Near-Road Air Quality Monitoring and Modeling: Towards a Mechanistic Understanding

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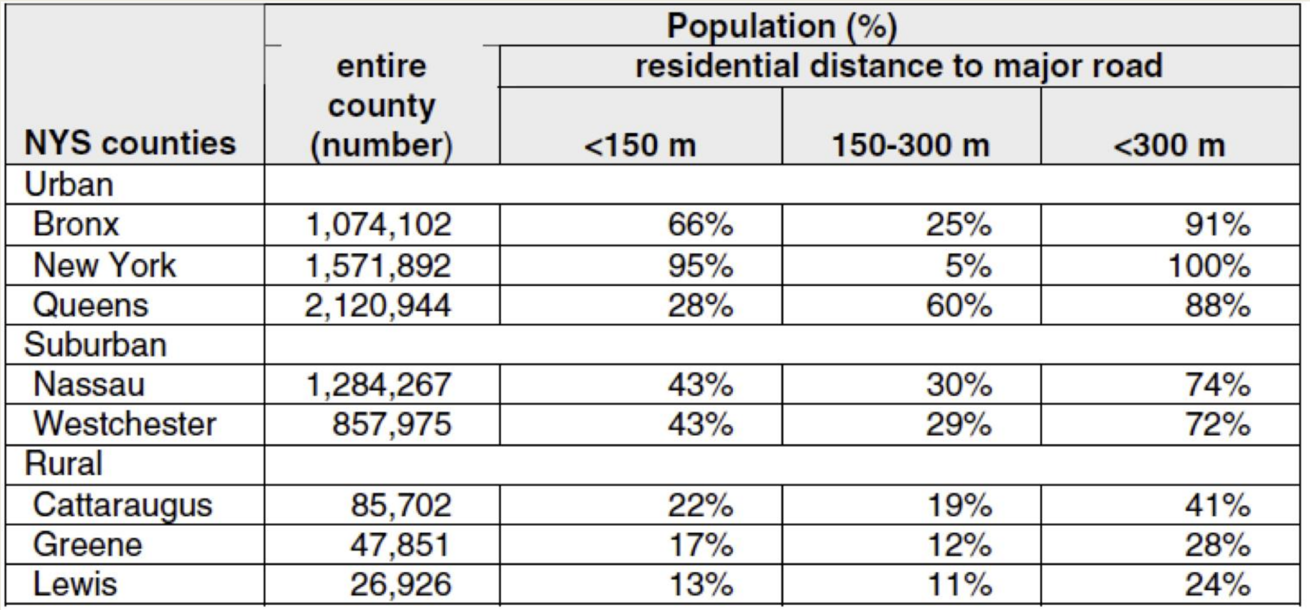
Outline

- An integrated monitoring and modeling approach for studying near-road air quality
- Development of CFD-VIT-RIT modeling system, an advanced project-level analysis tool
- Applications of CFD-VIT-RIT in project-level analysis
  - Spatial gradients of air pollutants near elevated highways
  - Chemical evolution of NO_2 near roadways
- Discussions

Near-road air pollution: Health effects and human exposure

New York: A large number of New York residents live within 150m and 300m of major roads in urban, suburban, and even rural counties.



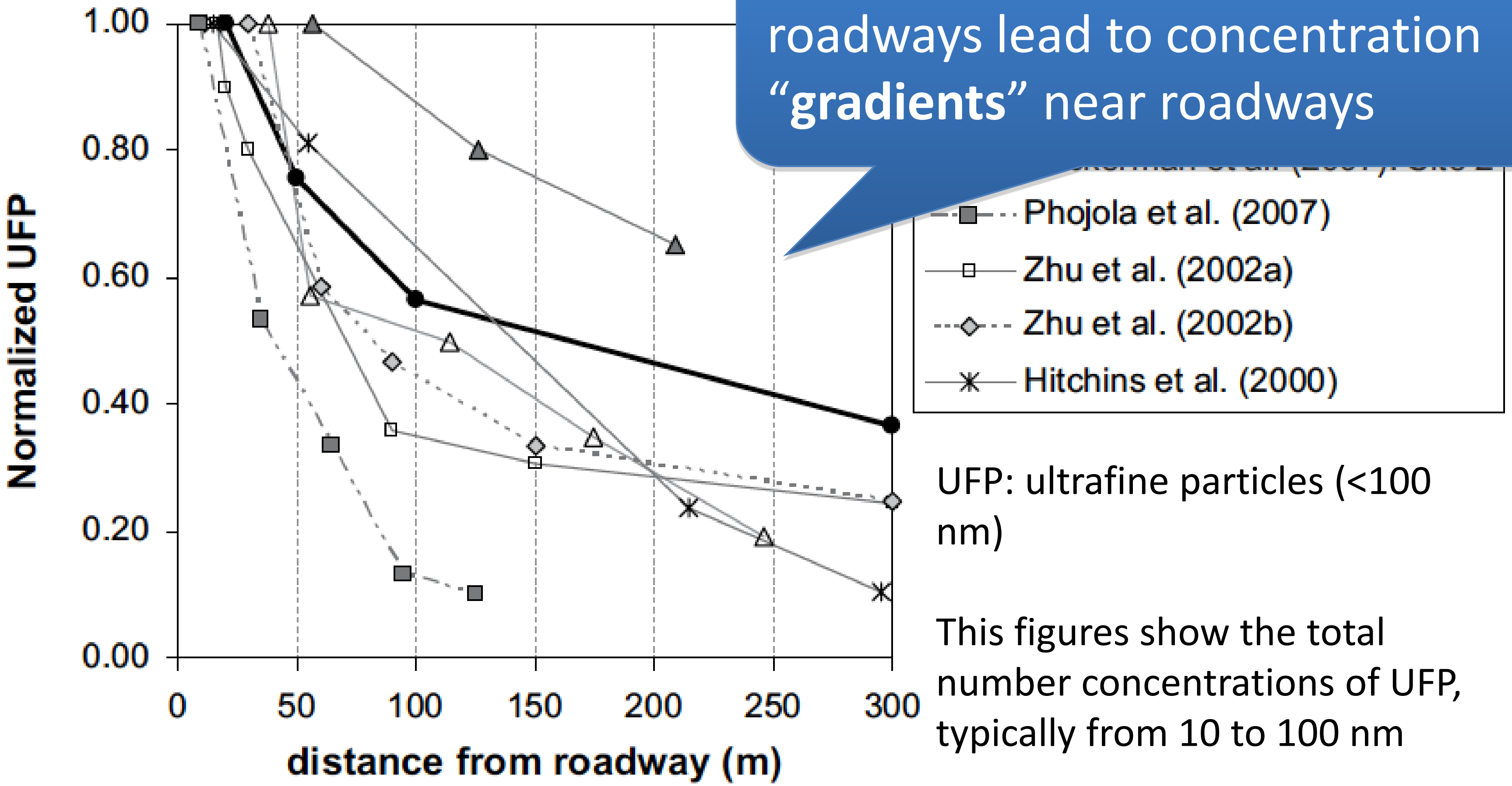
NYS counties	entire county (number)	Population (%)		
		residential distance to major road		
		<150 m	150-300 m	<300 m
Urban				
Bronx	1,074,102	66%	25%	91%
New York	1,571,892	95%	5%	100%
Queens	2,120,944	28%	60%	88%
Suburban				
Nassau	1,284,267	43%	30%	74%
Westchester	857,975	43%	29%	72%
Rural				
Cattaraugus	85,702	22%	19%	41%
Greene	47,851	17%	12%	28%
Lewis	26,926	13%	11%	24%

NYSERDA (2008) Assessment of carbonaceous PM2.5 for New York and the region.

Rationales for an integrated monitoring and modeling approach

- The atmospheric processes at project-level are complex, governing the transport and transformation of multiple air pollutants, which in turns determine their concentrations near roadways.
- Road design features such as alternative highway configurations and presence of roadside structures further influence the pollutant transport and transformation.
- The current project-analysis tools based on Gaussian plume models are not capable of handling complex roadway environments. Advanced modeling tools are needed.
- Advanced modeling tools can be used to interpret monitoring results and predict future near-road air quality

Characterizing near-road air pollution



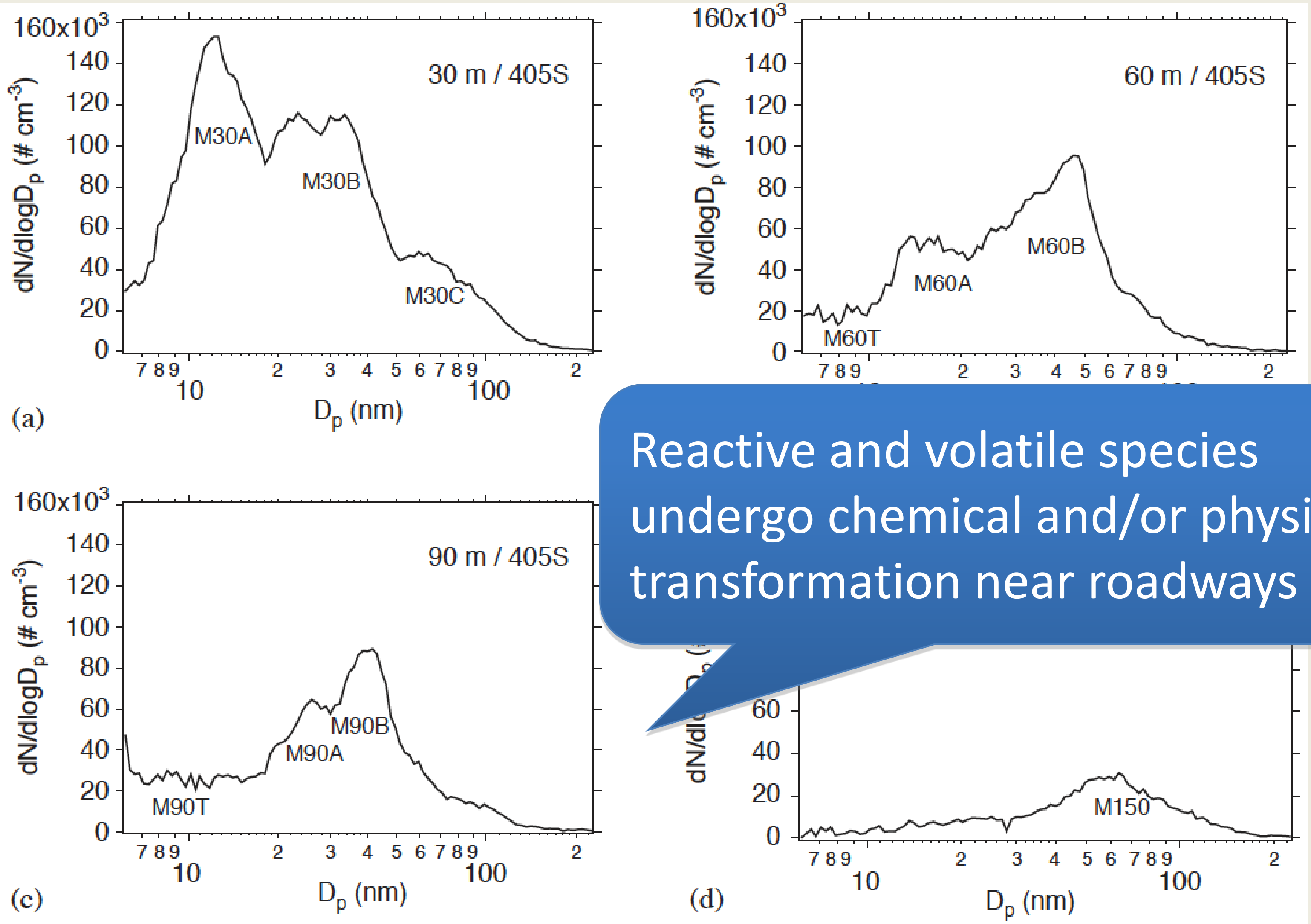
Elevated air pollution levels near roadways lead to concentration "**gradients**" near roadways

UFP: ultrafine particles (<100 nm)

This figures show the total number concentrations of UFP, typically from 10 to 100 nm

Hagler, G. S. W., R. W. Baldauf, et al. (2009). Atmospheric Environment **43(6): 1229-1234.**

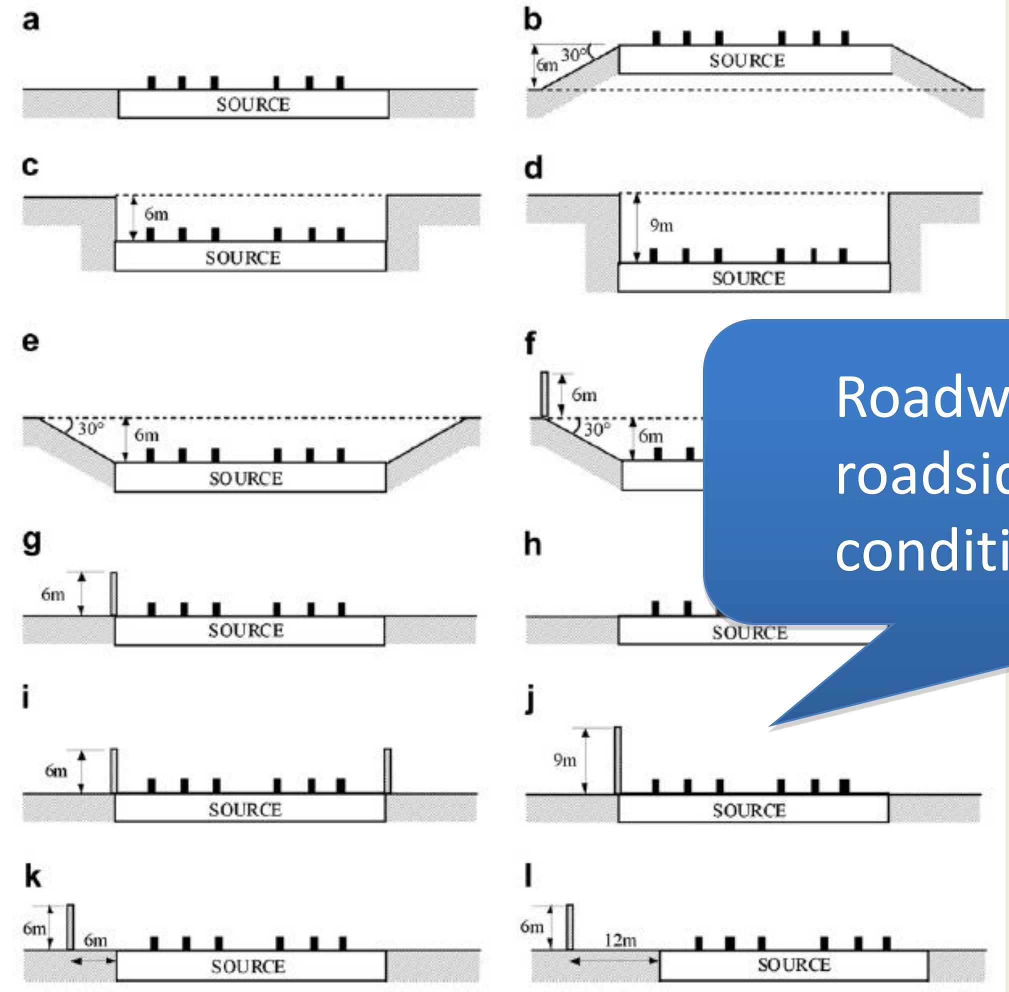
Characterizing near-road air pollution

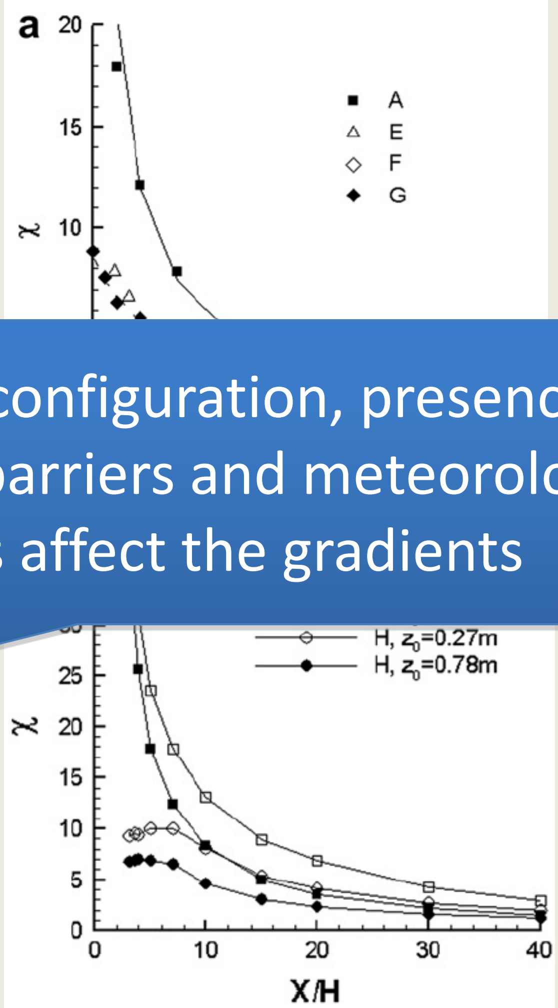


Reactive and volatile species undergo chemical and/or physical transformation near roadways

Zhang, K. M., A. S. Wexler, et al. (2004). Atmospheric Environment 38(38): 6655-6665.

Noise barriers and road configurations





Roadway configuration, presence of roadside barriers and meteorological conditions affect the gradients

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

Rationales for an integrated monitoring and modeling approach

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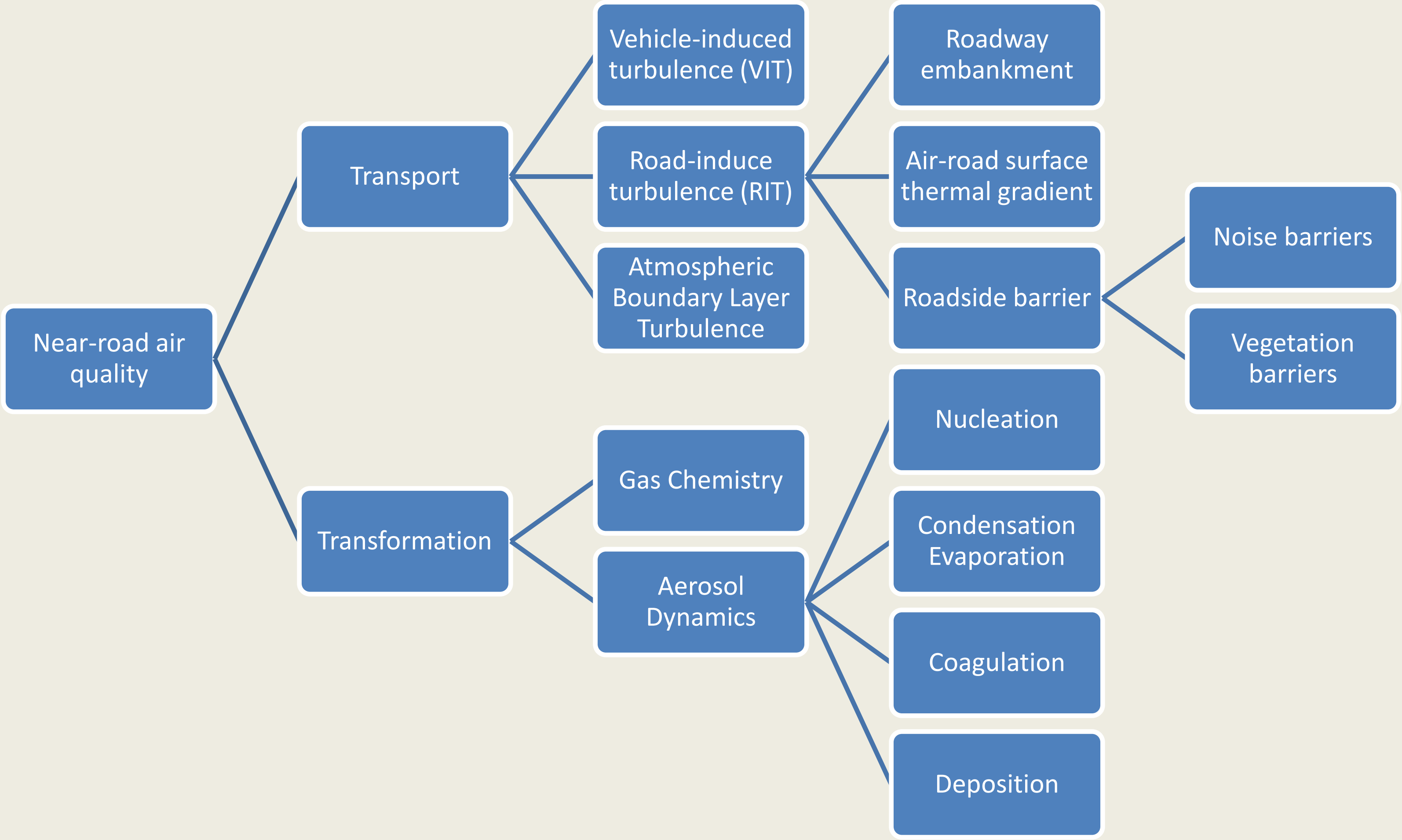
The nature of near-road air quality is 3-D turbulent reacting flows, coupling of transport and transformation

CFD-VIT-RIT, a micro-environmental air quality model for project-level analysis

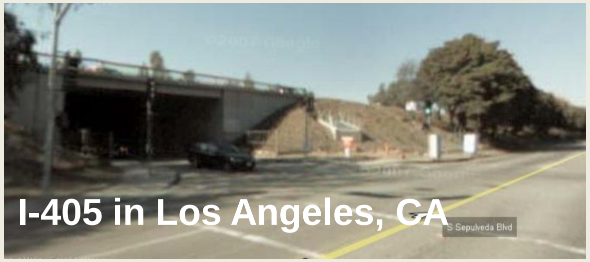



Center for Environmental Research at Hornsby Bend
Downwind Stationary Trailer
973
Upwind Stationary Trailer
Mobile Trailer
973

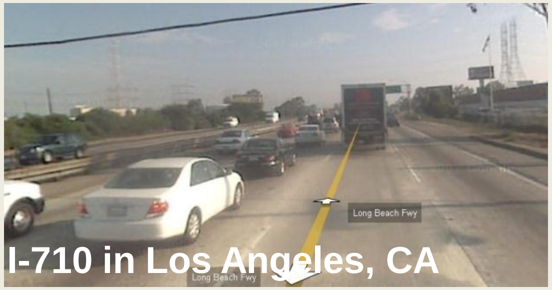

S Sepulveda Blvd


Long Beach Fwy
Long Beach Fwy

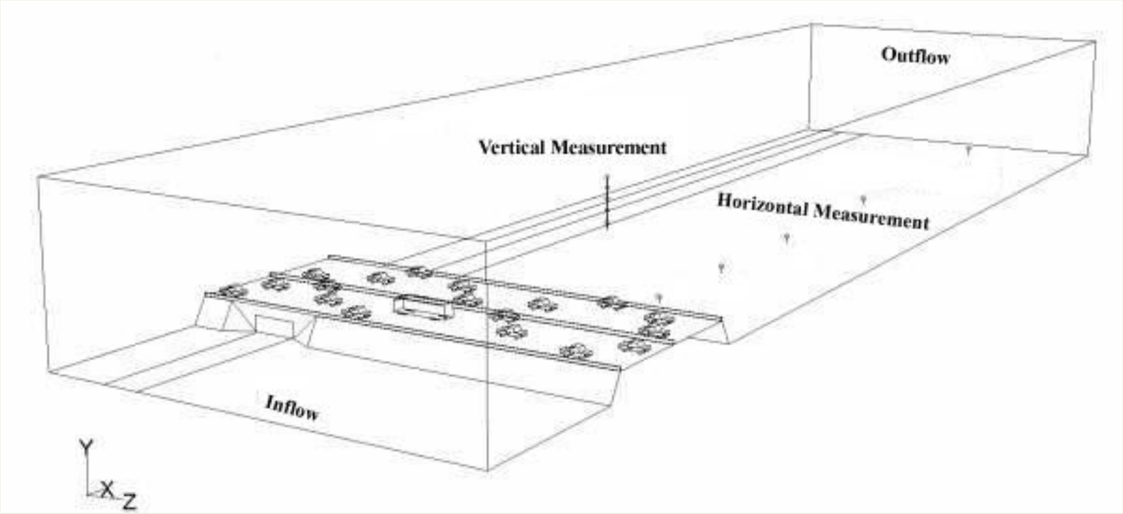
CFD-VIT-RIT: Roadway configurations



I-405 in Los Angeles, CA



I-710 in Los Angeles, CA

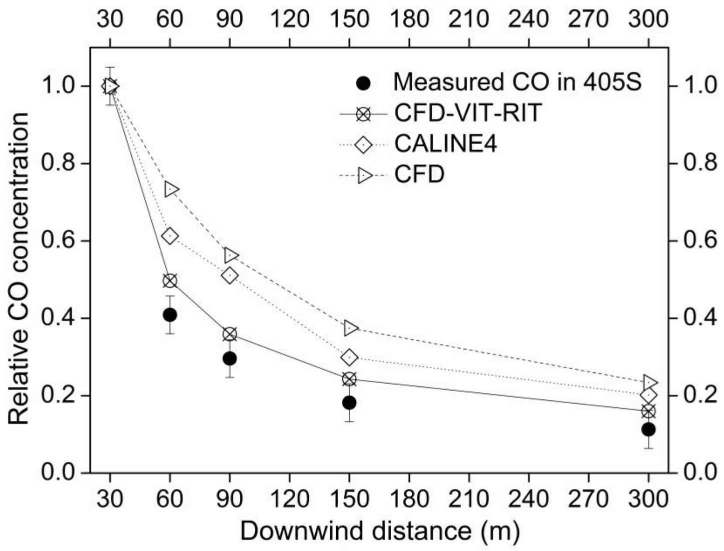


- We employed a Reynolds-averaged Navier–Stokes (RANS) model to simulate the turbulent mixing processes on and near roadways.
- The moving vehicles were modeled as moving walls with surface roughness to capture the vehicle-induced turbulence (VIT).
- We built the highway geometry to represent the realistic shape with elevated surface temperature to capture the road-induced turbulence (RIT).

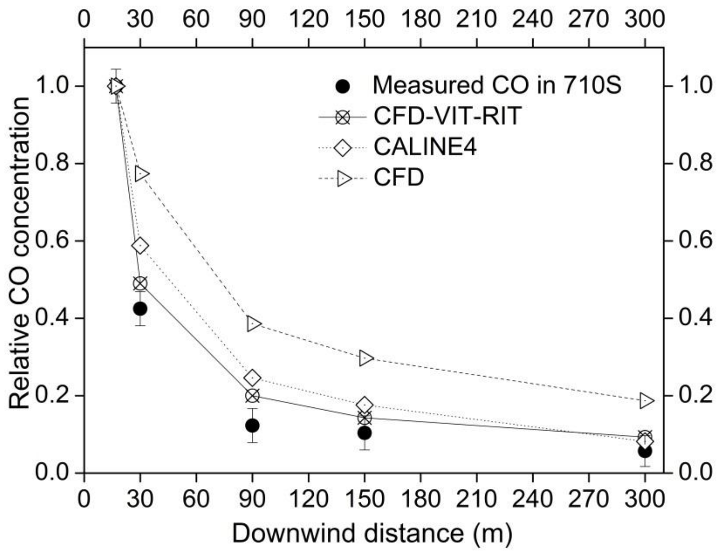
Wang, Y. and K. M. Zhang (2009). Environmental Science & Technology **43(20): 7778-7783.**

CFD-VIT-RIT: Horizontal gradients

Elevated Highway



Ground-level Highway

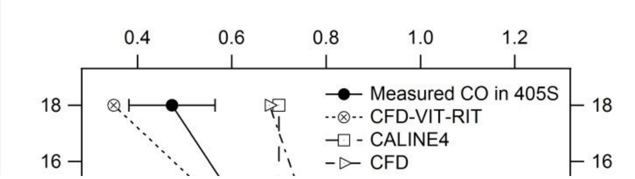


- CALINE4 appears to be adequate in capturing the horizontal gradients of inert species
- For ground-level highway, the predictions from CALINE4 and CFD-VIT-RIT are almost identical.

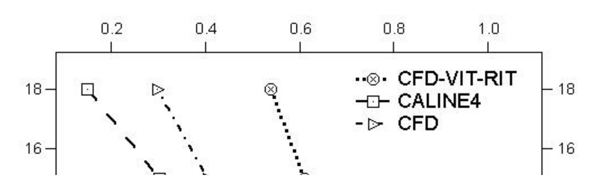
Wang, Y. and K. M. Zhang (2009). Environmental Science & Technology **43(20): 7778-7783.**

CFD-VIT-RIT: Veridical gradients

Elevated Highway



Ground-level Highway



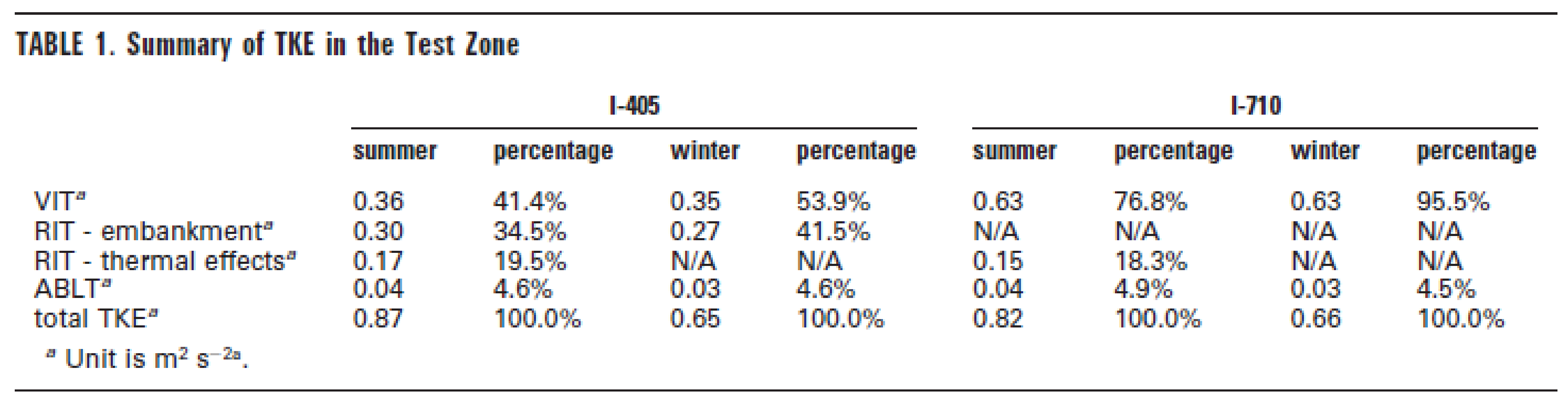


TABLE 1. Summary of TKE in the Test Zone

	I-405				I-710			
	summer	percentage	winter	percentage	summer	percentage	winter	percentage
VIT[a]	0.36	41.4%	0.35	53.9%	0.63	76.8%	0.63	95.5%
RIT - embankment[a]	0.30	34.5%	0.27	41.5%	N/A	N/A	N/A	N/A
RIT - thermal effects[a]	0.17	19.5%	N/A	N/A	0.15	18.3%	N/A	N/A
ABLT[a]	0.04	4.6%	0.03	4.6%	0.04	4.9%	0.03	4.5%
total TKE[a]	0.87	100.0%	0.65	100.0%	0.82	100.0%	0.66	100.0%

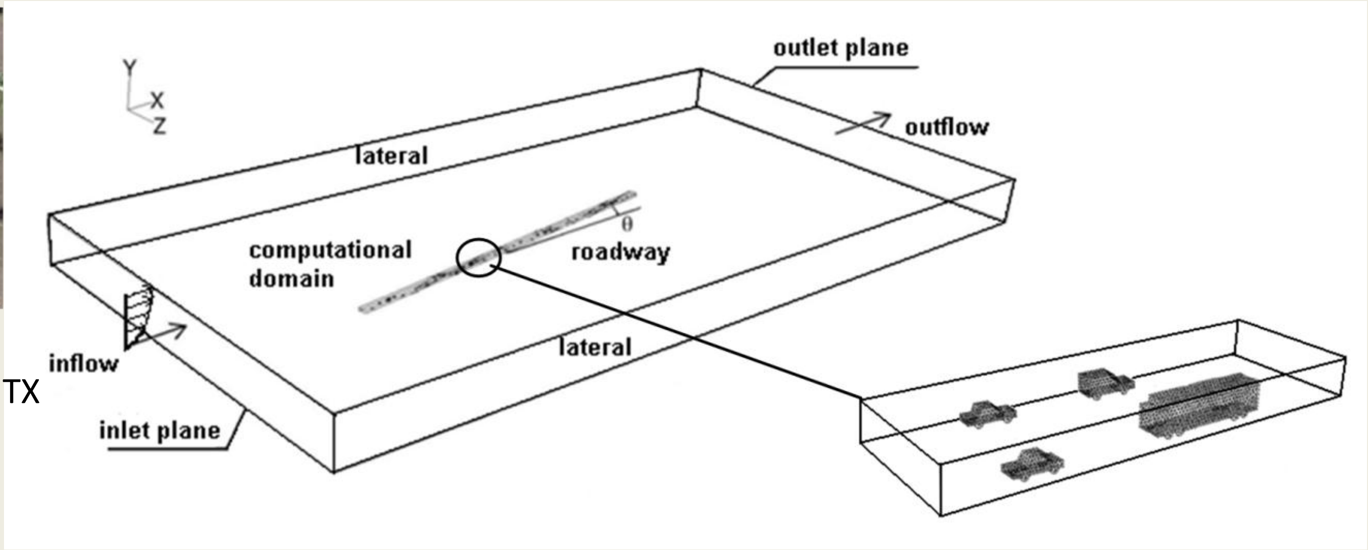
[a] Unit is $m^2 s^{-2}$.

- Due to its rigorous treatment of turbulence mixing mechanisms, CFD-VIT-RIT is able to capture the vertical gradient of inert species near elevated highways. The prediction from CALINE4 appears to be inadequate.
- A CFD model without detailed treatment of VIT and RIT adds no more benefits than CALINE4 besides high computational cost.

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

CFD-VIT-RIT: NOx chemistry near roadways

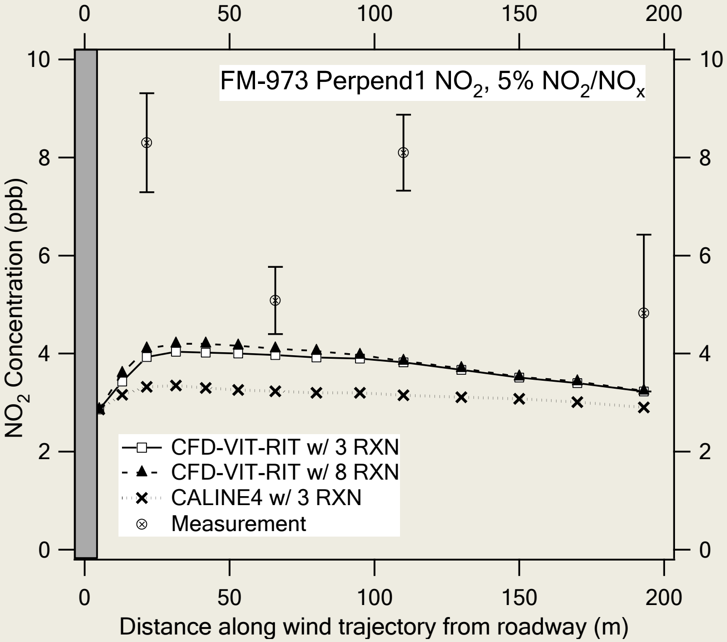
Highway FM 973 near Austin, TX

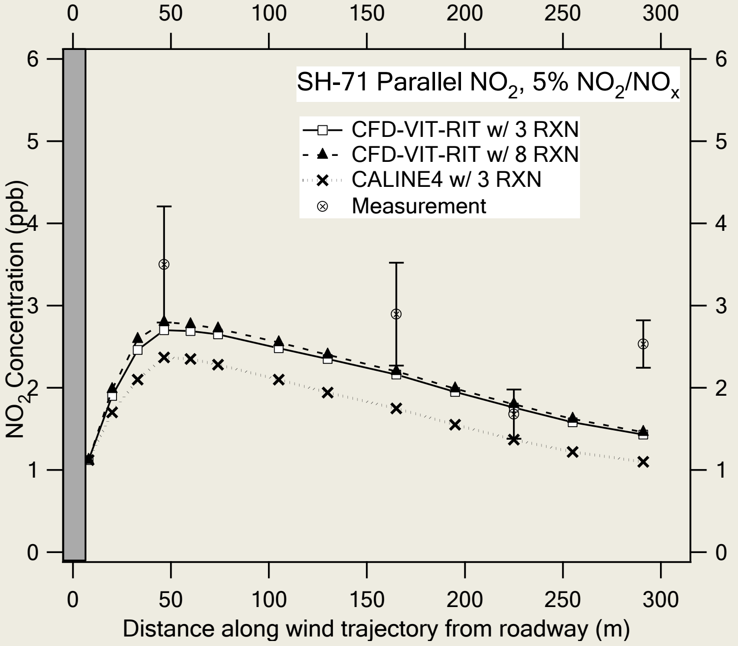


- We applied CFD-VIT-RIT to investigate the chemical evolution of NO_X near Highway FM-973 and SH-71 near Austin, TX.
- The horizontal gradient of NO and NO_x were measured, providing a good dataset for examining the capability of atmospheric models in capturing the chemical transformation of NO_2 near roadways.

Wang, Y. and K.M. Zhang et al. (2010). Accepted, Atmospheric Environment

NO_2/NOx Ratio

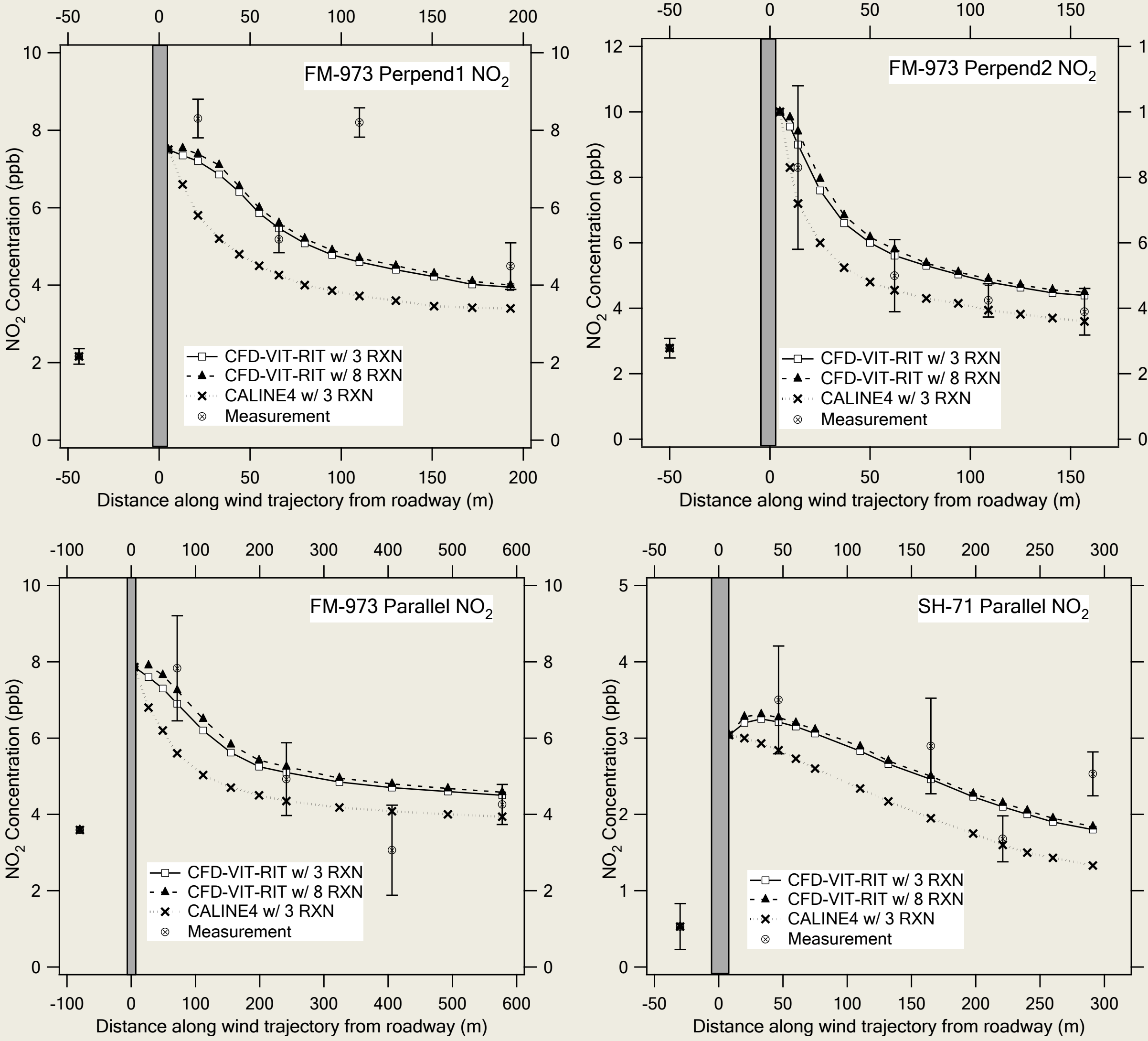




- Using **5%** NO2/NOx ratio, the default value in CALINE4, as the initial condition, neither CFD-VIT-RIT nor CALINE4 can achieve reasonable agreement with the measurement.
- The on-road NO_2/NOx ratio has changed over time due to several factors including the introduction of aftertreatment devices.
- We extrapolated the curbside NO_2/NO ratios based on measured downwind NO and NOx concentrations. The NO_2/NOx ratios ranged from **19 to 31%** for heavy diesel traffic fraction from 5 to 37%.

Wang, Y. and K.M. Zhang et al. (2010). Accepted, Atmospheric Environment

CFD-VIT-RIT: NOx chemistry near roadways

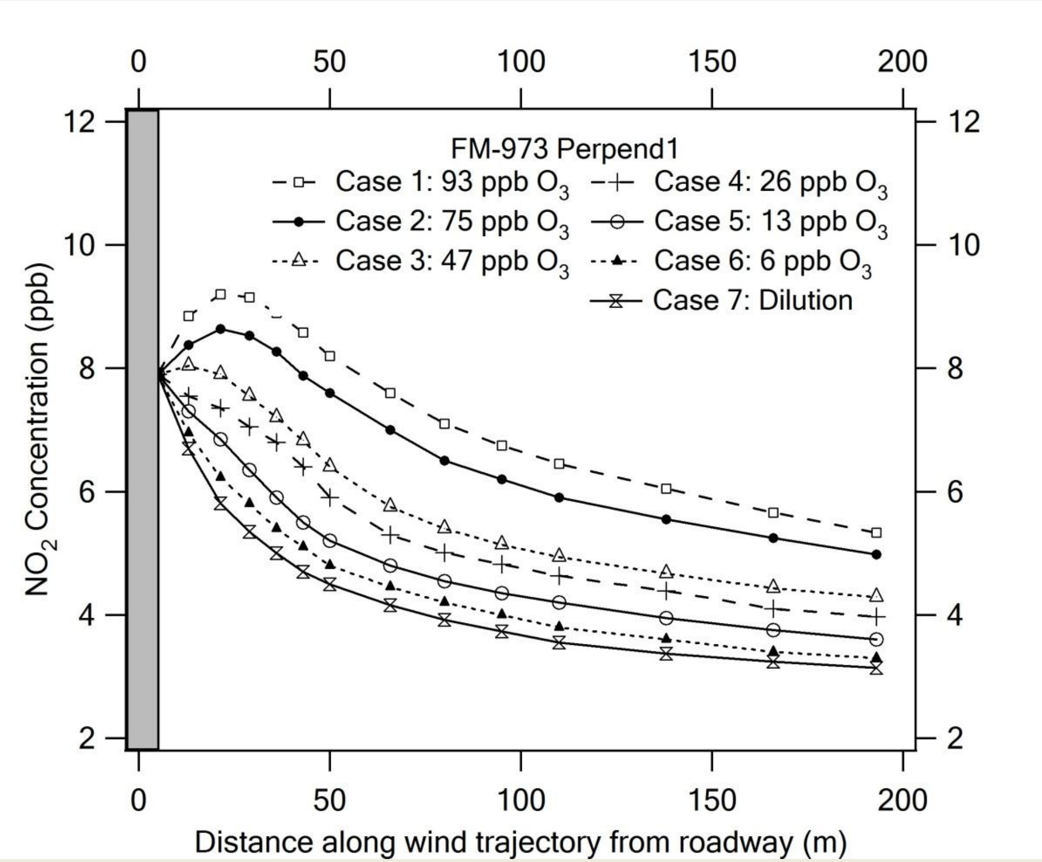


CFD-VIT-RIT couples RANS turbulence model with the finite rate chemical reaction model, which is shown to be capable of predicting both NOx and NO_2 profiles downwind.

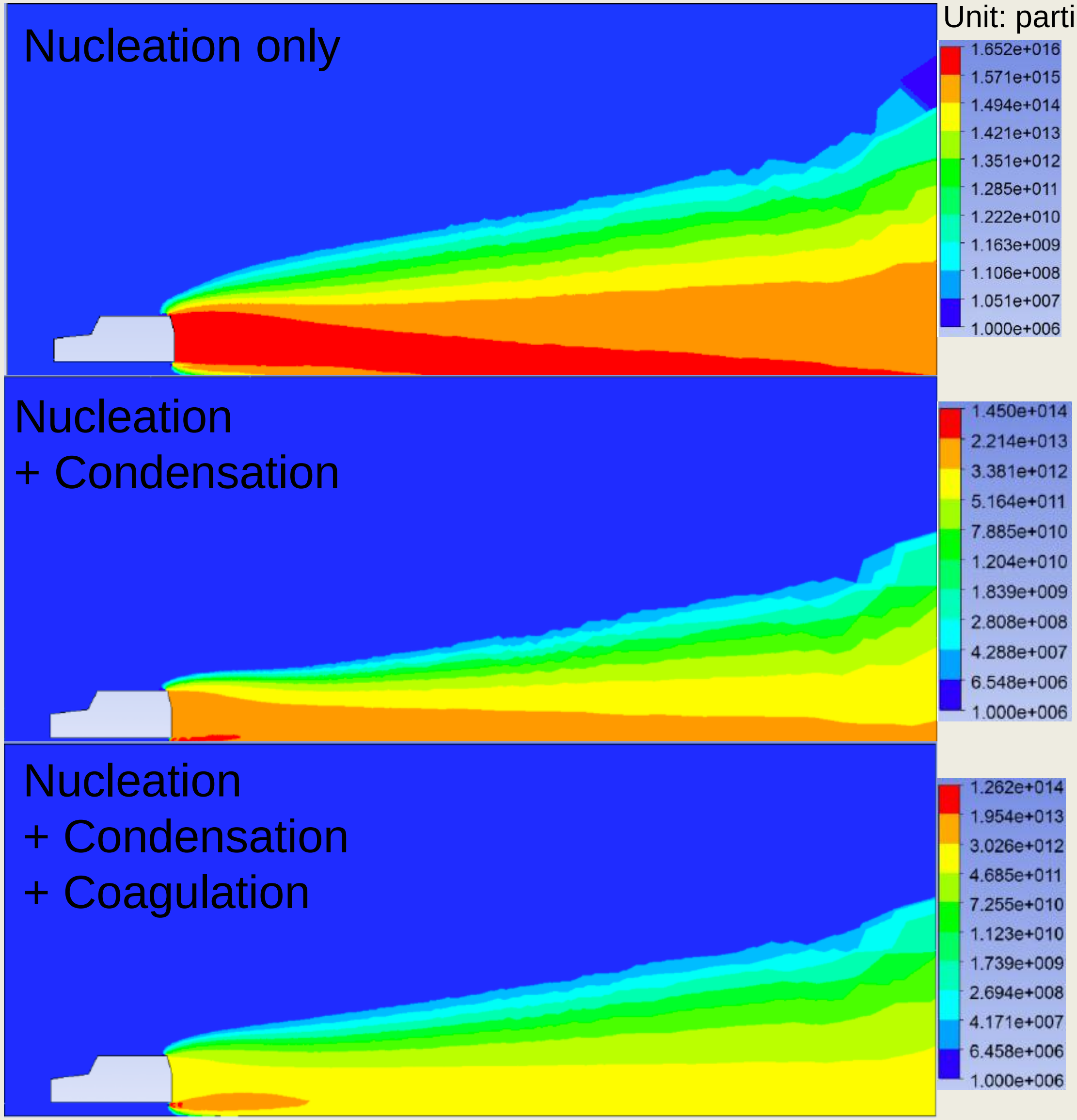
CALINE4 CALINE4 uses a Discrete Parcel Method, which assumes that the NO_2 concentration at a downwind receptor is solely governed by the initial concentrations and time of travel from element to the receptor. *CALINE4 consistently underpredicts NO_2 concentrations.*

Wang, Y. and K.M. Zhang et al. (2010). Accepted, Atmospheric Environment

CFD-VIT-RIT: NOx chemistry near roadways



CFD-VIT-RIT: Aerosol dynamics simulation

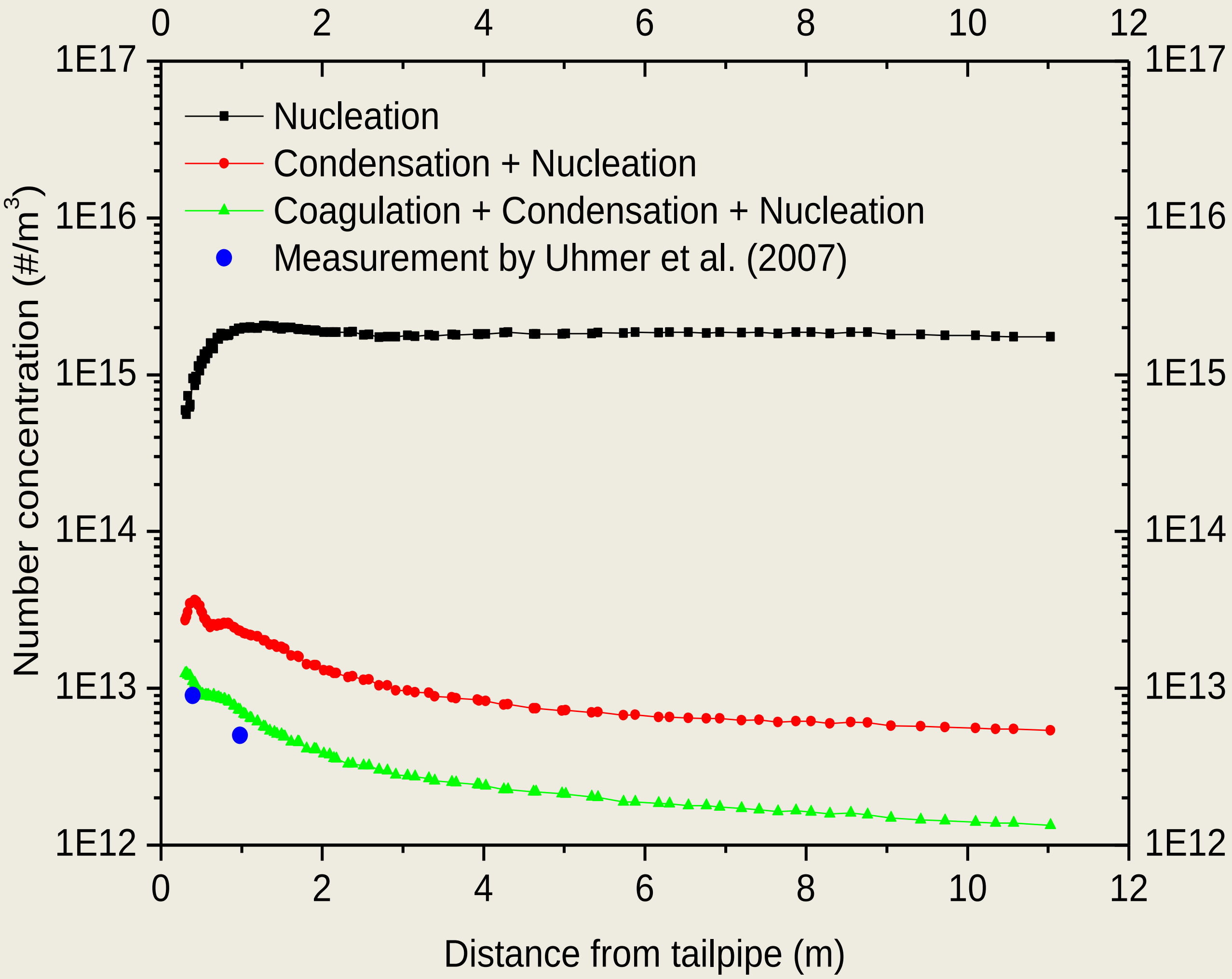


Unit: particles per cubic meter

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.

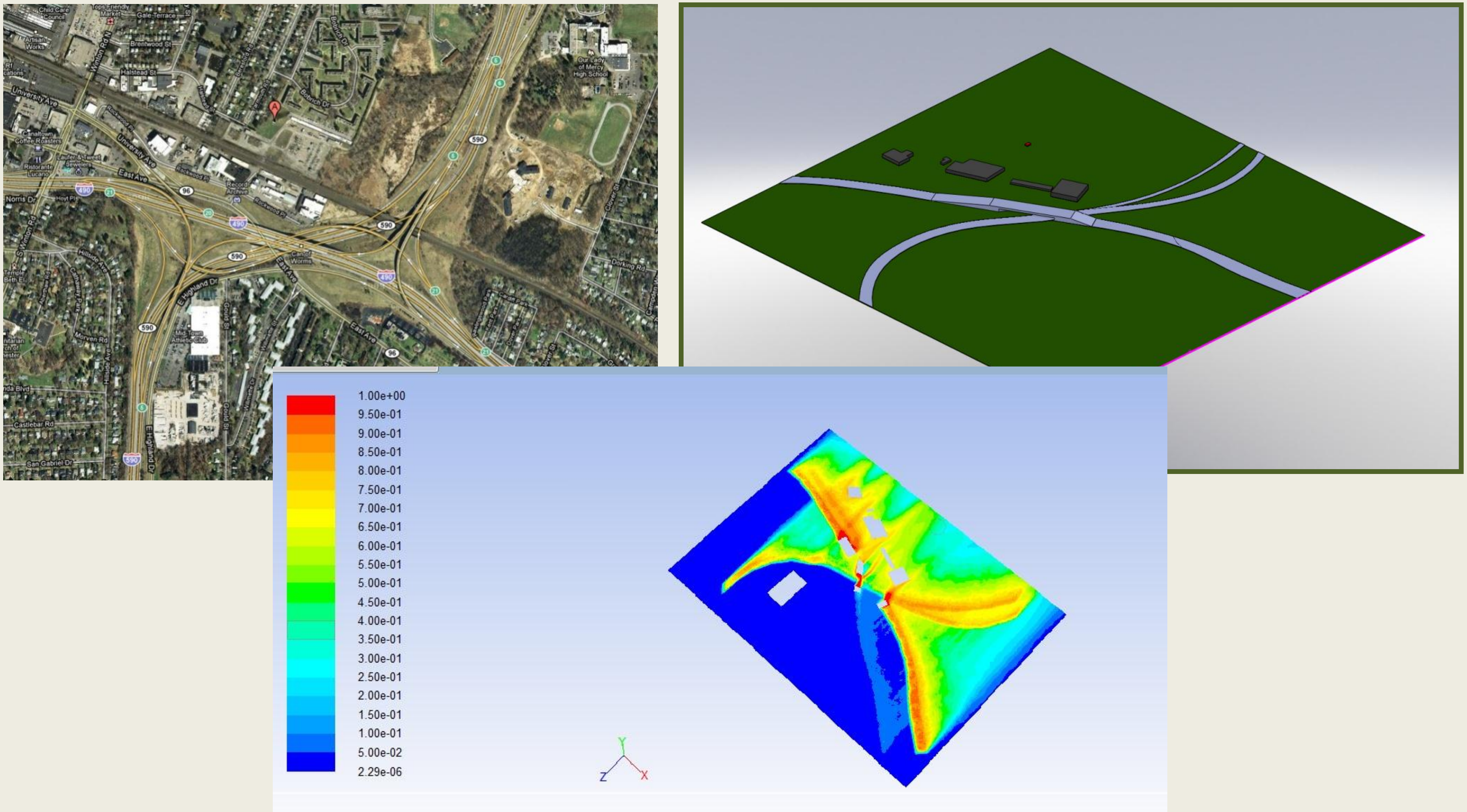
Wang, Y and K. M. Zhang, Unpublished

CFD-VIT-RIT: Aerosol dynamics

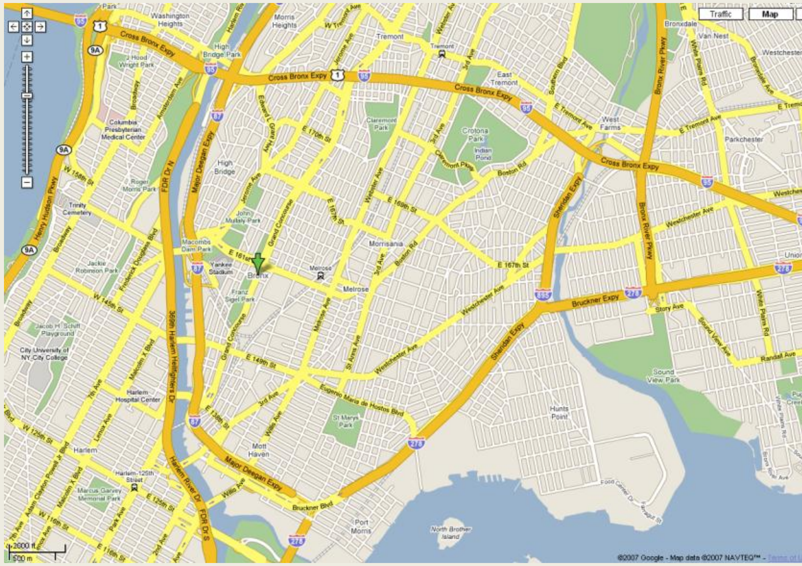


Wang, Y and K. M. Zhang, Unpublished

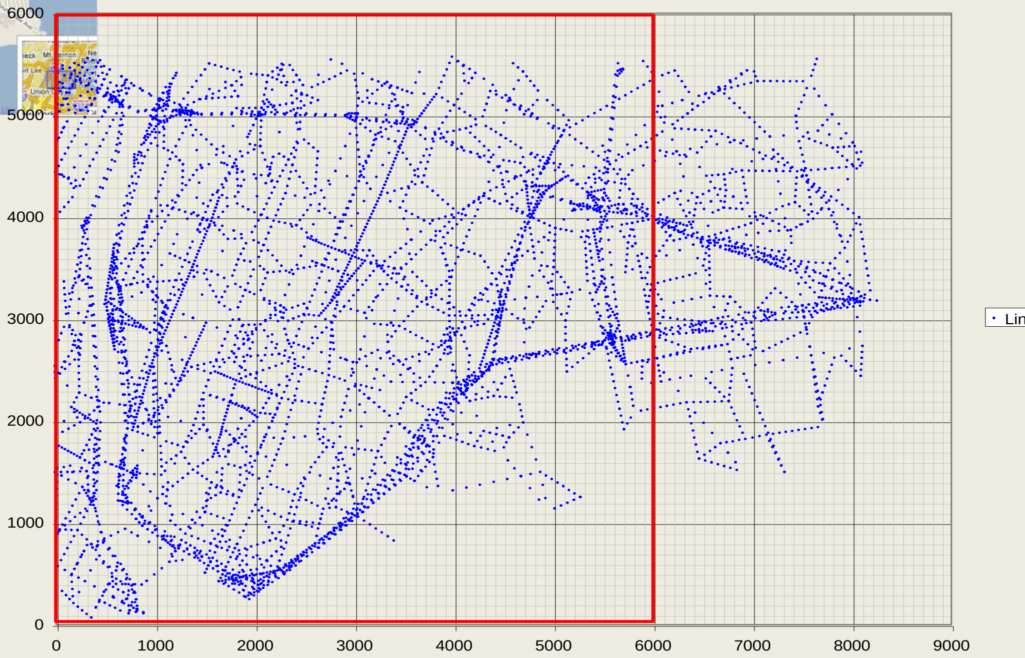
CFD-VIT-RIT: Pollutant dispersion near highway intersections



Modeling microenvironment air quality in South Bronx, NYC



- The simulation domain was a 6 km by 6 km area encompassing highways and arterial roads
- Link locations and traffic volume provided by NYMTC
- Emission factors provided by NYSDOT

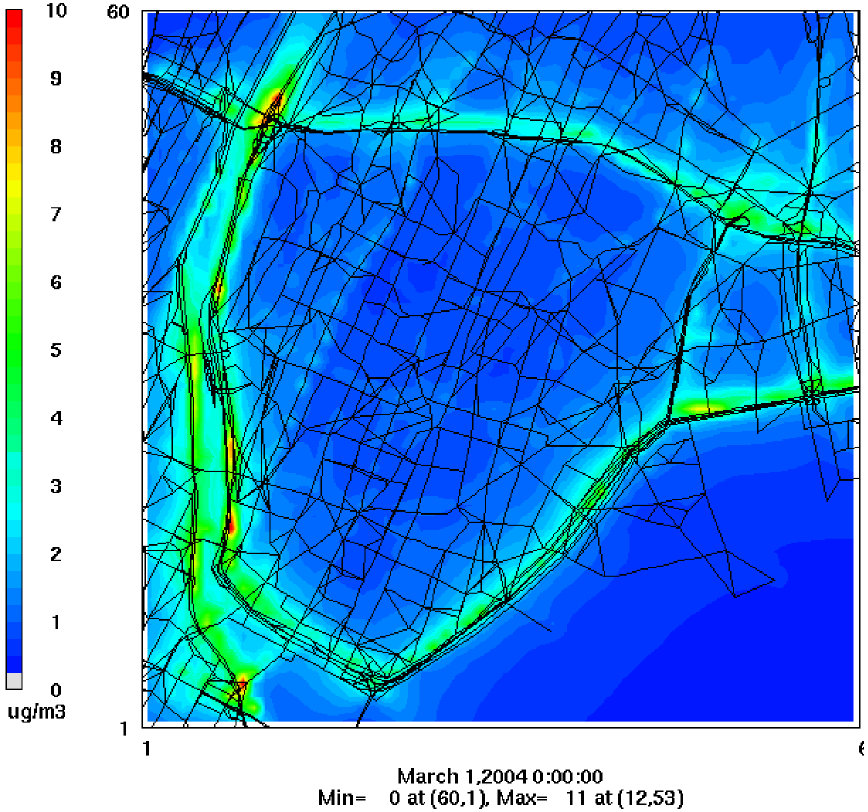


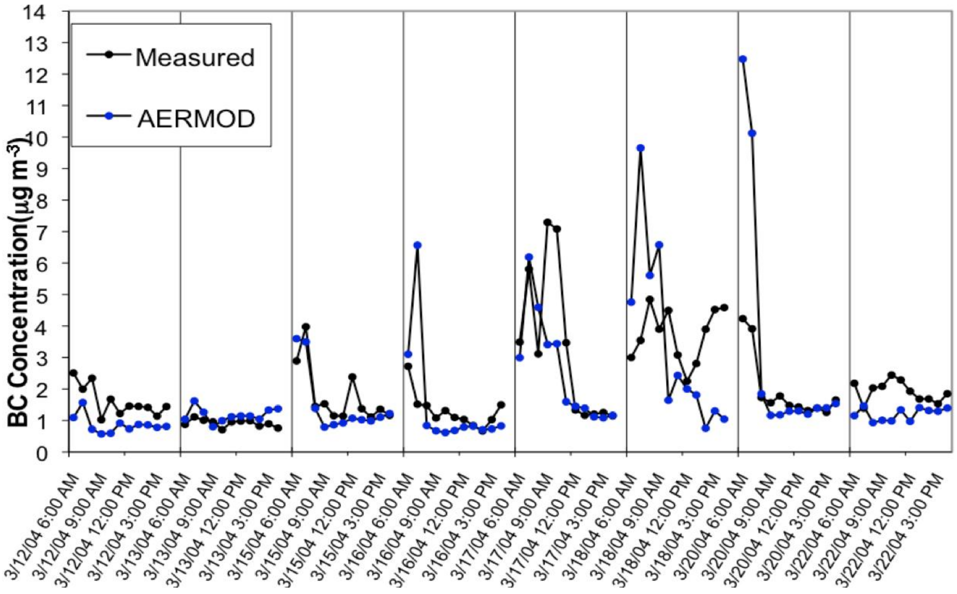
- The road links were divided to road segments to be modeled as area sources.
- We created over 6,000 road segments for simulation

Zhang et al. (2009) UTRC2 report 49777-22-19

Simulating Black Carbon Conc. in South Bronx w/ AERMOD

Highest 24-Hr Average BC in March 2004





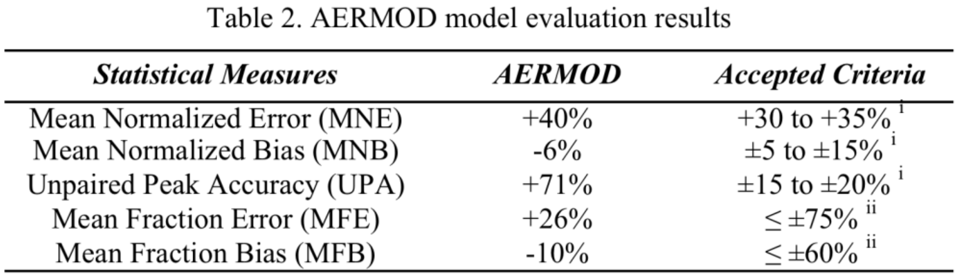


Table 2. AERMOD model evaluation results

Statistical Measures	*AERMOD*	*Accepted Criteria*
Mean Normalized Error (MNE)	+40%	+30 to +35% ^{i}
Mean Normalized Bias (MNB)	-6%	±5 to ±15% ^{i}
Unpaired Peak Accuracy (UPA)	+71%	±15 to ±20% ^{i}
Mean Fraction Error (MFE)	+26%	≤±75% ^{ii}
Mean Fraction Bias (MFB)	-10%	≤±60% ^{ii}

Zhang et al. (2009) UTRC2 report 49777-22-19

Discussions

- Turbulent reacting flow models based on computational fluid dynamics (such as CFD-VIT-RIT) have shown great promise in advancing our capability in project-level analysis.
- Those advanced modeling tools are not designed to replace the current Gaussian-based dispersion models. Rather, they can be used to analyze more complex roadway environments, and potentially to be incorporated into highway design processes.
- The caveat is that a CFD model without detailed treatment of atmospheric processes adds no more benefits than the Gaussian models.

Acknowledgment

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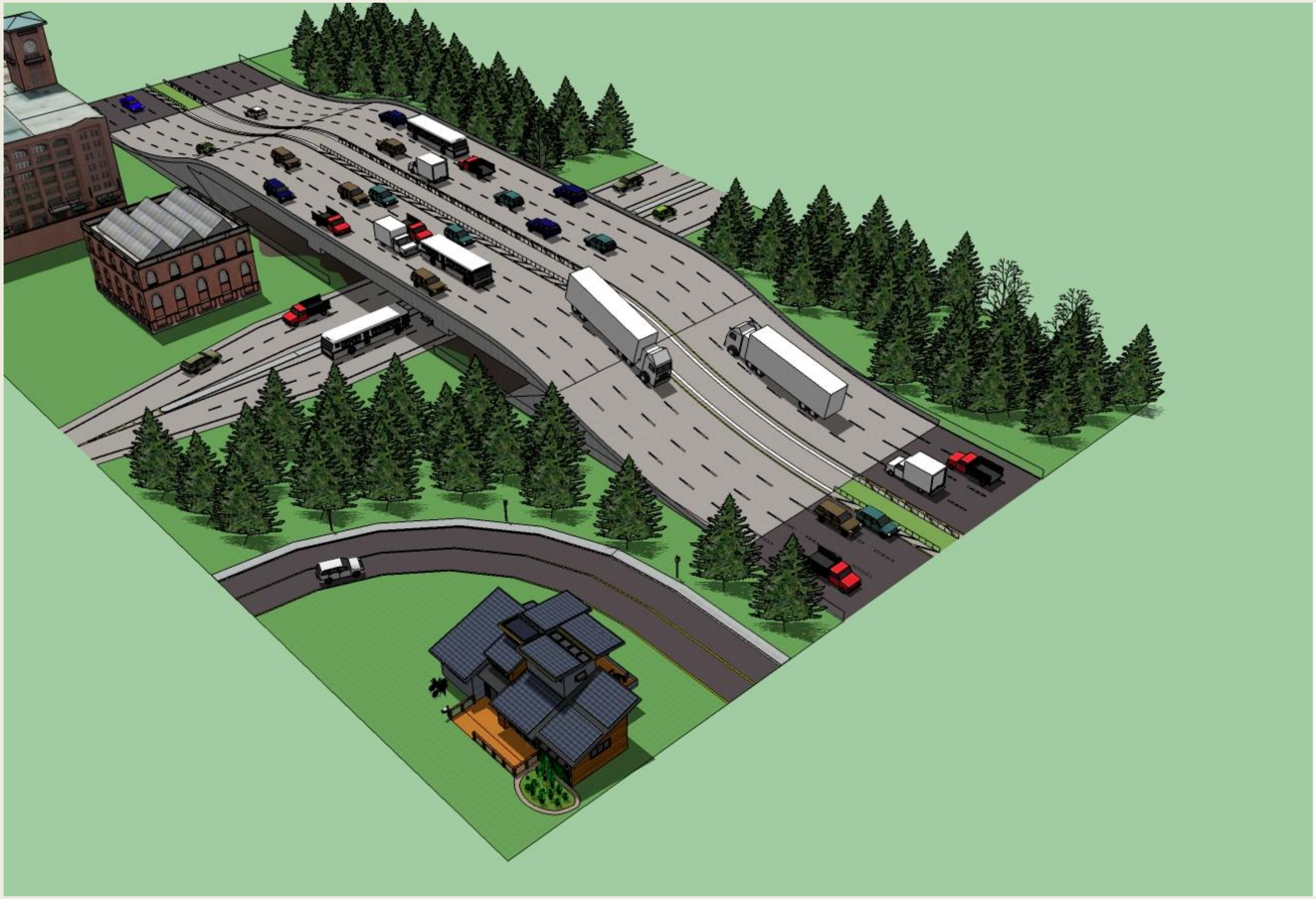
  - New York State Energy Research and Development Authority (NYSERDA)
  - California Air Resources Board (CARB)
  - University Transportation Research Center (UTRC2)
  - Cornell Center for a Sustainable Future

CFD-VIT-RIT: Micro-environment



A complex exposure environment

In a collaborative effort sponsored by the U.S. Federal Highway Administration, regulators, researchers, and consultants identify and prioritize research needs for the transportation community.

PARTICULATE MATTER: A Strategic Vision *for* Transportation-Related Research

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Most individuals have witnessed a bus or large truck emitting a thick smoke plume as it accelerates away from an intersection. Or they have seen the occasional car trailing a smoke cloud in its wake. When cars and trucks emit visible smoke, their contribution to air pollution is obvious. However, on-road vehicles, or "mobile sources", emit a range of pollution. Some pollutants, such as carbon monoxide (CO) and soot from diesel-powered trucks, are emitted straight from the tailpipe. Other vehicle emissions, like volatile organic compounds (VOCs), NO_x, and ammonia, interact in the atmosphere to form "secondary" pollutants, such as ozone or ammonium nitrate.

PHOTODISC