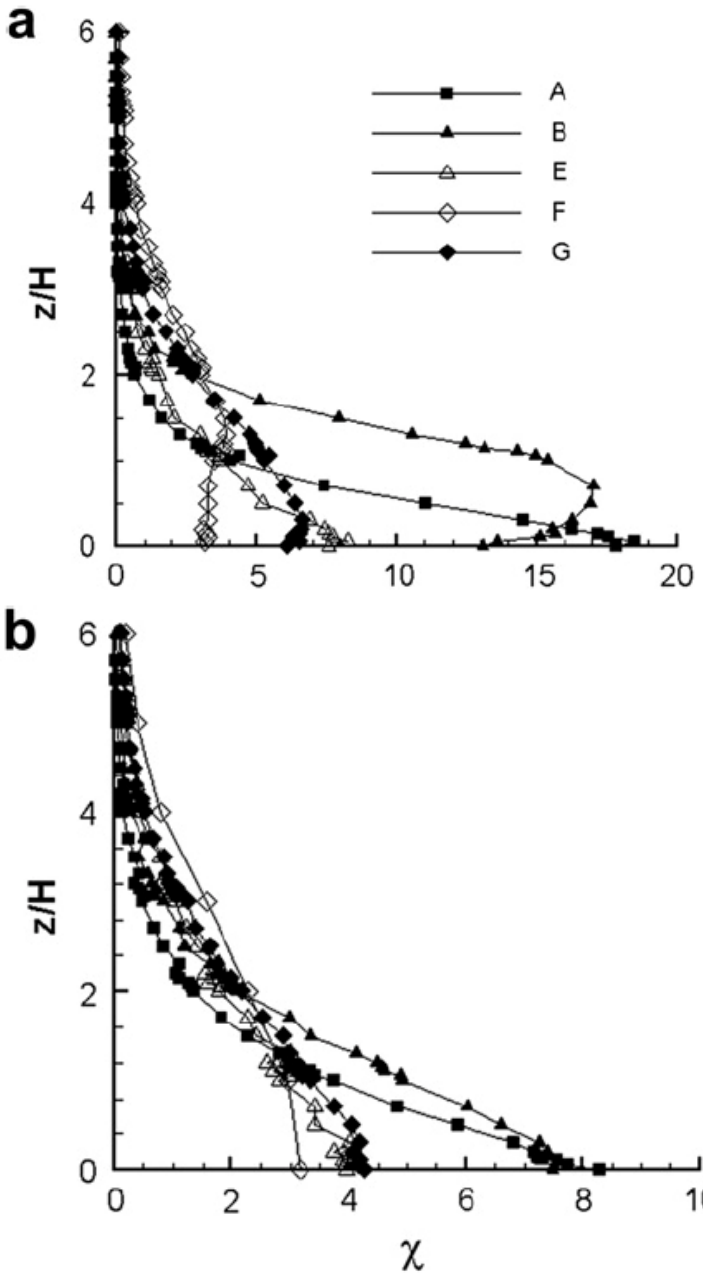

Wang, Y and K. M. Zhang, Unpublished

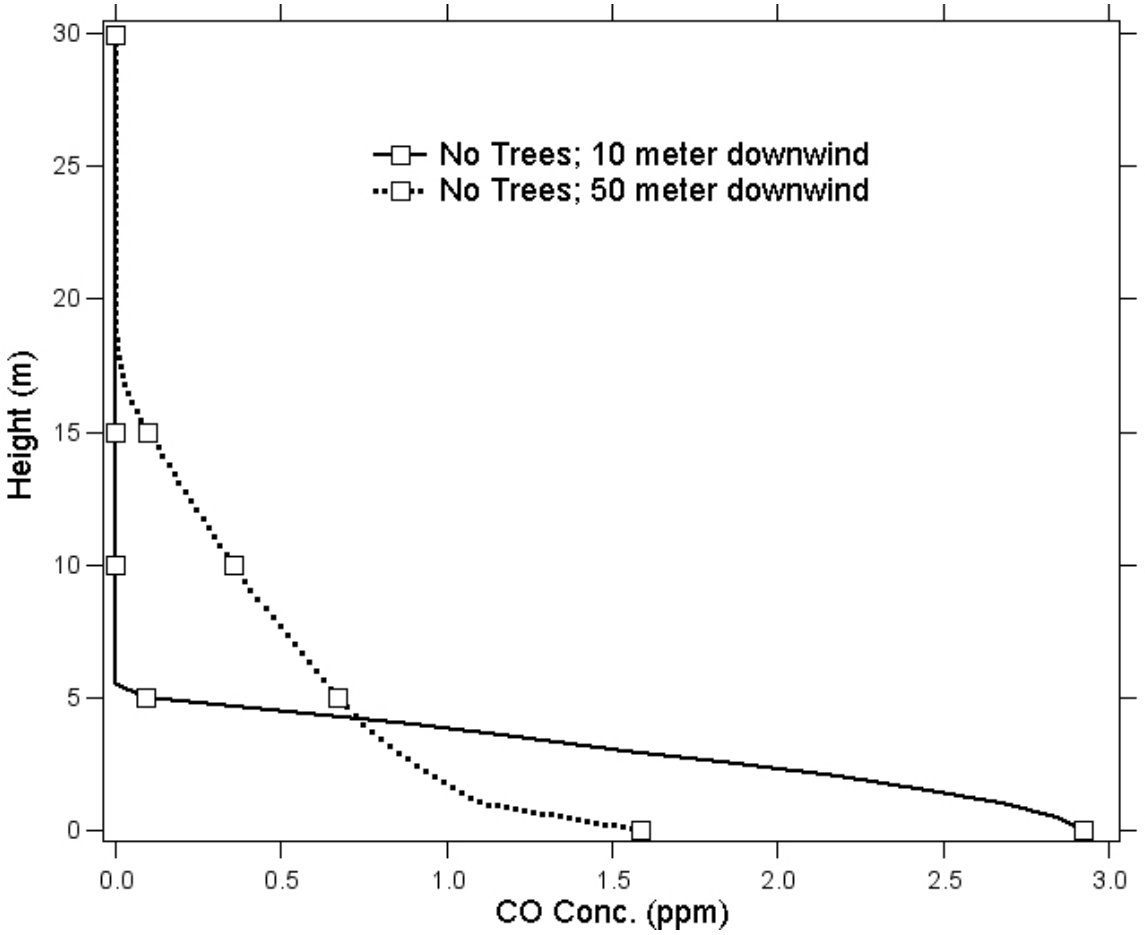
# Preliminary results on vegetation barriers





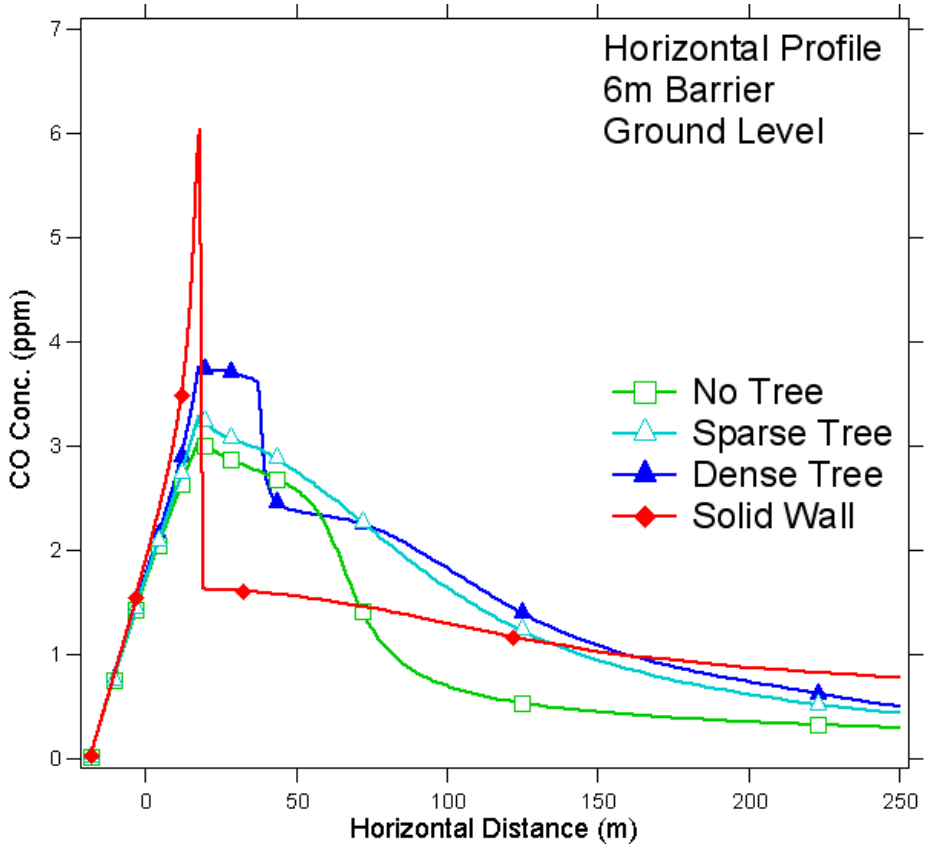



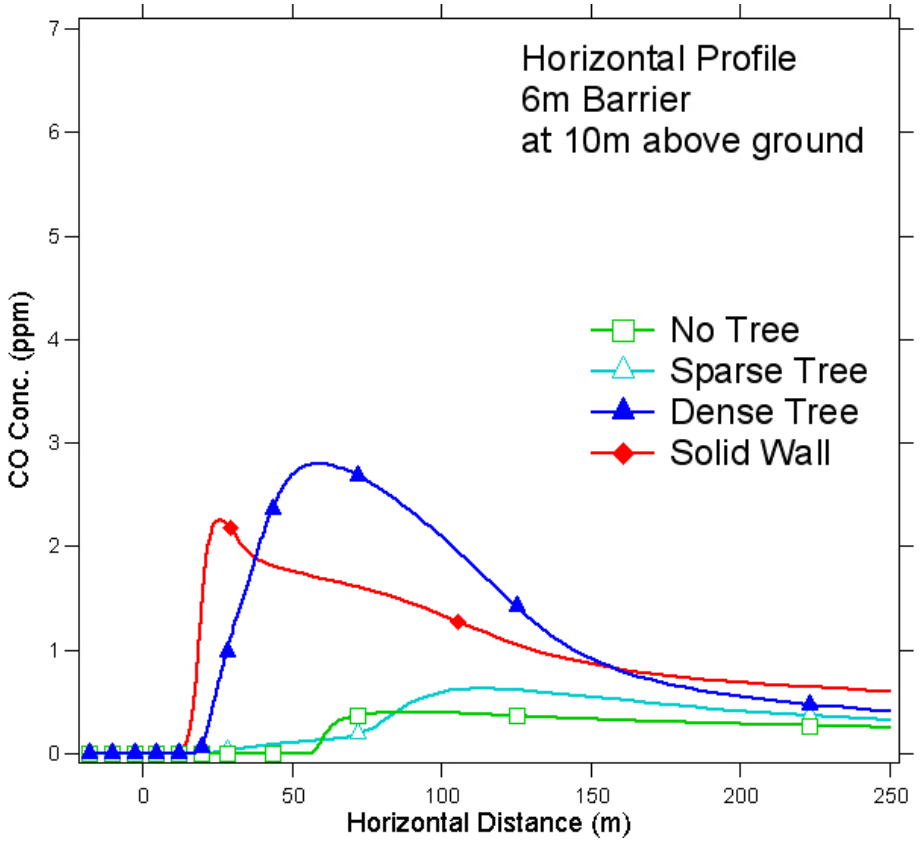



Heist, D. K., S. G. Perry, et al. (2009) Atmospheric Environment 43(32): 5101-5111

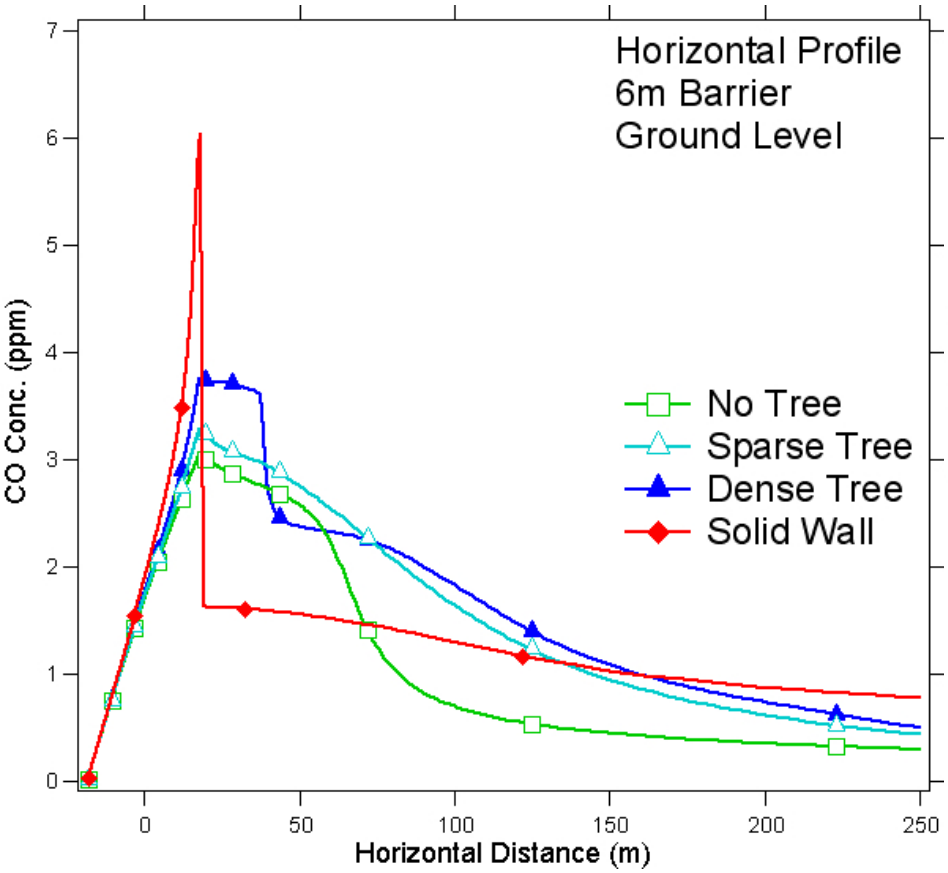
# Dense Tree vs Sparse Tree

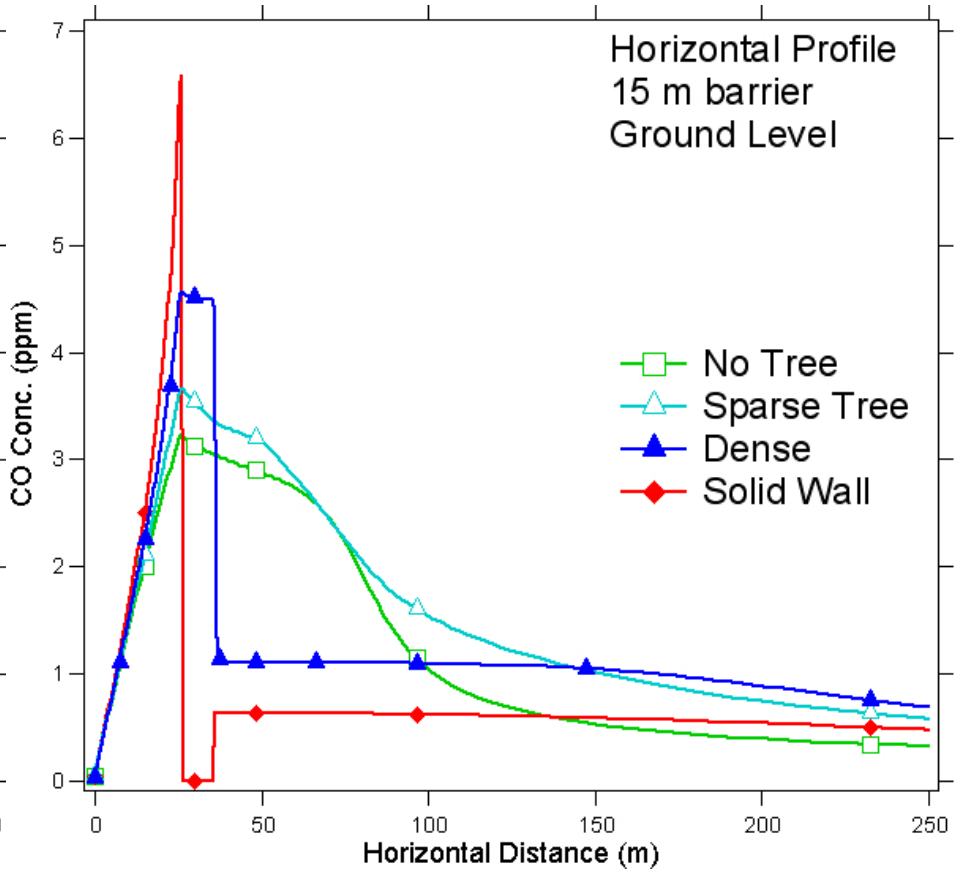



Steffens, J. T. and K. M. Zhang, Unpublished

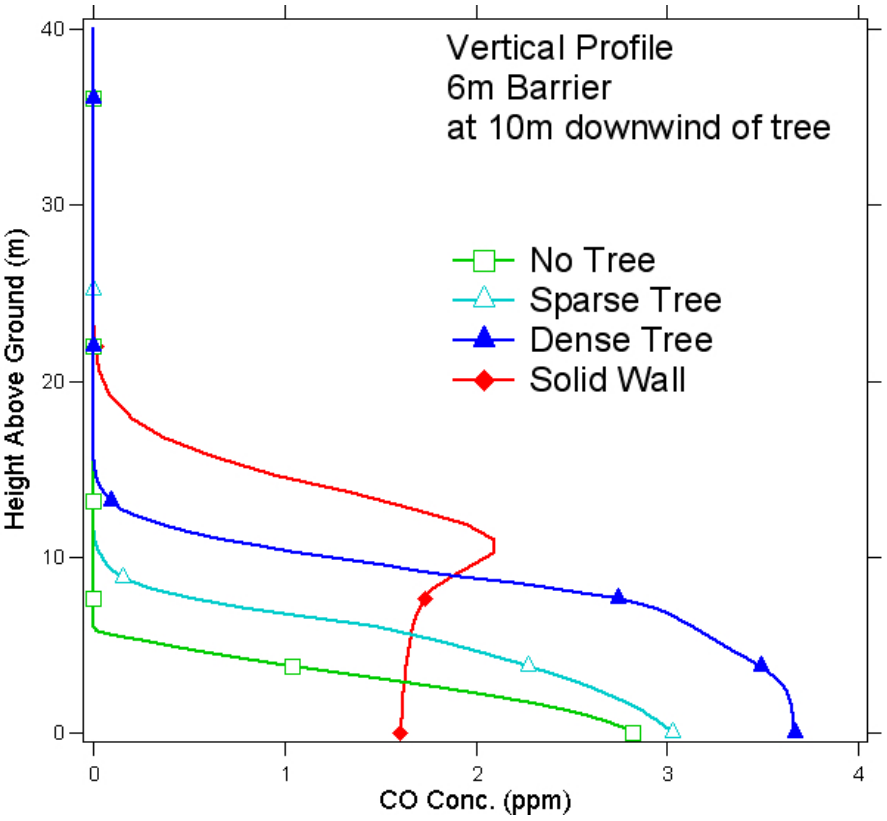
# Short Tree vs Tall Tree

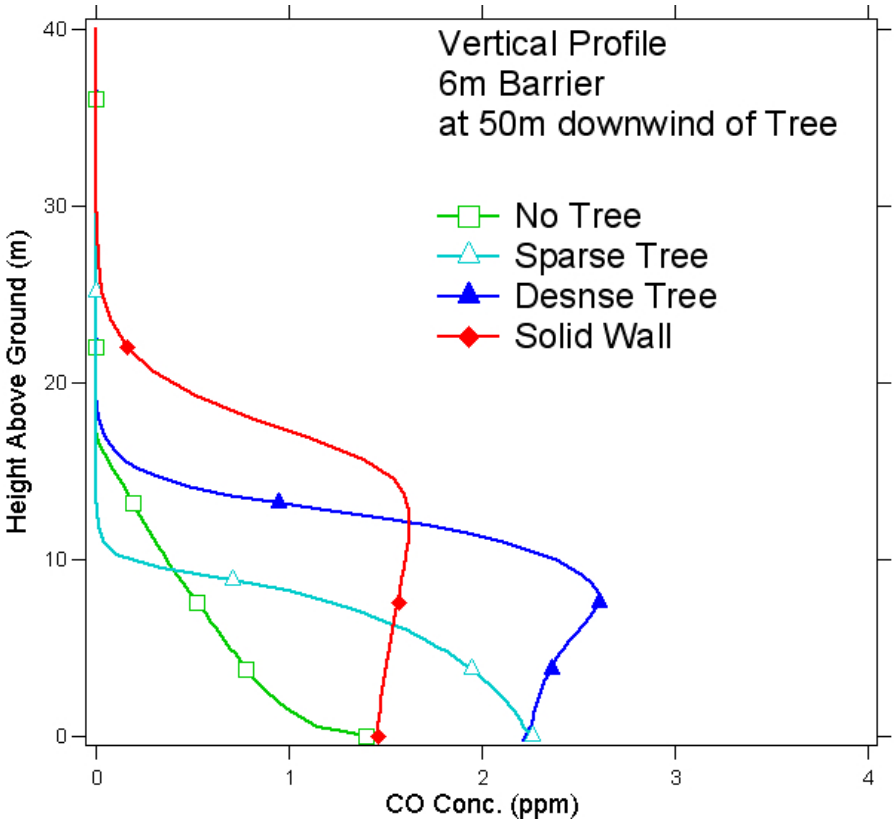



Steffens, J. T. and K. M. Zhang, Unpublished

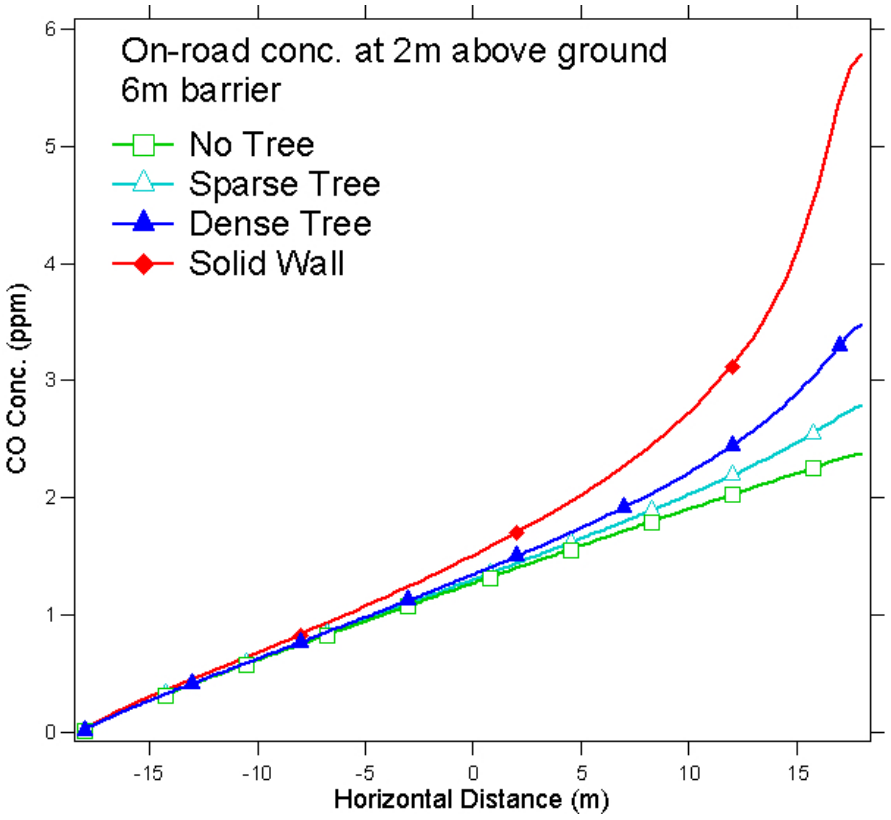
# Vertical Profiles

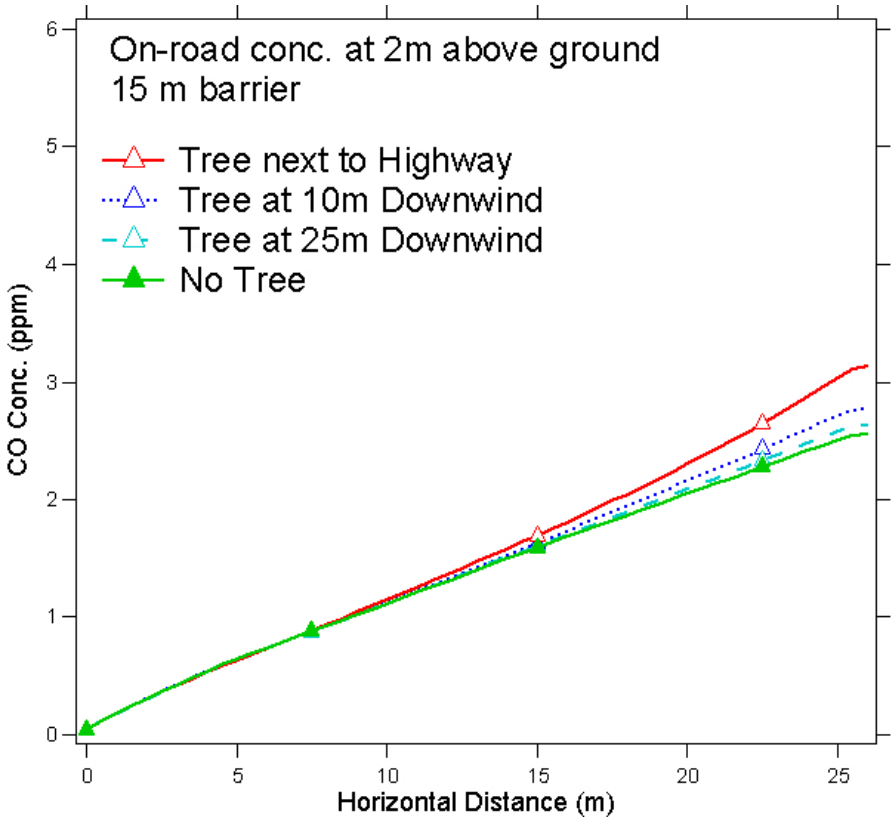



Steffens, J. T. and K. M. Zhang, Unpublished

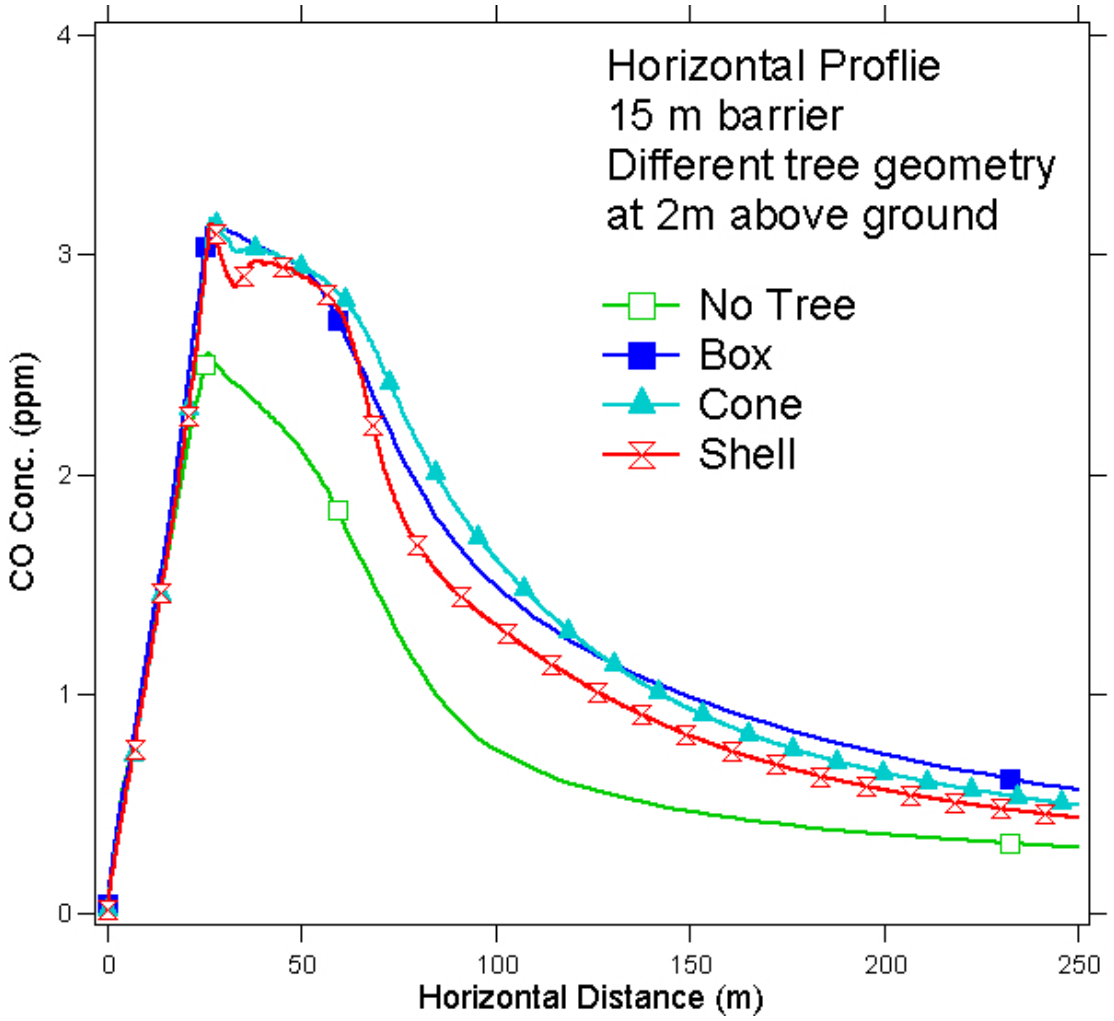
# On-road concentrations




Steffens, J. T. and K. M. Zhang, Unpublished

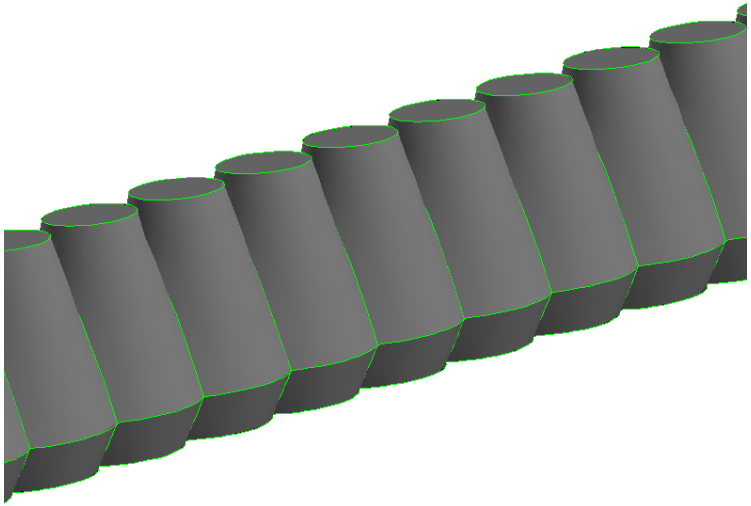
# Different Geometry




Steffens, J. T. and K. M. Zhang, Unpublished

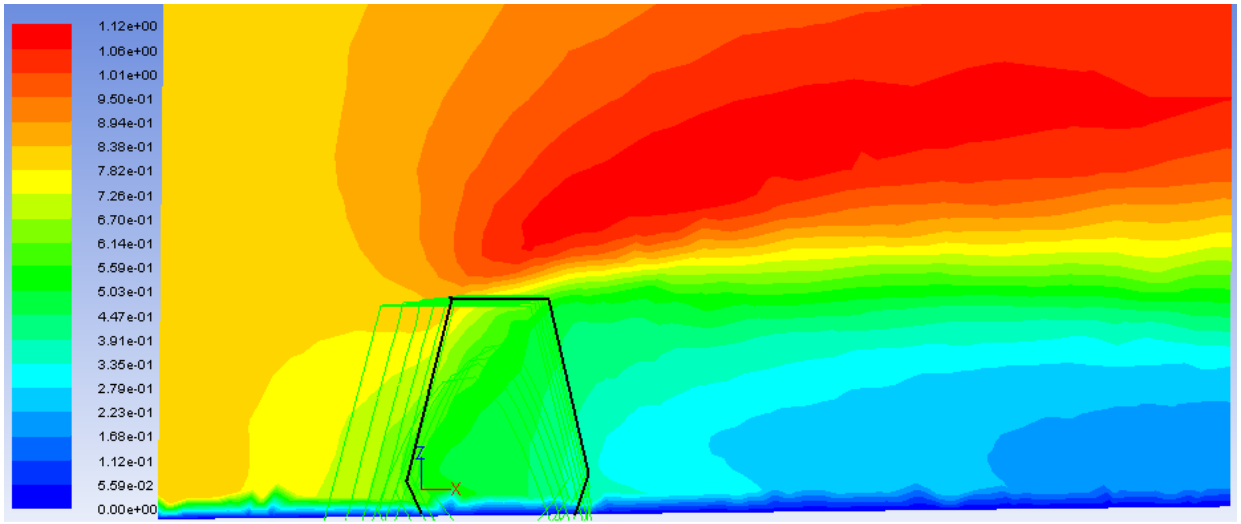
# Simulation of EPA field data

- Wind speed and angle at clearing used as conditions upwind of trees
- Average wind speed and TKE behind tree at 3 and 7 meters recorded



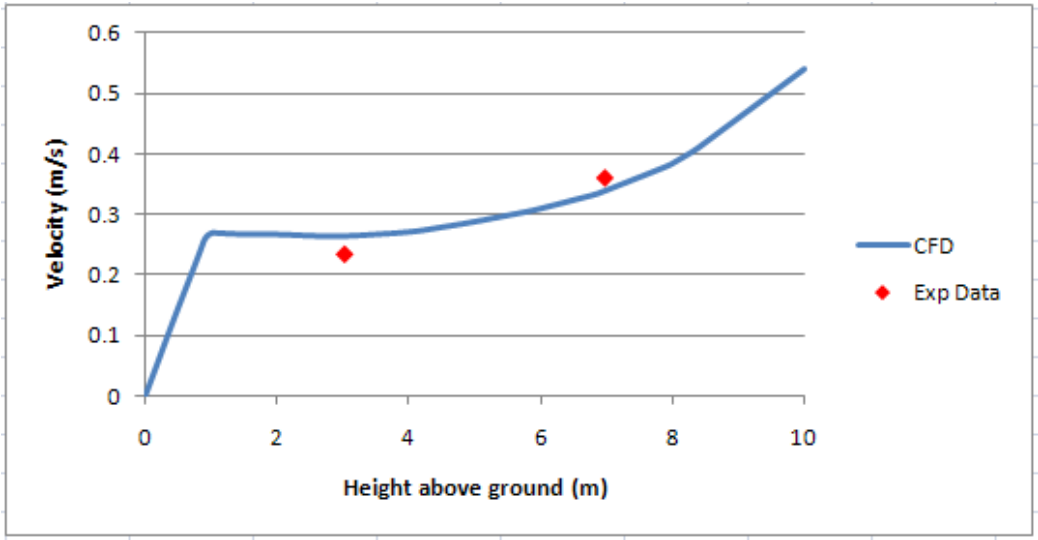
- By adjusting values for Cd and LAD, was able to reasonably match experimental velocity magnitudes (not directions) at the two sample points
- Could not get reasonable agreement in TKE data

# Simulation Results




•Cross section of Wind Velocity (Tree Outlined in Black)
•Vegetation Causes Wind Sheltering Effect

- Reasonable agreement between experiment and CFD in Velocity



# Limitations of the existing studies on vegetation barriers

- More on street canyons, less on environments near large roads.
- Few studies on NOx chemistry and PM2.5/PM10 deposition
- When dealing with PM deposition, no size distribution is used.
- No studies on aerosol dynamics and ultrafine particles.
- Few well-designed field studies are available to validate the models.
- The effects of local meteorology on the are not clear.

# Scientific gaps

- Better characterizations of leaf area density and drag coefficients for different types of trees and layouts are needed.
- Are the simulations capturing the enhanced mixing effect? It may be worthwhile revisiting the formation of the different turbulent source and sink terms. It is also related to the
- Deposition of particulate matter on leaf is not well understood, especially concerning ultrafine particles.
- It is critical to understand the effects on NOx chemistry and aerosol dynamics.
- CFD tools can be used to improve scientific understandings. Screening models are needed for regulatory and planning purposes.

# Implications

- From modeling perspective, there are no conclusive findings on the effects of vegetation barriers. More research is needed.
- Positive or negative, the effects of vegetation need to be considered in micro-scale air quality and human exposure studies in urban areas.
- A systematic study will guide the designs of vegetation barriers to achieve more benefits, and avoid potential negative effects.
- What is our main objective in mitigating near-road air pollution?
  - Maximum pollutant concentrations vs. overall concentration
  - Near-road concentrations vs. on-road concentrations
  - Ground-level vs. higher-elevation
  - …