Modeling Dispersion of Highway Emissions

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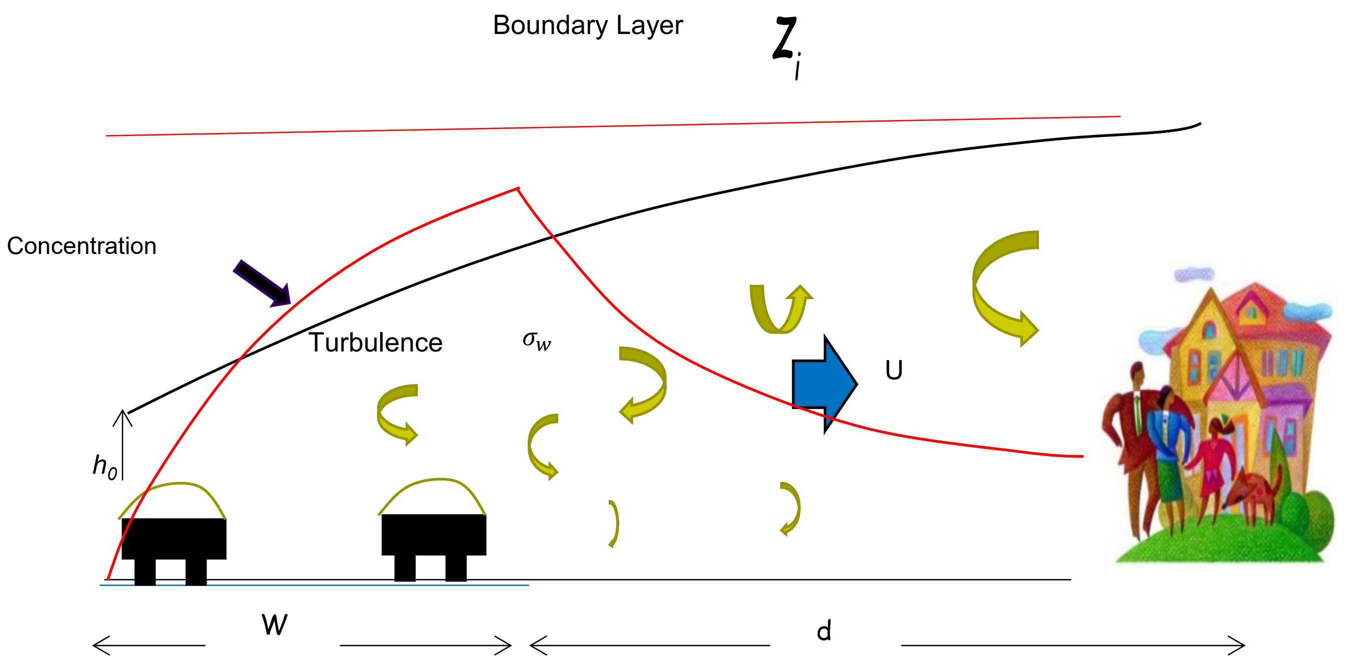
- Governing Processes
- Experiments and Field Studies
- Modeling dispersion of emissions from
  - Highways on flat terrain
  - Highways with different configurations
  - Roads in urban cores
- Emission Factors
- Summary

Introduction

- Studies have shown that living near roadways is implicated in adverse health effects. These studies include both short-term and long-term exposures (Health Effects Institute, 2010)- $NO_2, CO, SO_2, Particulate\ matter$
- These studies coupled with the fact that over 10% of the US population lives within 100 m from highways (Brugge, 2007) has motivated field, wind tunnel and modeling studies to examine the impact of highway emissions on near-road air quality.
- Such studies have been conducted since the 1970s, but recent health studies have added impetus to them.

Governing Processes



T = Traffic Flow Rate, vehicles/s

e_f = Emission Factor, g/m/vehicle

U = Wind Speed, m/s

σ_w = Turbulence Level, m/s

z_i = Mixed Layer Height. m

d = Distance from Road Edge, m

W = Width of Road, m

h_0 = Height of Vehicle, m

$$C = \frac{Q}{Uhw}$$

$Q = Emission\ rate$

$U = Wind\ Speed$

$h = Height\ of\ plume$

$w = width\ of\ plume$

$$C = \sqrt{\frac{2}{\pi}}\frac{Te_f}{W}\frac{1}{\sigma_w}\ln\left(1 + \frac{\sigma_w W}{h_0 U + \sigma_w d}\right)$$

$$C_{far} = \frac{Te_f}{Uz_i}$$

Field and Modeling Studies

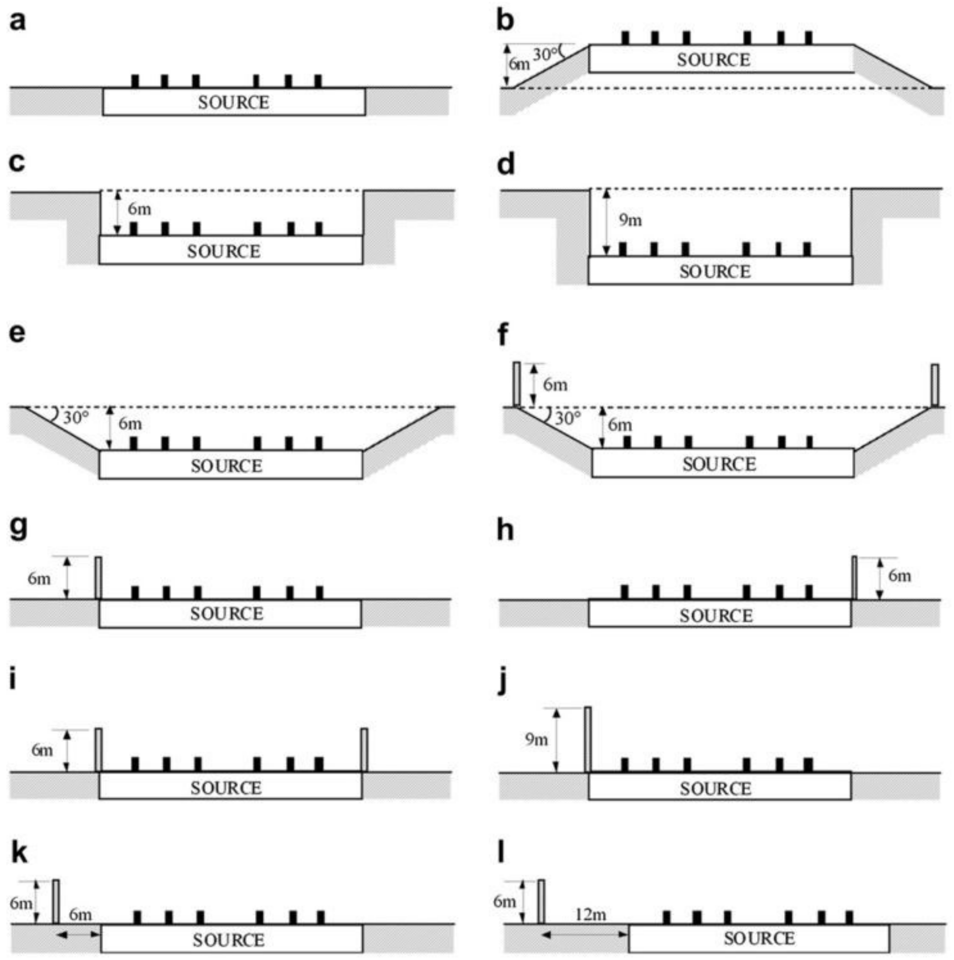
Field and Laboratory Studies

- Dispersion of releases from sources close to the ground
  - Green Glow, Prairie Grass (1956)
  - Project Sagebrush (2013)
- **Field studies to understand road dispersion** –GM tracer study (1980)- tracer released from 352 automobiles
- **New road field studies**
  - Caltrans (Benson,1989), Raleigh study (Baldauf et al., 2008), Idaho Falls Study (2008, Finn et al. 2010)

Models

- EPA Highway Model (1970s)
- CALINE Model (Benson, 1989)
- RLINE (Snyder et al., 2013)
- C-LINE (Barzyk et al, 2013

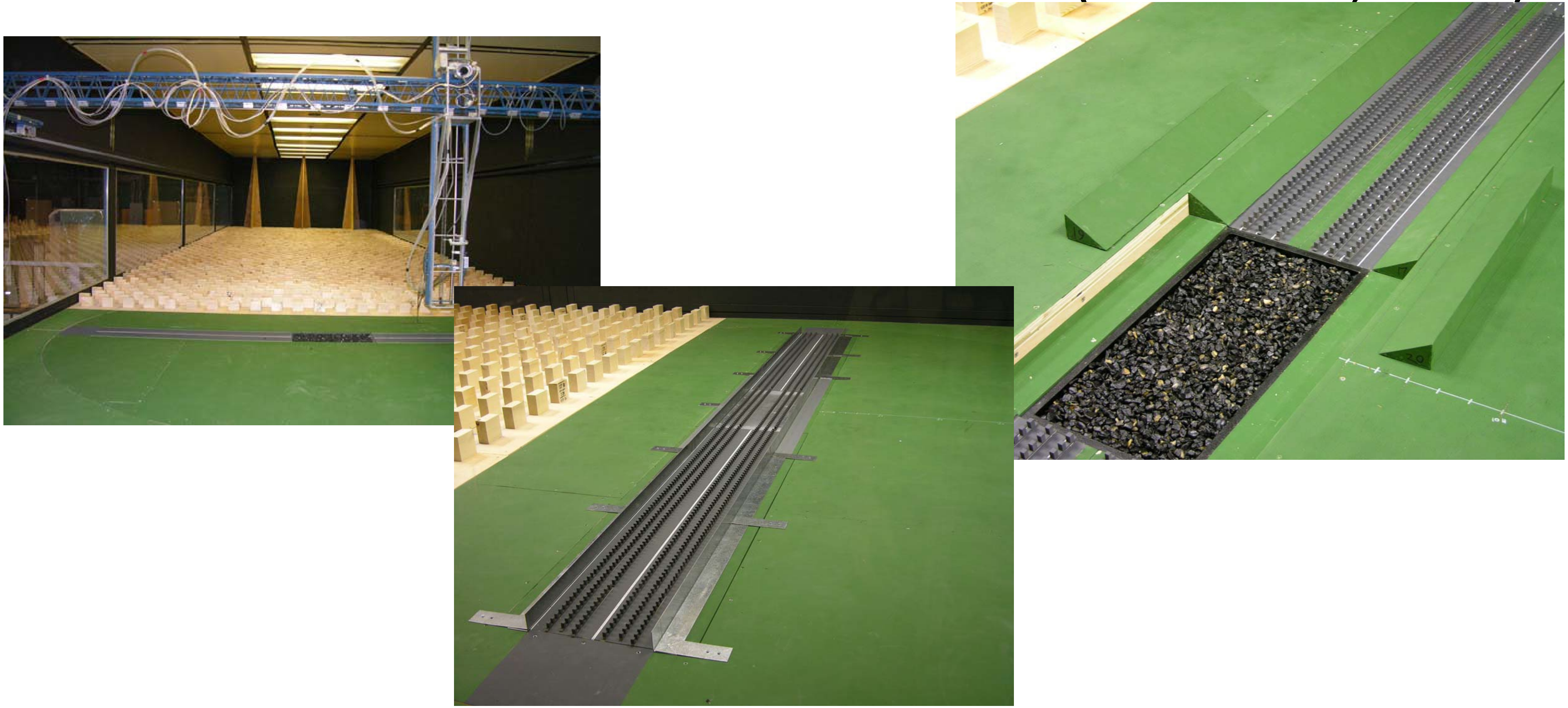
Wind Tunnel Studies at the USEPA (Heist et al, 2009)



RLINE Model, which is non-regulatory option in AERMOD, includes methods to compute concentrations associated with emissions from highways with and without noise barriers, and depressed highways.

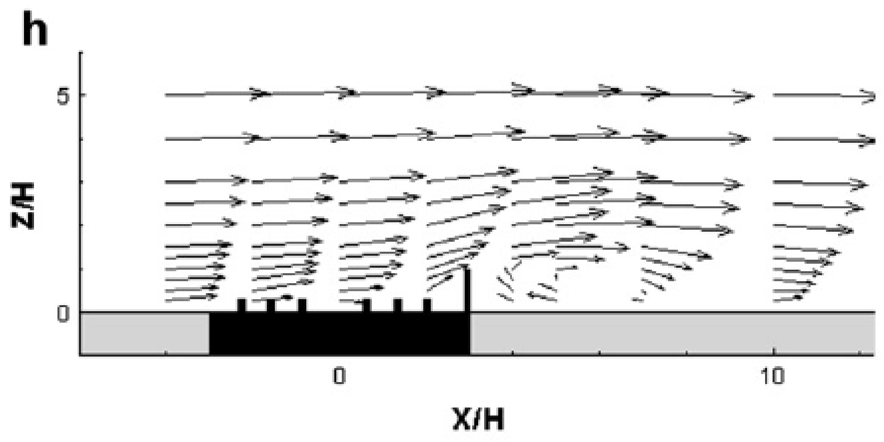
The RLINE model was developed using data from the wind tunnel study, and the field study described in the next slide.

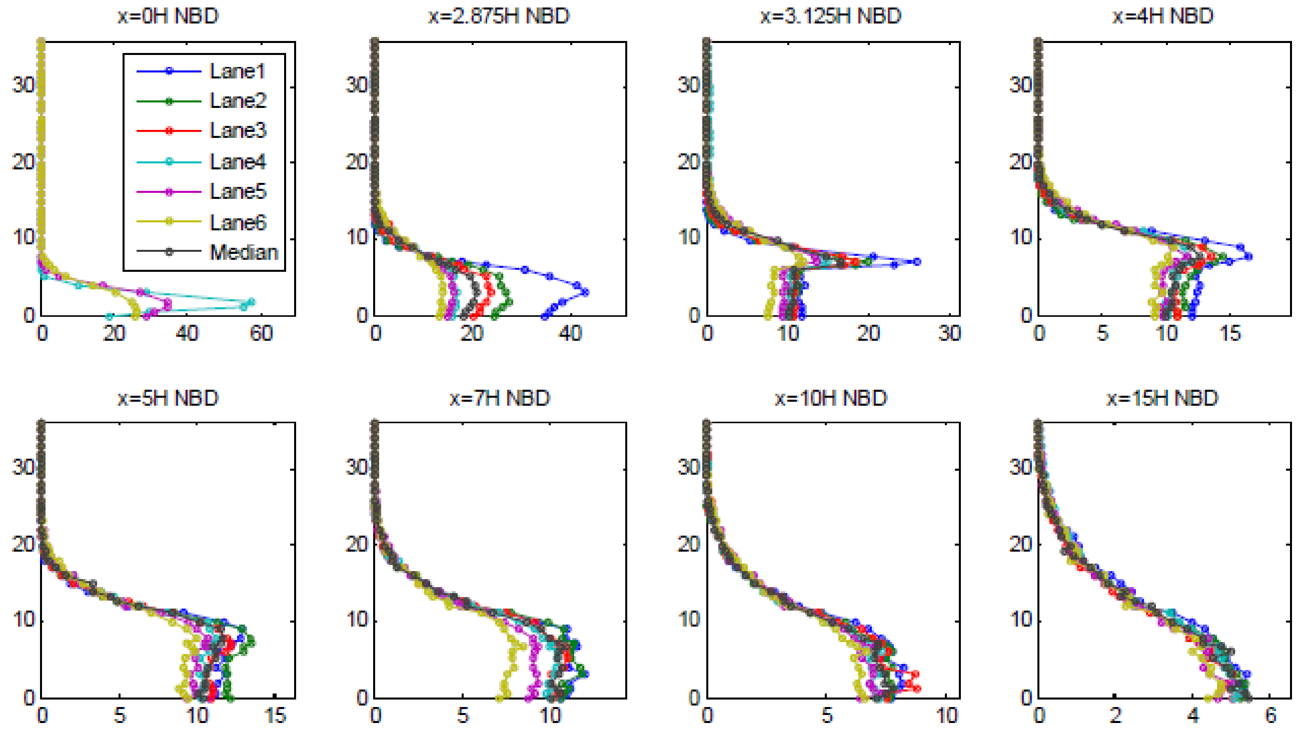
Wind Tunnel Studies at the USEPA (Heist et al, 2009)



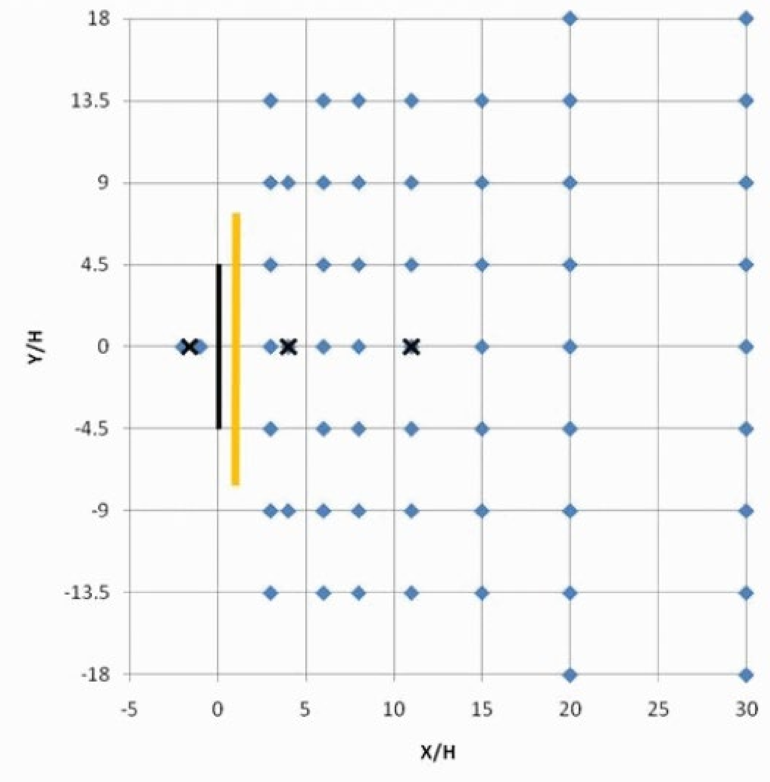
Barrier Effects

Wind Tunnel Results (Heist et al, AE, 43, 5101-5111)



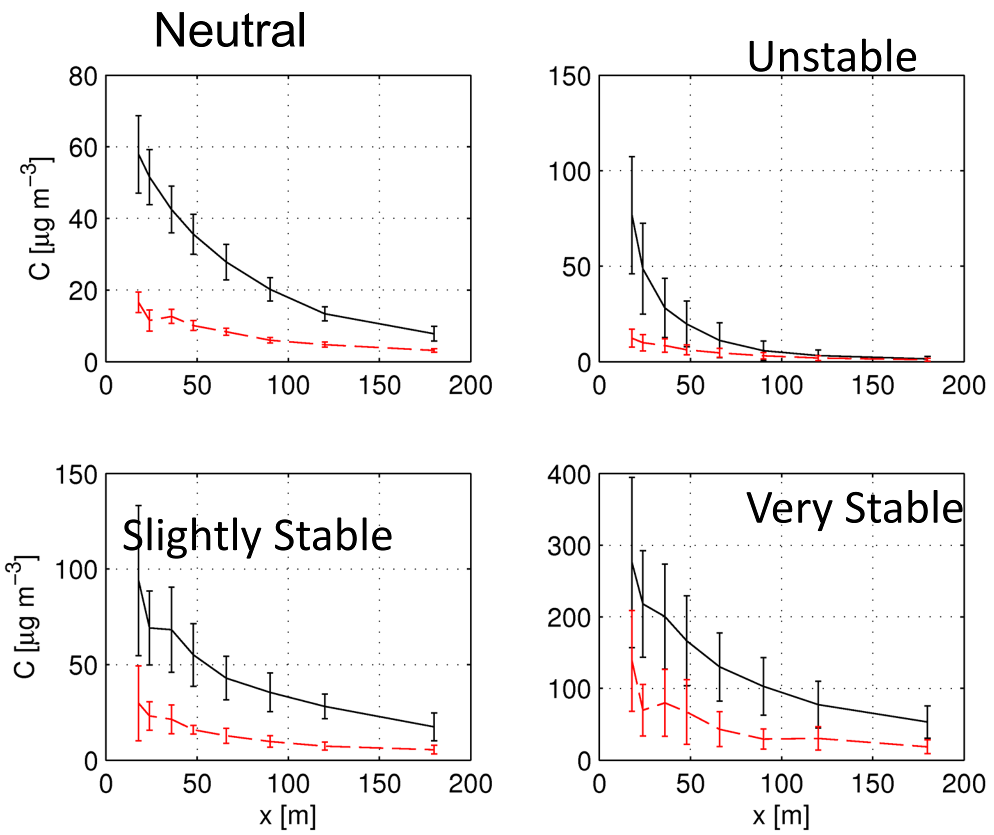


Idaho Falls Study (Finn et al., 2010)



- ❑ SF_6 simultaneously released from two sources
- ❑ Concentrations measured at 56 receptors
- ❑ Spanned neutral, unstable, and stable conditions

Idaho Falls Study (Finn et al., 2010)



- With Barrier

- Without Barrier

Meteorological approach flow conditions at the non-barrier reference anemometer at $x = -1.6H$, $z = 3$ m for the selected 15-min cases. P–G is the Pasquill–Gifford stability class determined by the Solar Radiation Delta-T (SRDT) method (EPA 2000).

Test	z/L	Stability	P–G	WS (m s^{-1})	WD (deg)	u_* (m s^{-1})	H (W m^{-2})	σ_θ (deg)
2	−0.312	Unstable	B	1.4	201	0.29	200.0	28.8
1	−0.016	Neutral	D	5.5	219	0.55	73.4	11.4
3	0.048	Weakly stable	D	3.6	209	0.35	−54.1	8.7
5	0.379	Strongly stable	F	1.6	203	0.12	−15.2	8.5

Variation of mean centerline concentrations with distance from source with and without the barrier. Concentration is normalized, and distances are in m.

A field study to estimate the impact of noise barriers on mitigation of near road air pollution

Ranga Rajan Thiruvenkatachari[1] · Yifan Ding[1] · David Pankratz[1] · Akula Venkatram[1]

(a)

(b)

Fig. 2 a Picture of the SF_6 gas cylinder with the pressure regulator, the electronic solenoid (green and white box) that could be operated from within the vehicle, and the mass flow controller. b The SF_6 gas from the mass flow controller was looped into the vehicle exhaust

Fig. 4 Upwind meteorological measurement site containing two 3-D sonic anemometers mounted 3 m and 5 m above the ground

Modeling Approach

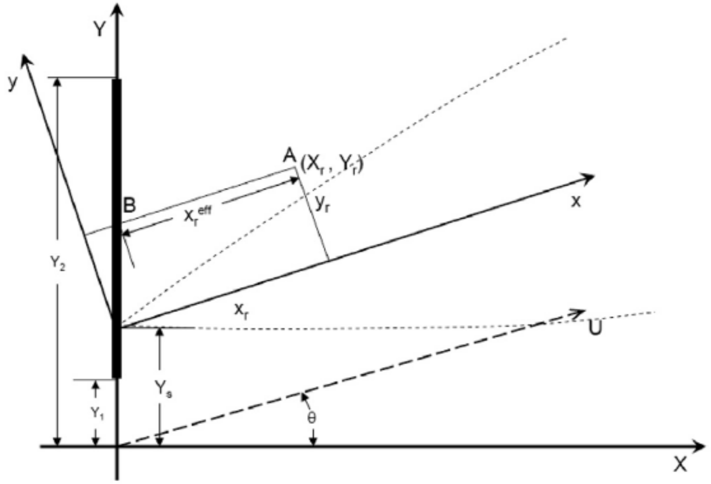
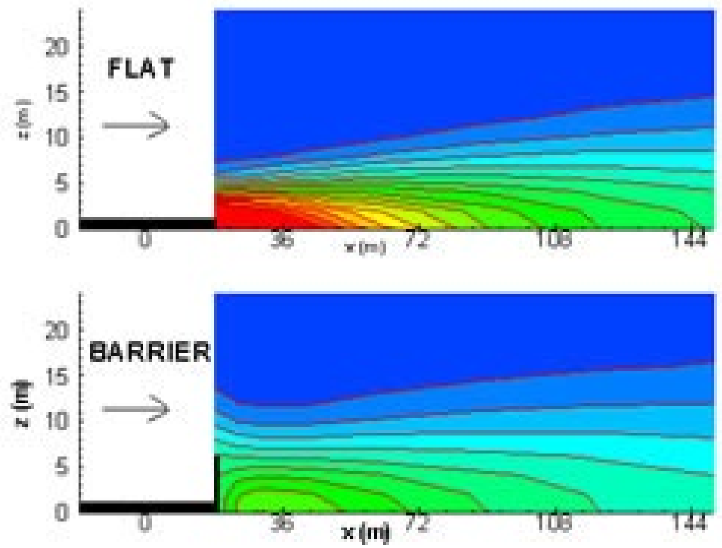
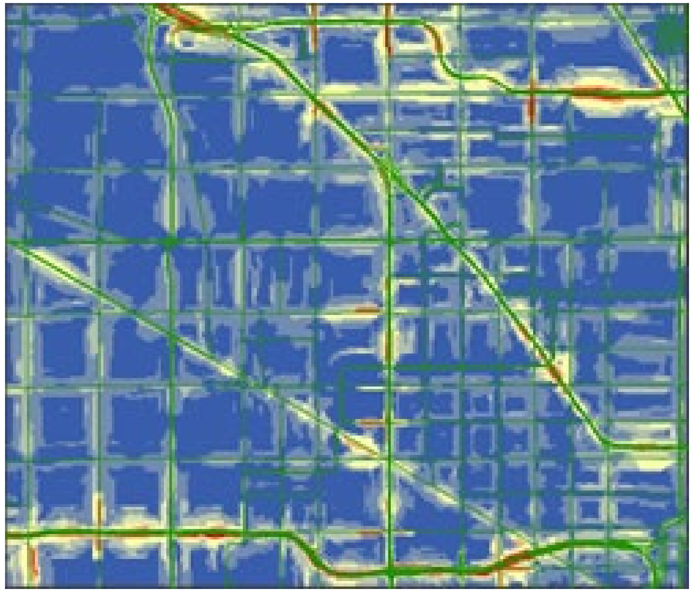


Fig. 1. Coordinate system used to calculate contribution of the point source at Y_S to concentrations at (X_r, Y_r). The system x−y has the x-axis along the mean wind direction, which is at an angle θ to the fixed X axis. The dotted lines represent the plume originating from an elemental point source at $(0, Y_S)$.





- ❑ Discrete vehicles replaced by a continuous line source.
- ❑ Emission rate=$Emission\ factor \times Traffic\ flow\ rate$
- ❑ Line source modeled as a set of point sources

Reformulation of Plume Spreads for Flat Terrain (Venkatram et al., 2013)

Stable Conditions

$$\sigma_z = 0.57 \frac{u_*}{U} x \left(1 + 3 \frac{u_*}{U} \left(\frac{x}{L} \right)^{2/3} \right)^{-1}$$

$$\sigma_y = 1.6 \frac{\sigma_v}{u_*} \sigma_z \left(1 + 2.5 \frac{\sigma_z}{L} \right)$$

Unstable Conditions

$$\sigma_z = 0.57 \frac{u_*}{U} x \left(1 + 1.5 \left(\frac{u_*}{U} \frac{x}{|L|} \right) \right)$$

$$\sigma_y = 1.6 \frac{\sigma_v}{u_*} \sigma_z \left(1 + 0.5 \frac{\sigma_z}{|L|} \right)^{-1/2}$$

Comparison of Performance of RLINE with those of other Models (Heist et al., 2013)

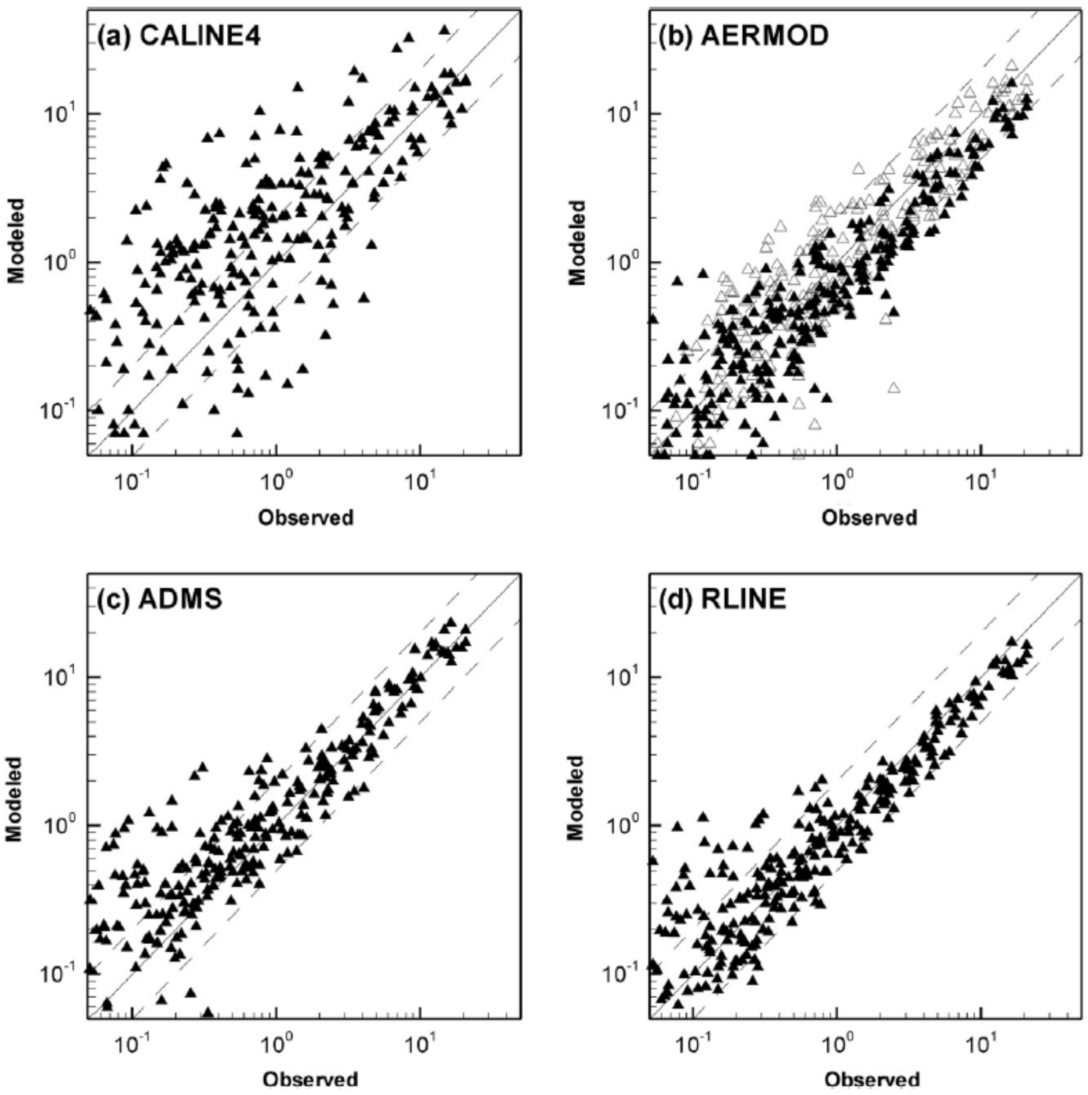
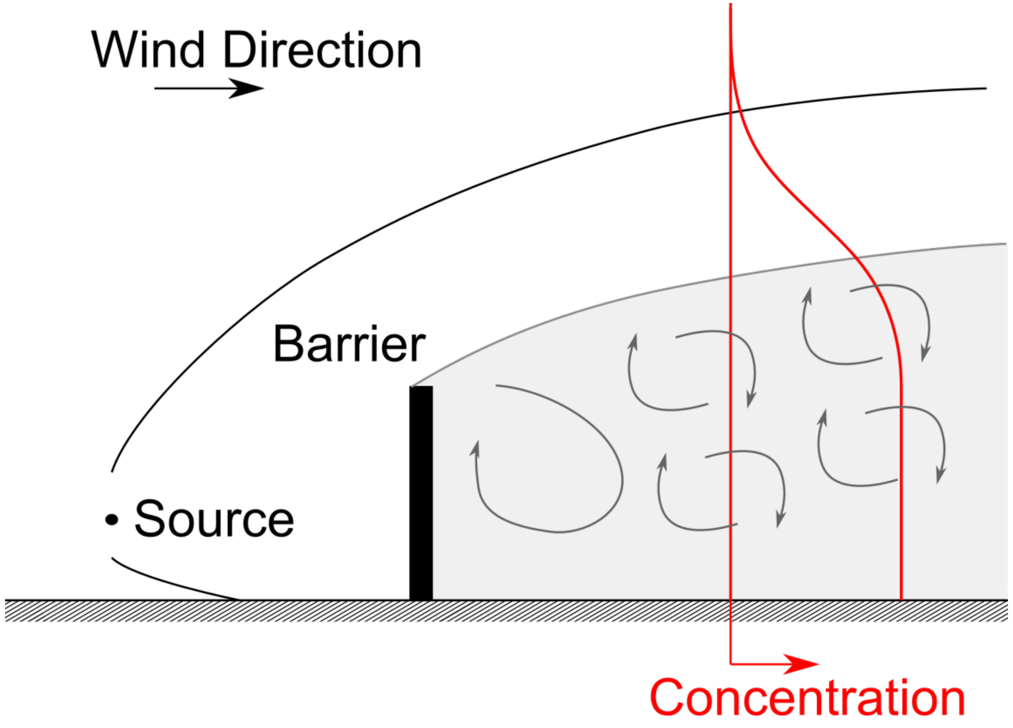


Table 2
Model statistics comparison from all test days for the Idaho Falls tracer study.

Model	FB	NMSE	R	FAC2
CALINE4	0.42	1.94	0.76	0.59
AERMOD-V	0.38	1.26	0.84	0.59
AERMOD-A	0.32	1.25	0.82	0.59
ADMS	0.36	1.14	0.88	0.70
RLINE	0.23	0.96	0.85	0.73

Barrier Model (Schulte et al, 2014)

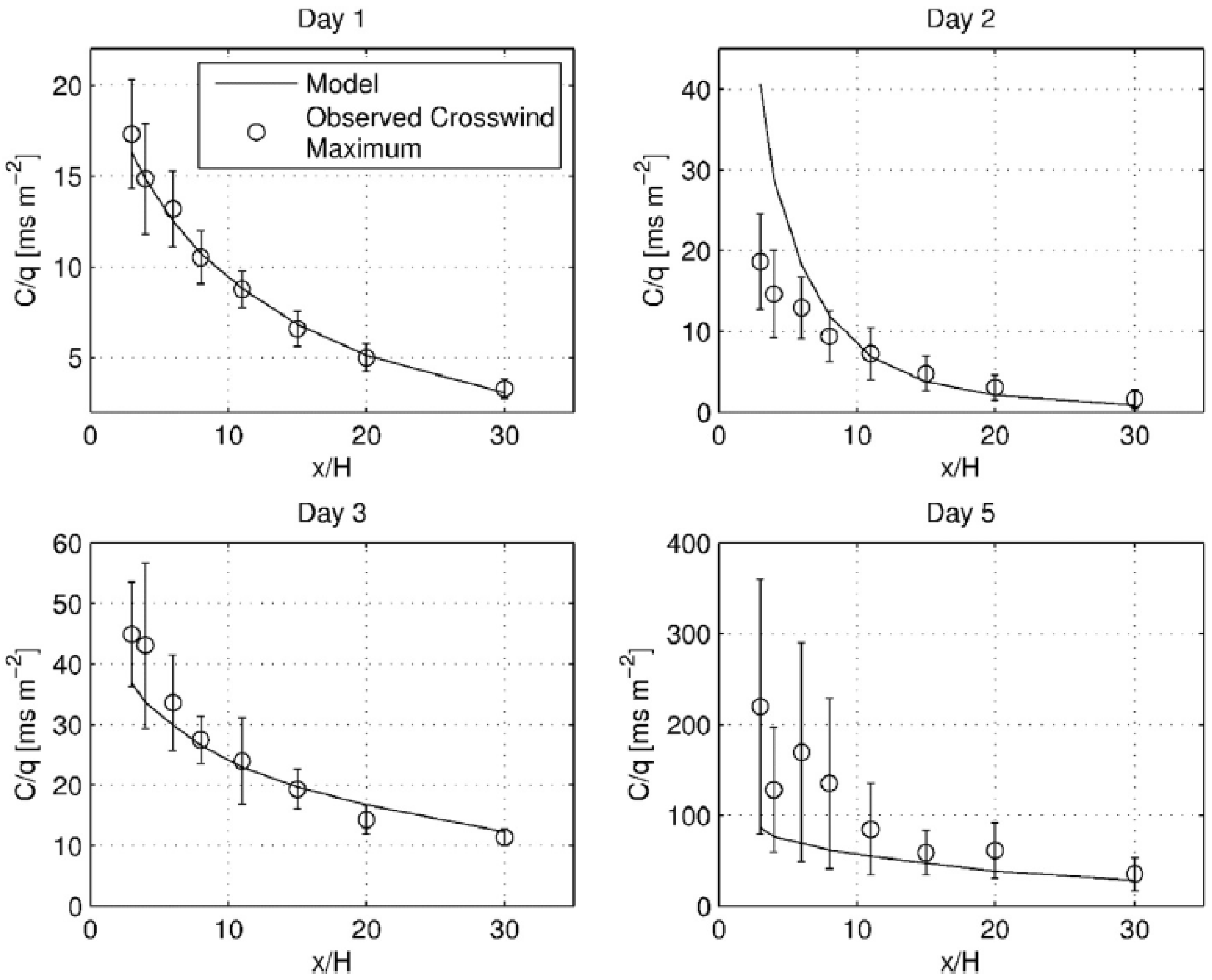


- Concentration is well mixed over the height of the barrier, *H*

$$U\sigma_{zbarrier}(x) = U(z_{eff})\alpha\sigma_z(x) + U\left(\frac{H}{2}\right)\sqrt{\frac{\pi}{2}}H$$

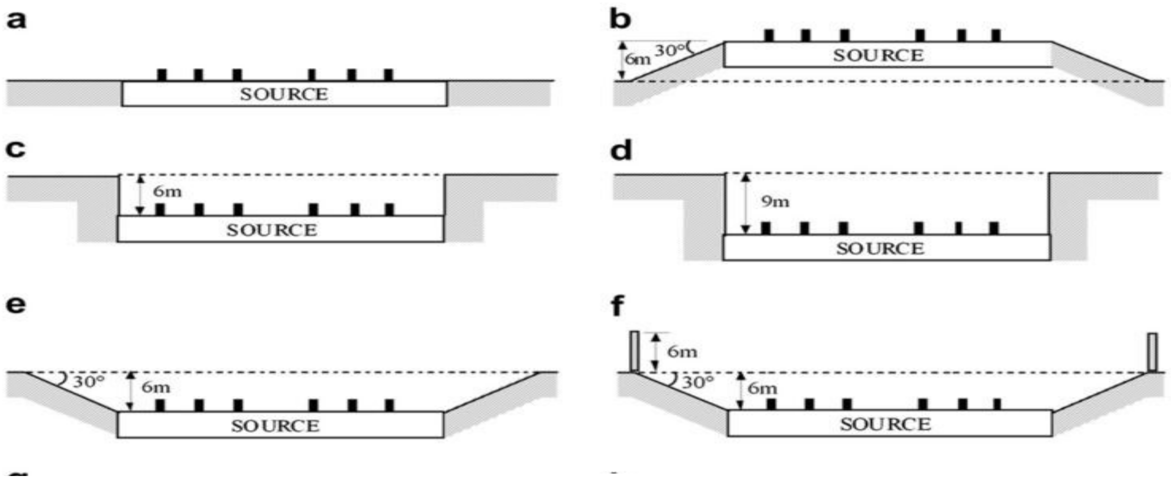
- Concentration is well mixed over the height of the barrier, *H*

Evaluation of Barrier Model (Schulte et al, 2014)

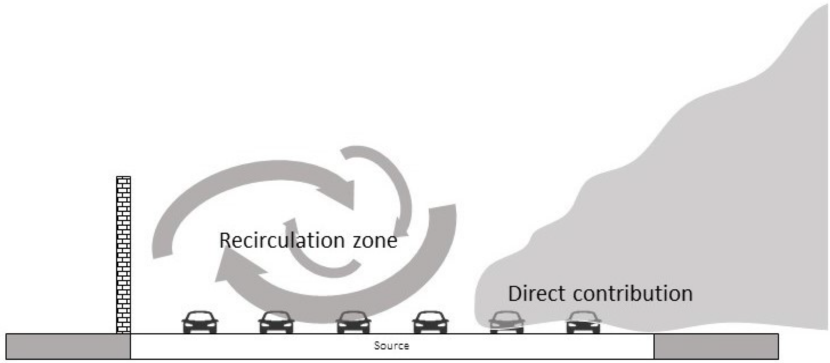


Performance of model in describing crosswind maximum concentrations measured during the Idaho Falls Tracer Study (Finn et al., 2010)

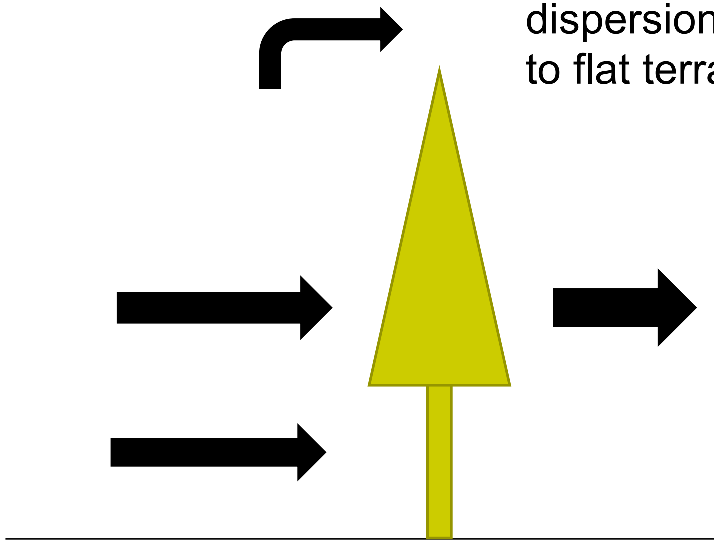
Modeling Dispersion for Other Road Configurations



Plume is assumed to be mixed through the depression before it affects receptors



Effects Related to Vegetative Barriers



Plume that goes above has enhanced dispersion, decreases concentration relative to flat terrain.

Plume going through is subject to less turbulence and hence less dispersion. Increases concentration.

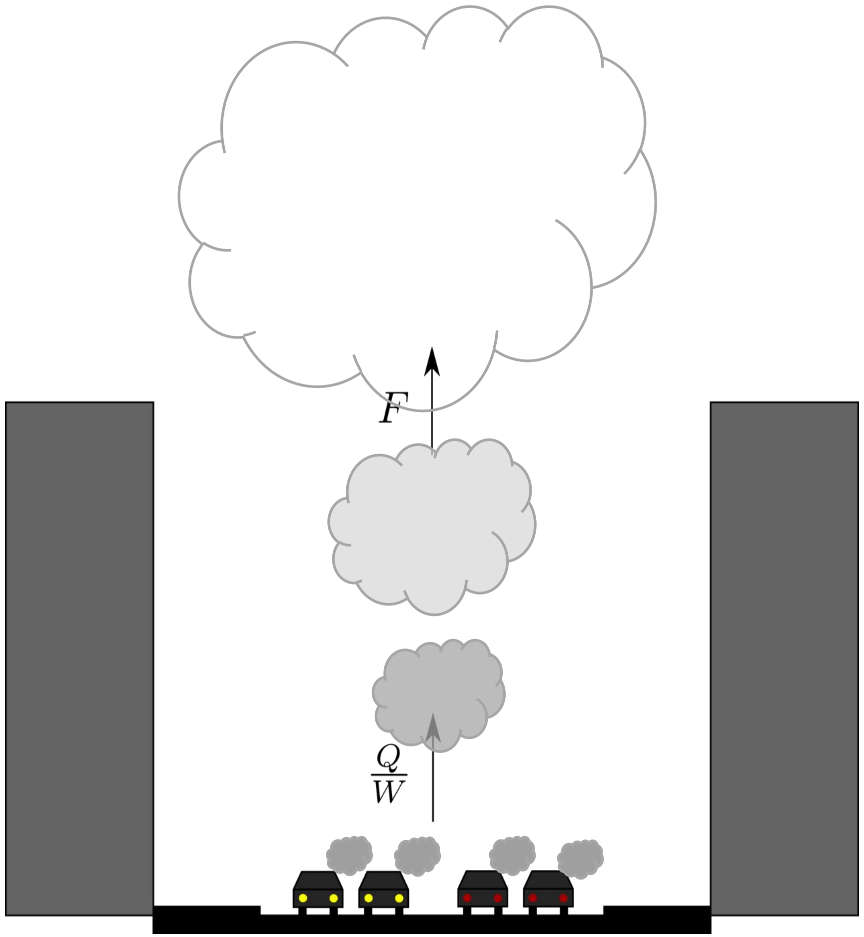
Combination of two effects can increase or decrease concentrations depending on the porosity of vegetation and micrometeorology, and pollutant deposition characteristics.

Effects of Buildings on Dispersion

? →

Do transit oriented developments (TOD) with high building densities increase the impact of vehicle emissions by reducing ventilation?

Models for Effects of Buildings on Dispersion



$$C_s = \frac{Q}{\beta \sigma_w W}\left(\frac{1+a_r}{1+\frac{h_0}{H}(1+a_r)}\right) + C_r$$

Roof concentration, C_r, corresponds to flat terrain conditions

Magnification~aspect ratio= $a_r = \frac{H}{W}$

Street averaged OSPM ?
(Berkowicz, 2000)

Q	Street emission rate
C_s	Surface concentration averaged over the street
C_r	Roof concentration
W	Street width
H	Building height
a_r	Aspect Ratio (H/W)
σ_w	Average standard deviation of vertical velocity fluctuations
β	Empirical constant
h_0	Initial vertical mixing

Evaluation of Buildings Effects Model

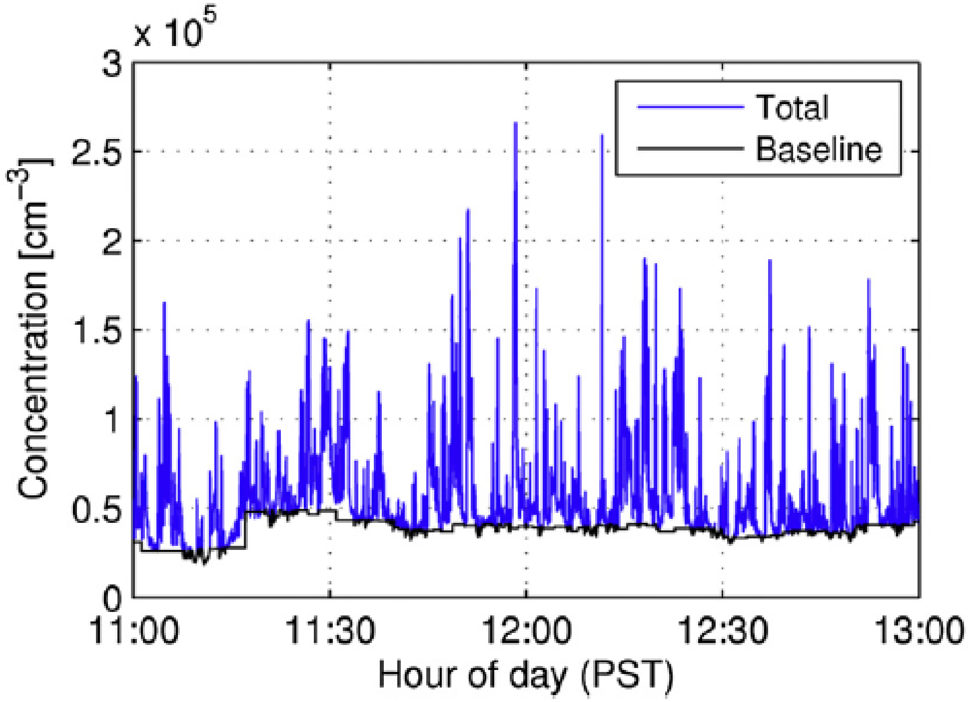
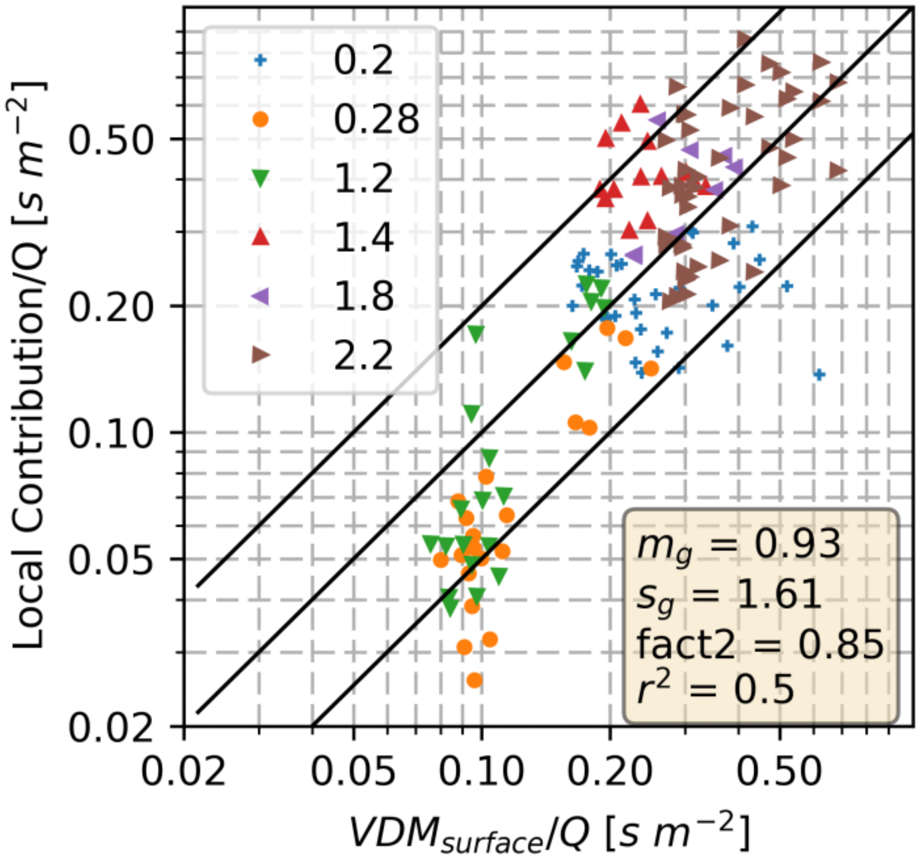
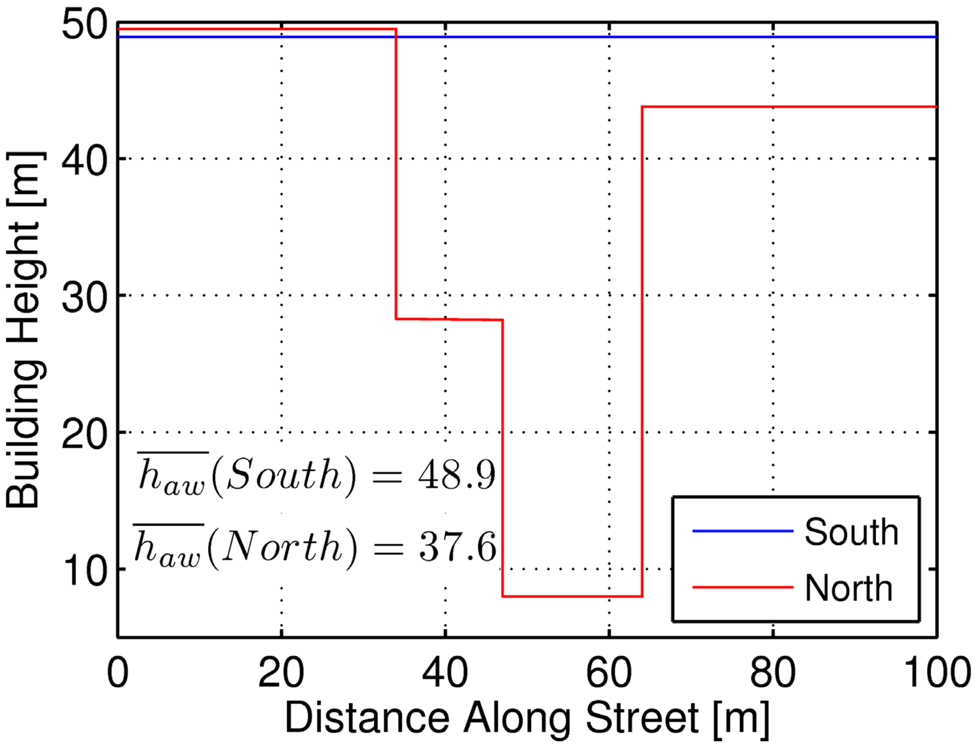


Fig. 7. Sample UFP concentration time series from a building section surface monitor used in the Los Angeles 8th St. measurements. The solid black line is the 10th percentile baseline or background and the blue corresponds to the local contribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



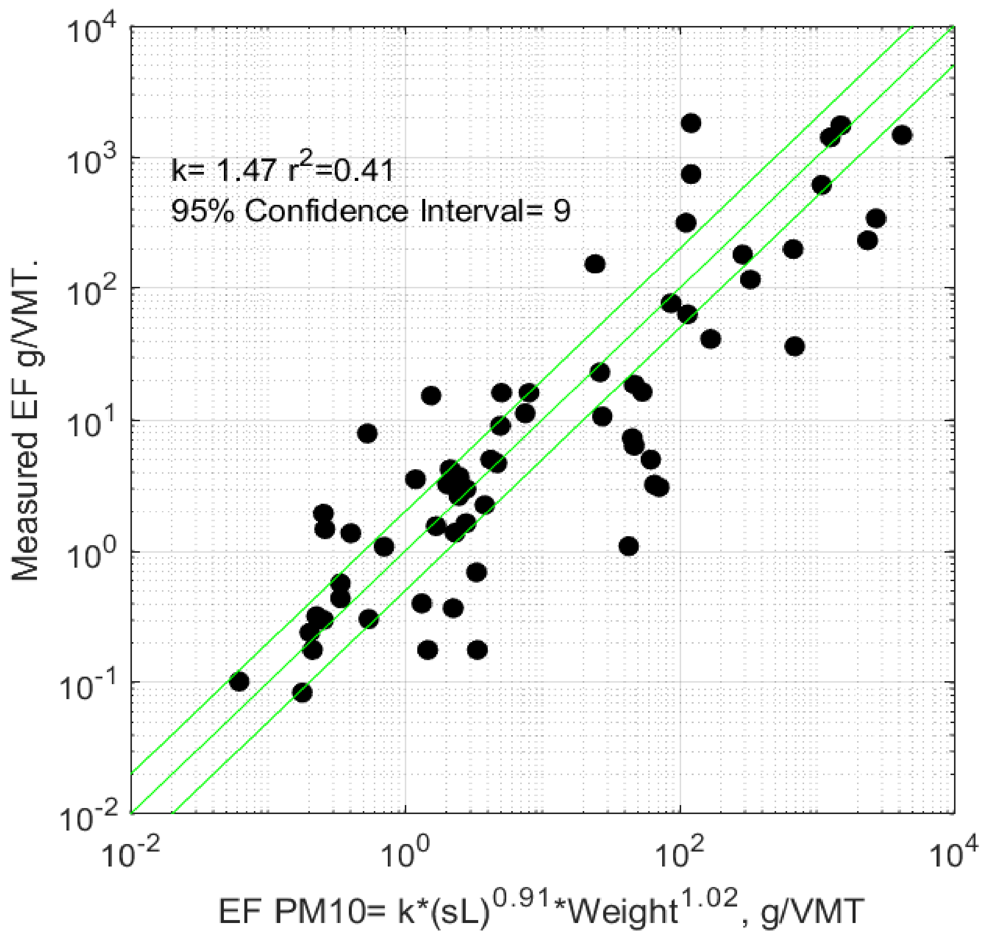
Computing Effective Height

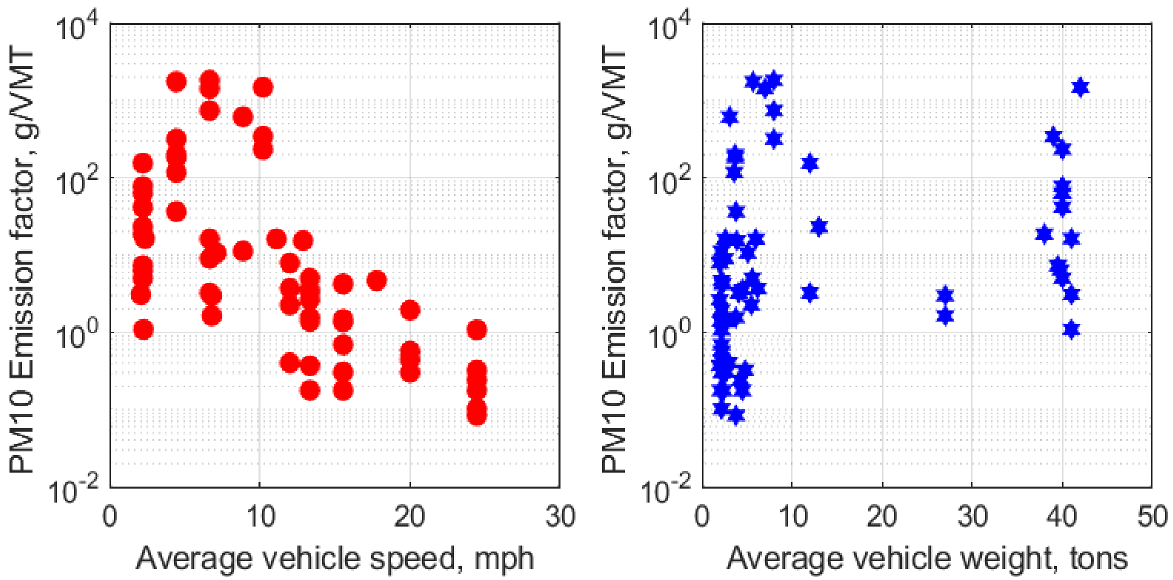
Google earth view of 8th St LA field site.



$$H = \frac{1}{L}\sum_i h_i b_i$$

Resuspended Dust, PM10, AP-42 Model





- ❑ Vehicle speeds less than 25 mph
- ❑ 65% of the average vehicle weights over 3 tons
- ❑ Mean silt loading of over 20 g/VMT

Data used to formulate the AP-42 model are not relevant to estimating emissions of PM from high traffic roads.

Mobile Sampling Platform for Highways

Measurement of silt loading on active roads

Measurement of PM emission factors using mobile monitors

Measurement of micrometeorology using mobile monitor

Dust Collection System

Spring-loaded arm keeps brush on the road

Silt collected using sequential sieving machine

Field Studies

Summer 2023

Summer 2024

PM Emission Factor Models

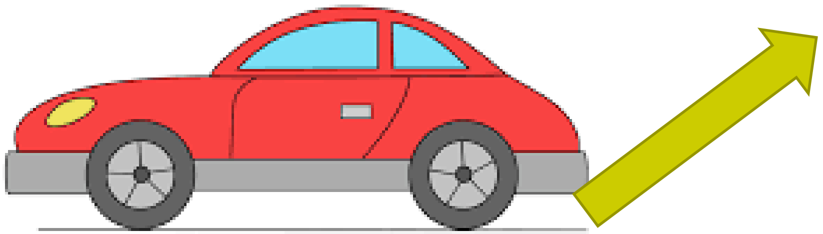
Two models

- ❑ AP-42 Model
- ❑ Mechanistic model

Work Done $=\mu W d$

Kinetic Energy of particles $=EF.d.v^2$

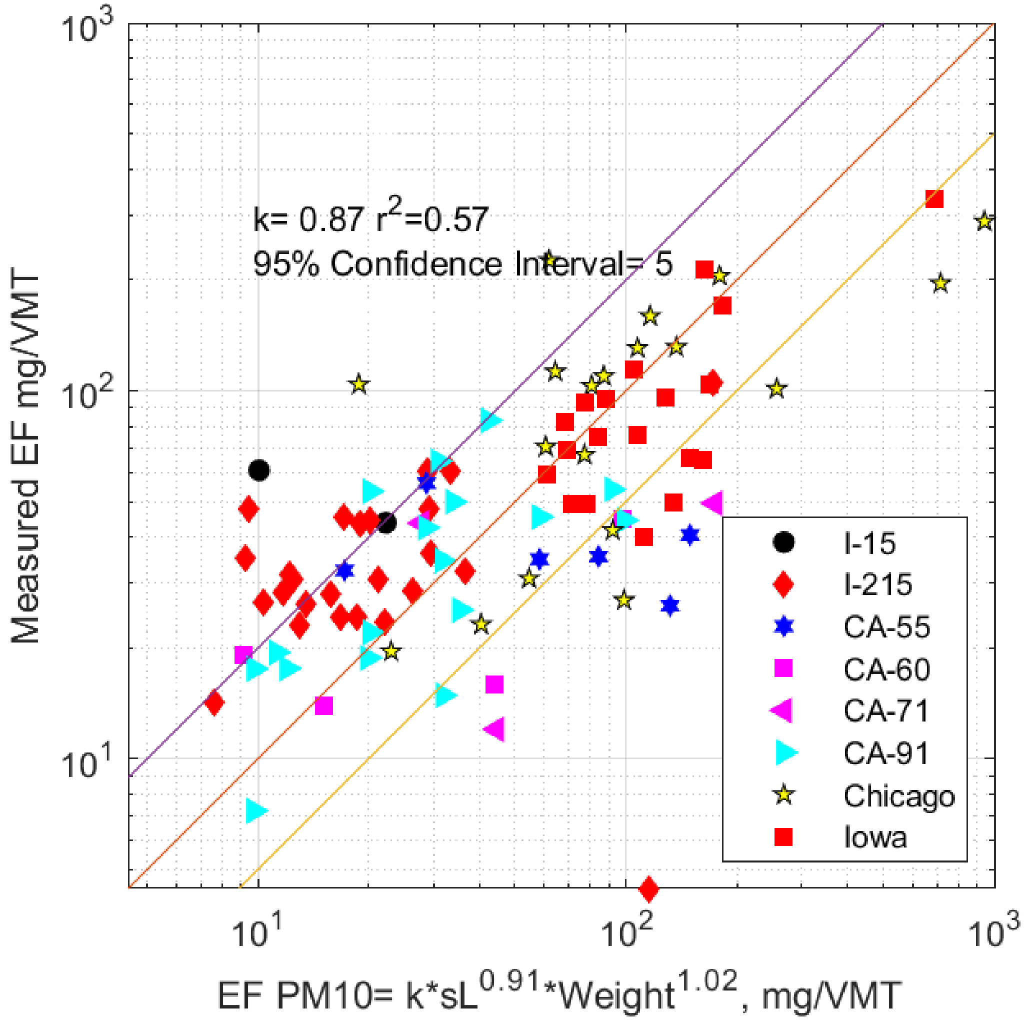
$$EF = \frac{k\mu W}{v^2}$$

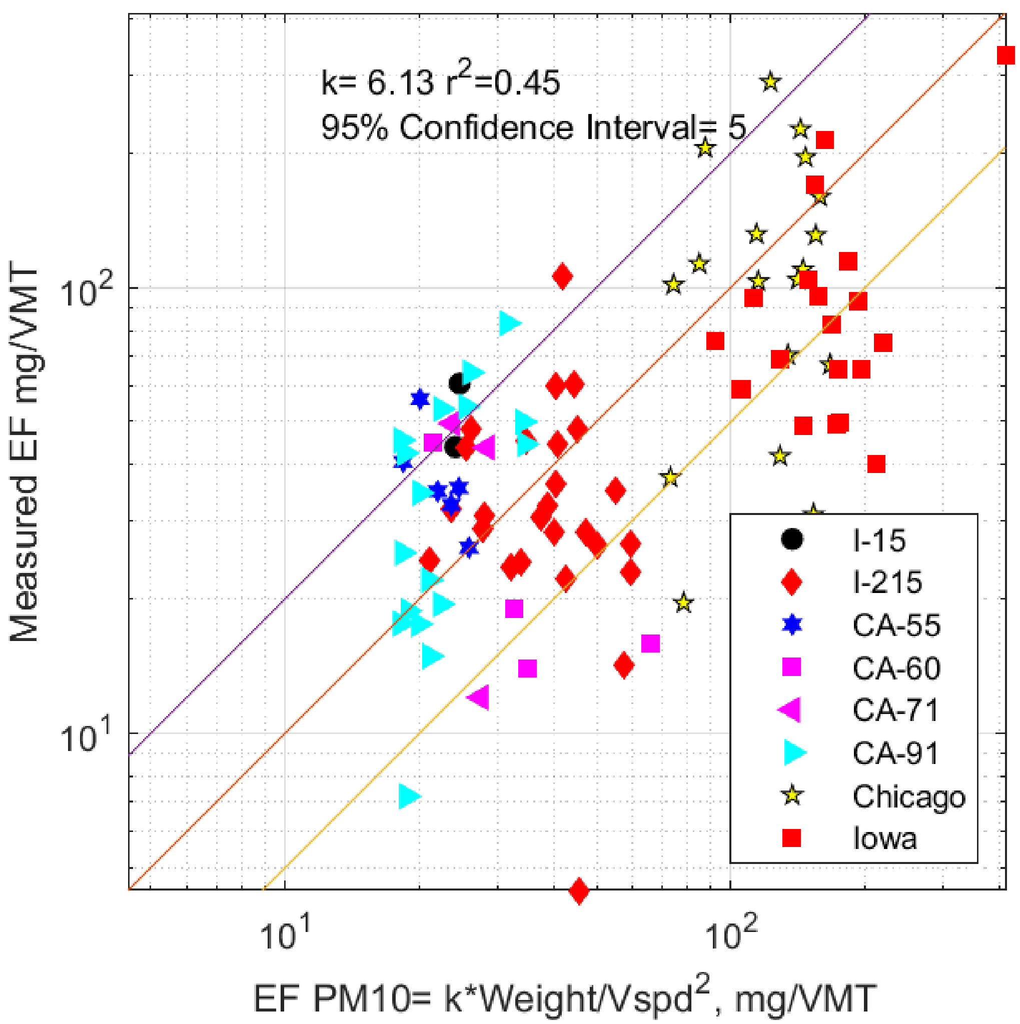


$$d.EF.v^2$$

$$\mu W d$$

Results PM10- Summer 2023, 2024





Research Gaps and Future Directions

- Models for dispersion from different road configurations-elevated, depressed roads-need improvement and evaluation with observations
- Models for building effects require more evaluation.
- Models overestimate concentrations under low wind speeds (Askariyeh et al., 2017). Need methods to account for wind meandering under these conditions.
- Need methods to account for
  - Conversion of NOx to NO_2
  - Impact of porous vegetative barriers
  - Estimating “edge” effect of roadside barriers
  - Estimating micrometeorological model inputs in urban areas

Conclusions

- Solid barrier always leads to reduction of near-road concentrations relative to those without barrier.
- The addition of vegetation enhances the effect of the solid barrier. The additional effect is relatively small, and can sometimes reduce the mitigating effect of the solid barrier at high wind speeds.
- The impact of solid barriers, upwind and downwind, as well as depressed roads can be incorporated into current flat terrain models: EPA's RLINE model: RLINE_MODELDESCRIPTION_5-23-13.PDF, https://www.cmascenter.org/r-line/
- Vegetation effects have been incorporated into model, but needs further development.

Take-Home Messages

- Current models for dispersion of emissions from highways with and without barriers provide adequate estimates of concentrations associated with highway emissions. These models have been incorporated in frameworks to examine the impact of traffic scenarios (Vallamsundar et al., 2016). New version of AERMOD includes a non-regulatory option for RLINE application.
- Data sets from field and wind tunnel studies are available for development and evaluation of highway dispersion models.
- Street canyons between tall buildings magnify concentrations that would occur in the absence of buildings. The magnification depends on the ratio of the effective height to width of the street. Available dispersion models do not account or building effects.

List of Abbreviations

AERMOD- AMS/EPA Regulatory Model

AMS- American Meteorological Society

CFD-Computational Fluid Dynamics

OSPM- Operational Street Pollution Model

RLINE- Research Line Source Dispersion Model

USEPA- United States Environmental Protection Agency

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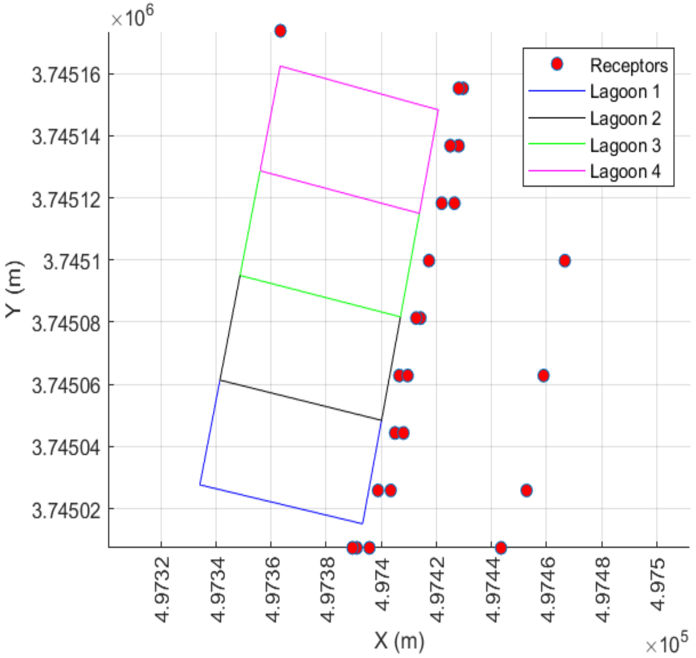
Students: Nico Schulte, Seyedmorteza Amini, Faraz Ahangar, Wenjun Qian, Jing Yuan, Yifan Ding, Amir Saeidi, Tianyi Wang, Ranga Thiruvenkatachari

Estimating Emissions from Lagoons in Southern California Dairy

Valerie Carranza, Faraz Ahangar, Ranga Rajan Thiruvenkatachari, Francesca Hopkins, Akula Venkatram



Approach

1. Estimates from dispersion model are fitted to measurements to estimate emissions
2. Inputs are roughness length, surface friction velocity, Monin-Obukhov length, wind speed at 3 m, standard deviations of turbulent velocities. Obtained by processing sonic anemometer measurements
3. Dispersion from area source computed by modeling the area as a set of line sources perpendicular to the wind direction. Number of line sources determined by convergence criterion set for integral over line sources~ 500 lines

Estimating Emissions

Minimize the sum of the squares of residuals between model estimates and measurements

$$S = \sum_i \left(C^i_{meas} - C^i_{pred} \right)^2 = \sum_i \left(C^i_{meas} - \left(C_b + \sum_j E_j D_{ji} \right) \right)^2$$

i = Measurement index

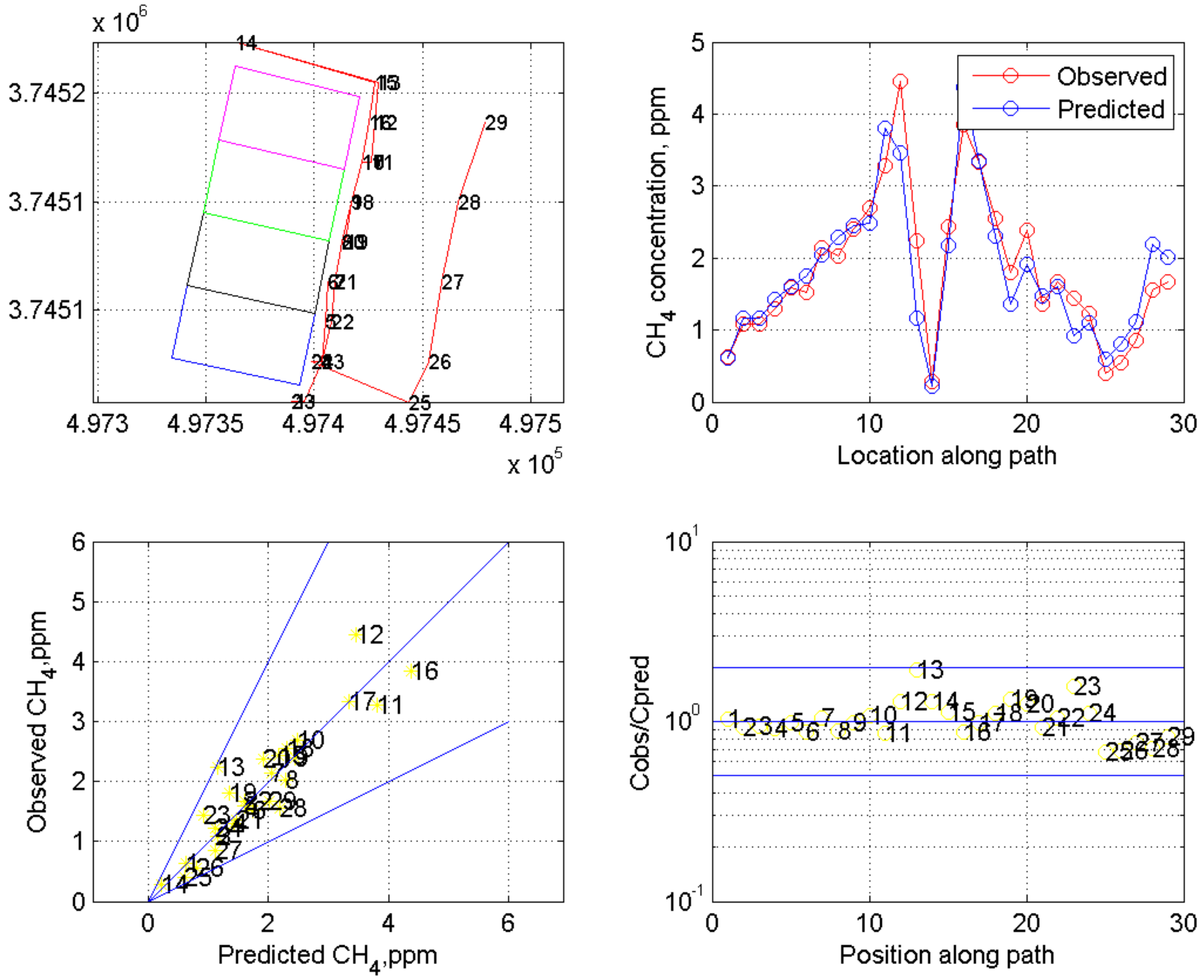
j = Source index, 1 - 4

E_j = Emission from each source

D_{ji} = Modeled concentration from source j to measurement i assuming unit emission rate

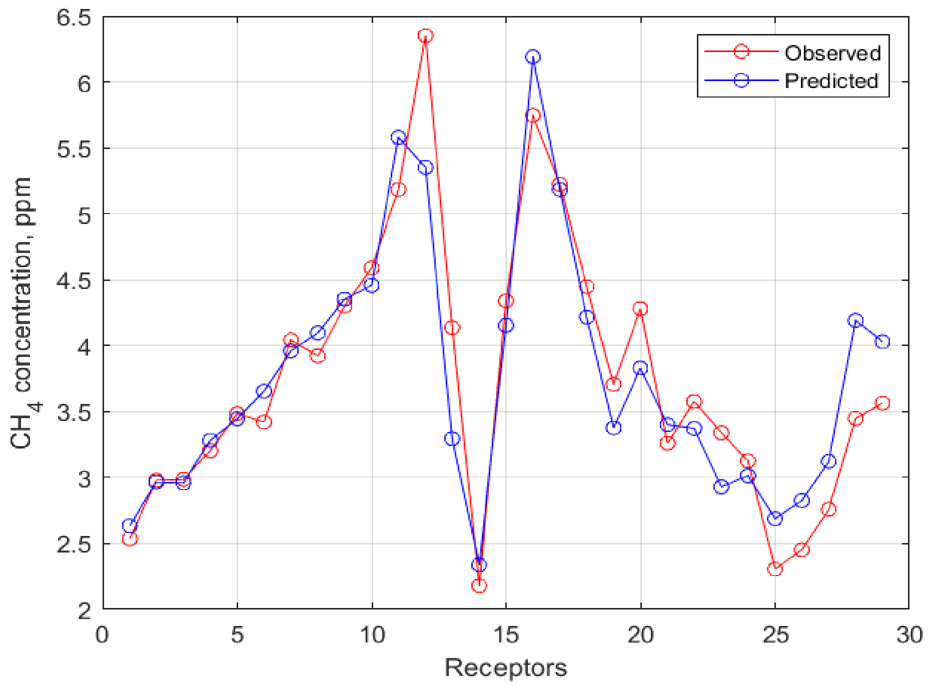
C_b = Background Concentration

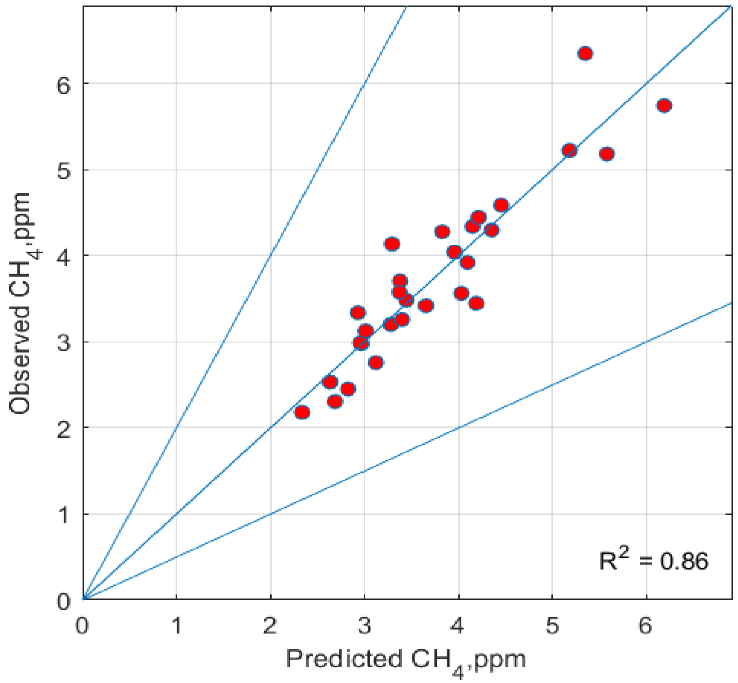
Results



x 10^6
3.7452
3.7451
3.7451
4.973
4.9735
4.974
4.9745
4.975
x 10^5
Observed
Predicted
CH4 concentration, ppm
Location along path
Observed CH4,ppm
Predicted CH4,ppm
Cobs/Cpred
Position along path

Fits to CH_4 Measurements





Inferred CH_4 Emissions

Source	Best Fit	Lower Limit	Upper Limit	Range/Best Fit
Background CH_4, ppm	2.3	2.0	2.8	0.35
Source 1, kg/day, (kg/m^2/yr)	42 (8)	5.9	75	1.65
Source 2, kg/day, (kg/m^2/yr)	55 (10)	33	78	0.82
Source 3, kg/day, (kg/m^2/yr)	92 (17)	62	121	0.64
Source 4, kg/day, (kg/m^2/yr)	204 (37)	165	243	0.38

The 95% confidence intervals for the emission rates are computed through a version of bootstrapping: the residuals ϵ_j are added randomly to the model estimates to create 1000 sets pseudo observations, which are then fitted to the measurements to create a distribution of emission rates.