In-Vehicle Air Exchange Rates, Inside-to-Outside Ratios, and Exposures to Traffic-Related- Particulate Air Pollutants

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Talk Overview

Part I: In-Vehicle Testing:

Ia. Importance of air exchange rate (AER)

Ib. Tests of ultrafine PM inside-to-outside ratios (I/O)
Methods, results, models

Ic. Fleet simulations and in-vehicle exposures

On-Road Tests:
Part II: On-road concentration prediction models

Part III: Emission factors from on-road measurements

Goal of Part I:

To fully characterize what determines in-vehicle particle concentrations and develop predictive models

Motivation

In-vehicle exposures to traffic-related pollution contribute large fraction of overall exposure

Determining health effects of ultrafine PM (UFP) will need to take in-vehicle exposures into account

Epidemiologically-sized studies need epi-friendly models (inputs based on easy –to-obtain information)

Specific Aims

Test a large, representative sample of vehicles (never previously done) for AER (n=59), I/O ratios

Establish relationship between AER and I/O ratios for UFP, develop models

Extend to other traffic-related particulate pollutants (black carbon, particle-bound PAH, PM2.5, etc.)

Assumption:

in-vehicle concs = on-road concs x I/O

In-Vehicle AER Background

- **The rate of air turnover inside a vehicle. often measured in air changes per hour**
  - Rates near zero if vehicle stationary, windows closed.
  - Goes up dramatically outside air ventilation setting used, or if windows open
  - If windows closed and ventilation on recirculate, goes up with speed and vehicle age or mileage
    - Eg., 15 hr^{-1} +/- 10 hr^{-1} at 55 mph
    - Closed window hHomes usually in range of 1 hr^{-1}
- **I/O ratios for traffic-related particulates < 1.0, due to losses, but can range from nearly 0 to nearly 1.0**
  - I/O = f (air exchange rate [AER])
  - Ideal would be a model of the form:

    I/O = f (vent setting, vehicle characteristics, speed)

Better Determination of AER

Found CO_2 to be an excellent tracer gas, as produced by vehicle occupants

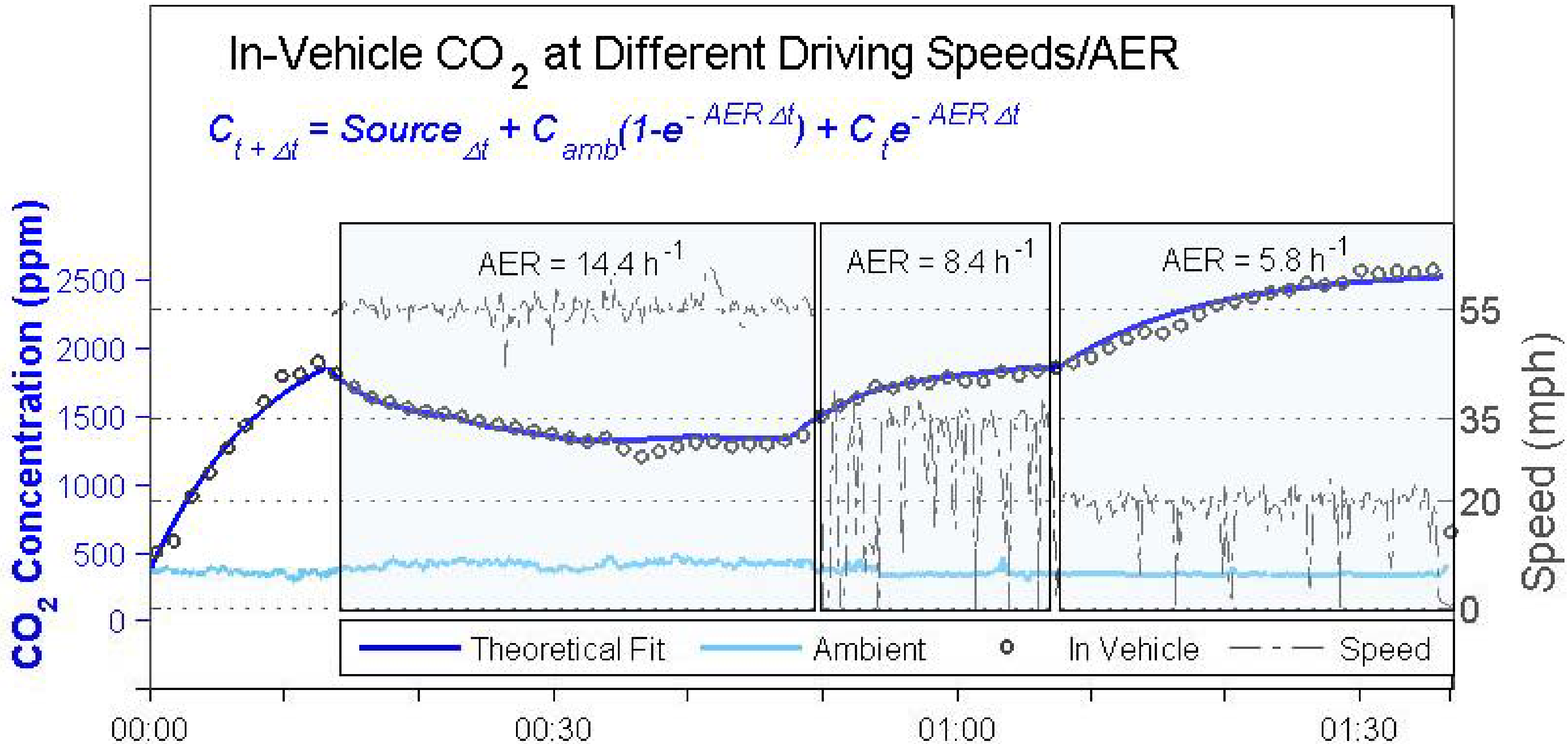
Easy to measure; easy to produce (respiration), steady while resting

Measurements:

- Build-up rate while parked with windows closed (AER ~ 0) gives source strength
- Steady-state concentration at steady speed reflects AER

Tested representative sample (age, manufacturer) of 59 cars at 3 - 4 speeds each, multiple ventilation and fan settings.

CO_2 Concentrations during AER Measurement



Build-up rate (stationary) steady state @ 55 mph 40mph 20 mph

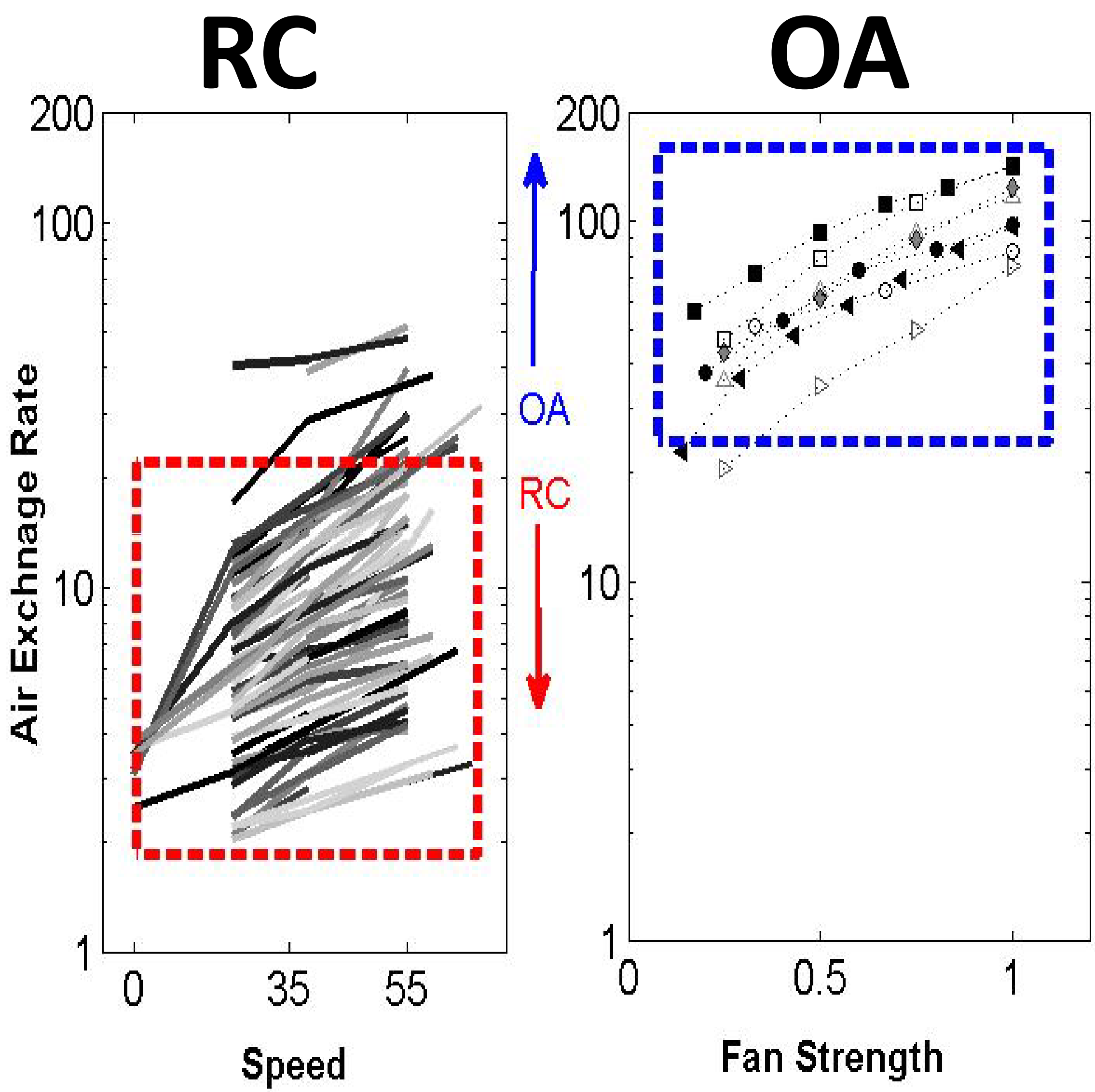
Results: 59 Vehicles

Recirculation (RC)

- Low AERs
- Strong function of speed
- Large car-to-car variability (increases with age, mileage)

Outside air (OA)

- Order of magnitude higher AER
- Fan speed important



AER Models

Separate models for OA and RC ventilation settings; log transformed AER

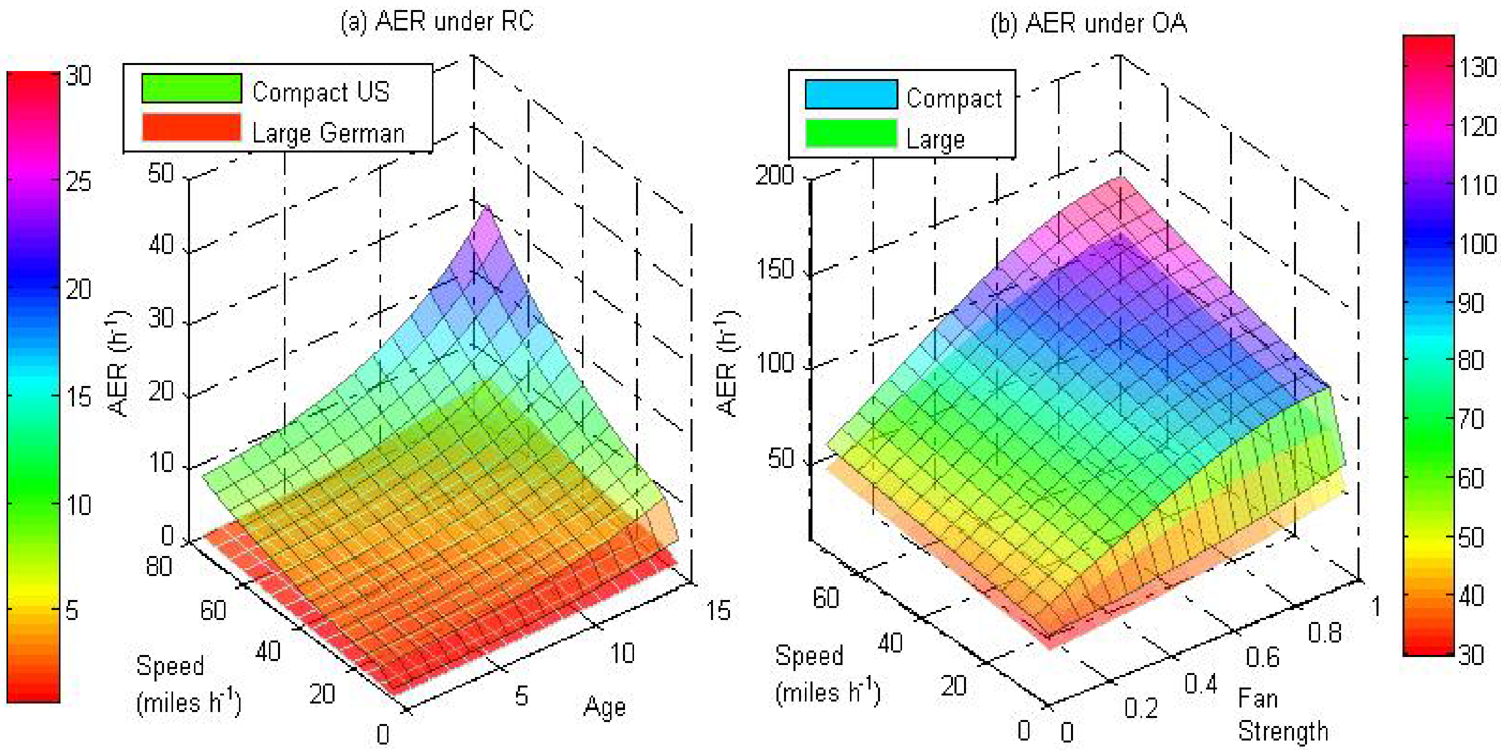
Generalized estimation models (GEE) to take into account the correlation of multiple measures on each vehicle
(not independent samples).

Variables tested:

Speed; veh age, mileage, manufacturer, interior volume, frontal area; fan setting;

- Squared terms;
- Interactions (e.g., speed x age)

GEE Model Results for AER



RC: speed, age

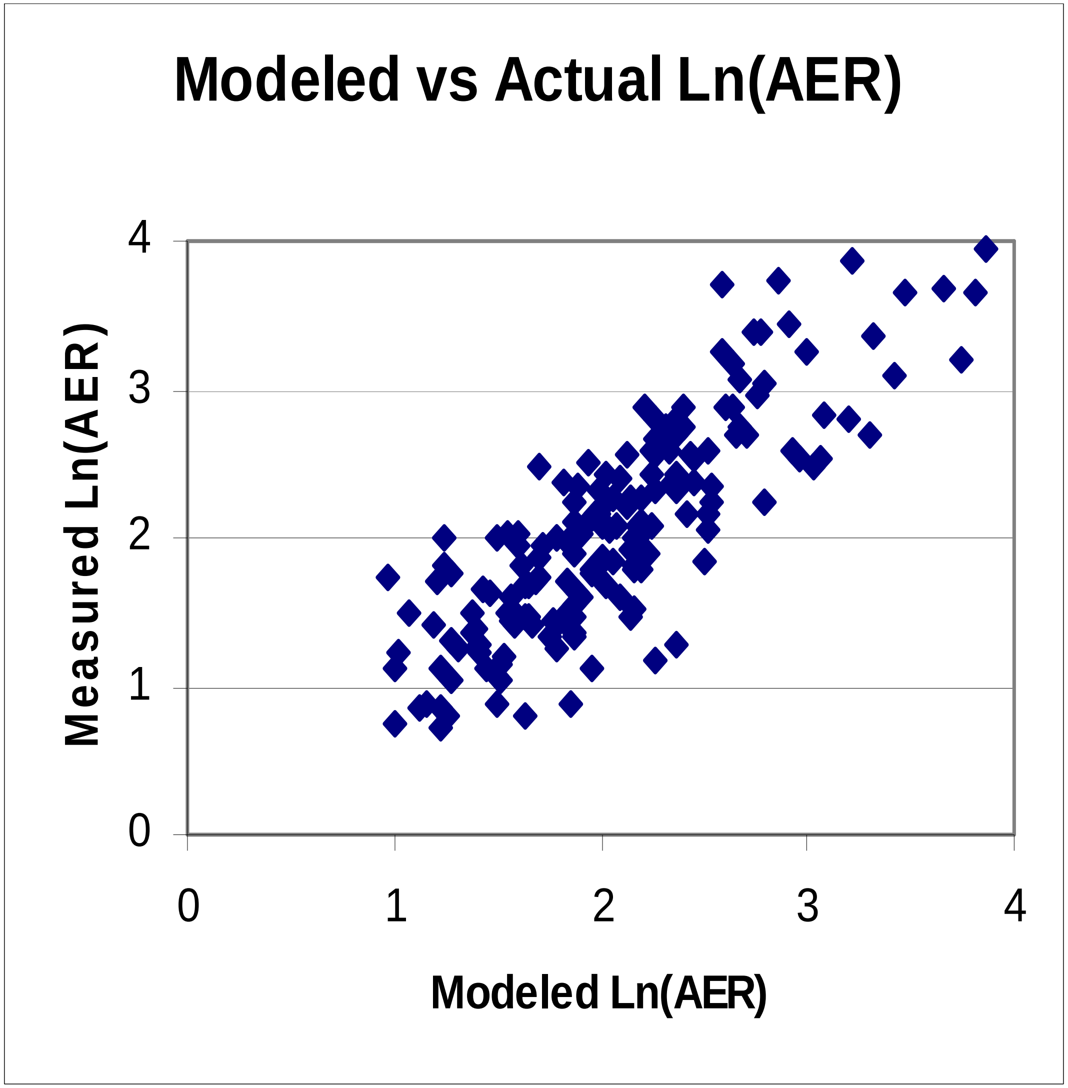
OC: fan strength*, speed

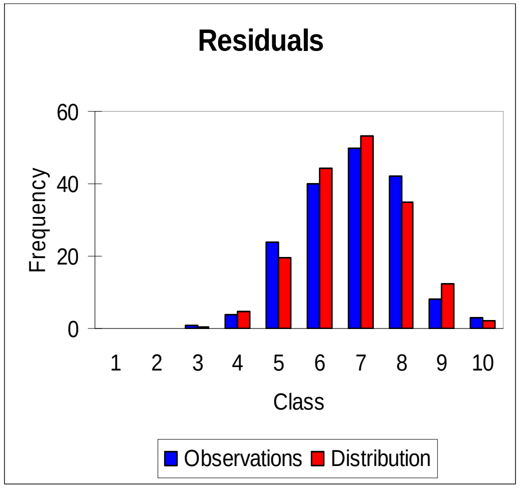
(*"notch number" fraction of max)

Top and bottom surfaces are compact (top) and large cars

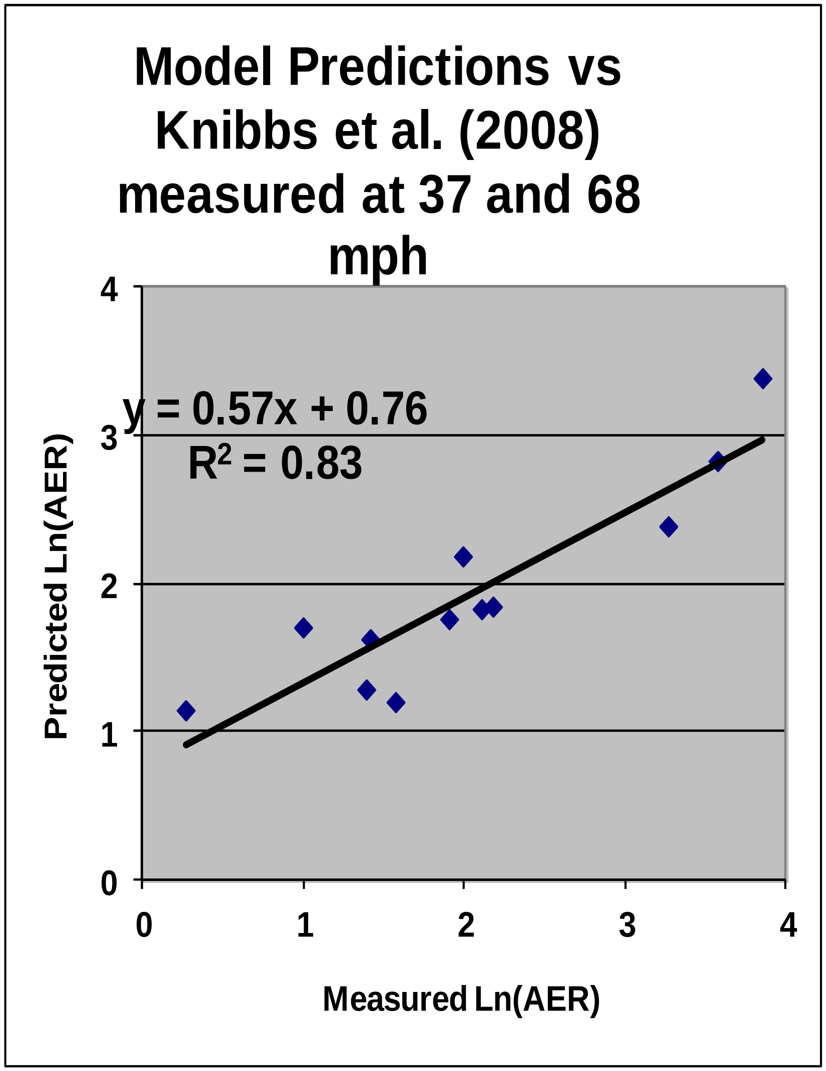
AER Model Performance R^2=0.7

AERs range from ~2 to >50 (Ln(2)=0.7 to Ln(54)=4.0)





Comparison to Other Studies



Decent agreement considering different method (SF6), different country (Australia), and higher speeds

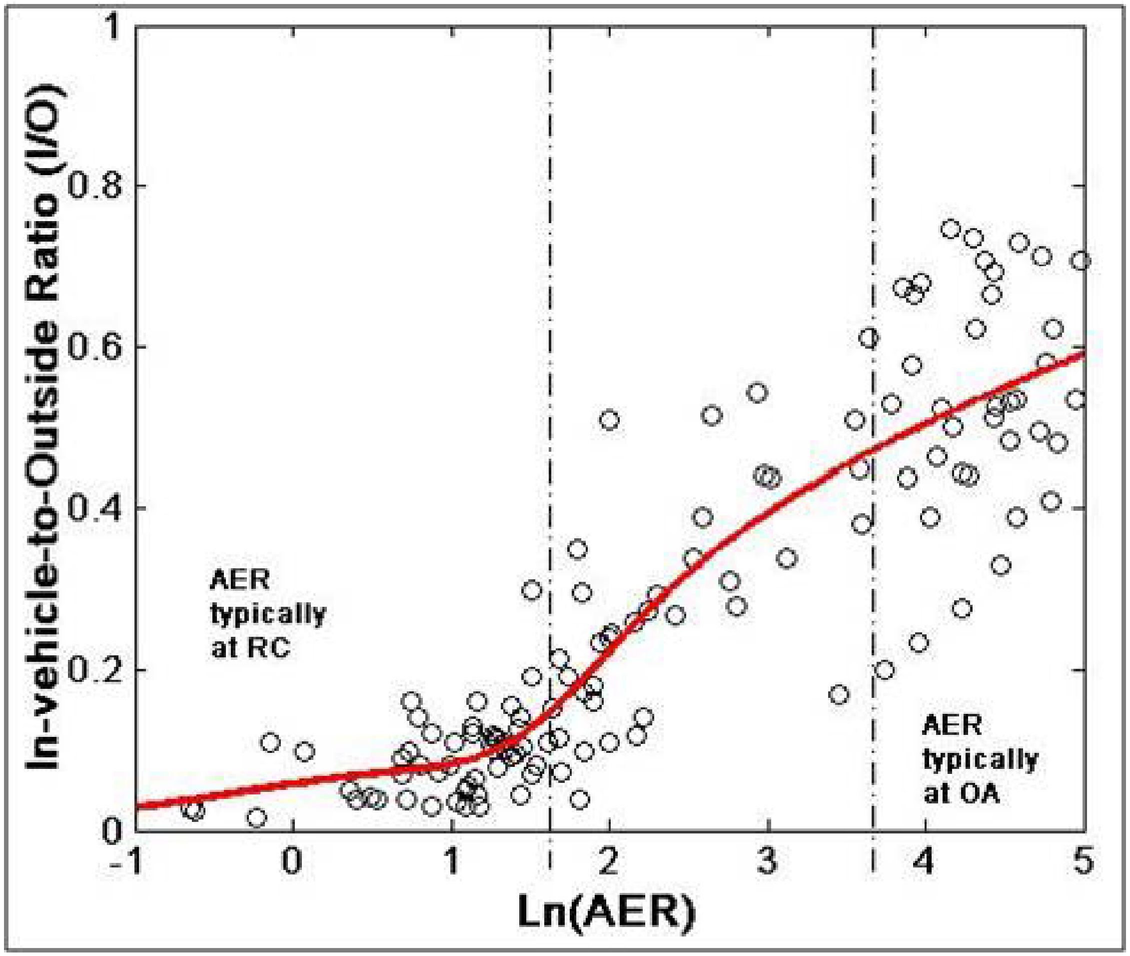
Ib. Inside-to-Outside UFP Measurement Methods

UFP measured using condensation particle counter (CPC) TSI 3007. Evaluated effect of particle size from SMPS.

260 I/O measurements (diff speed, vent/fan settings).

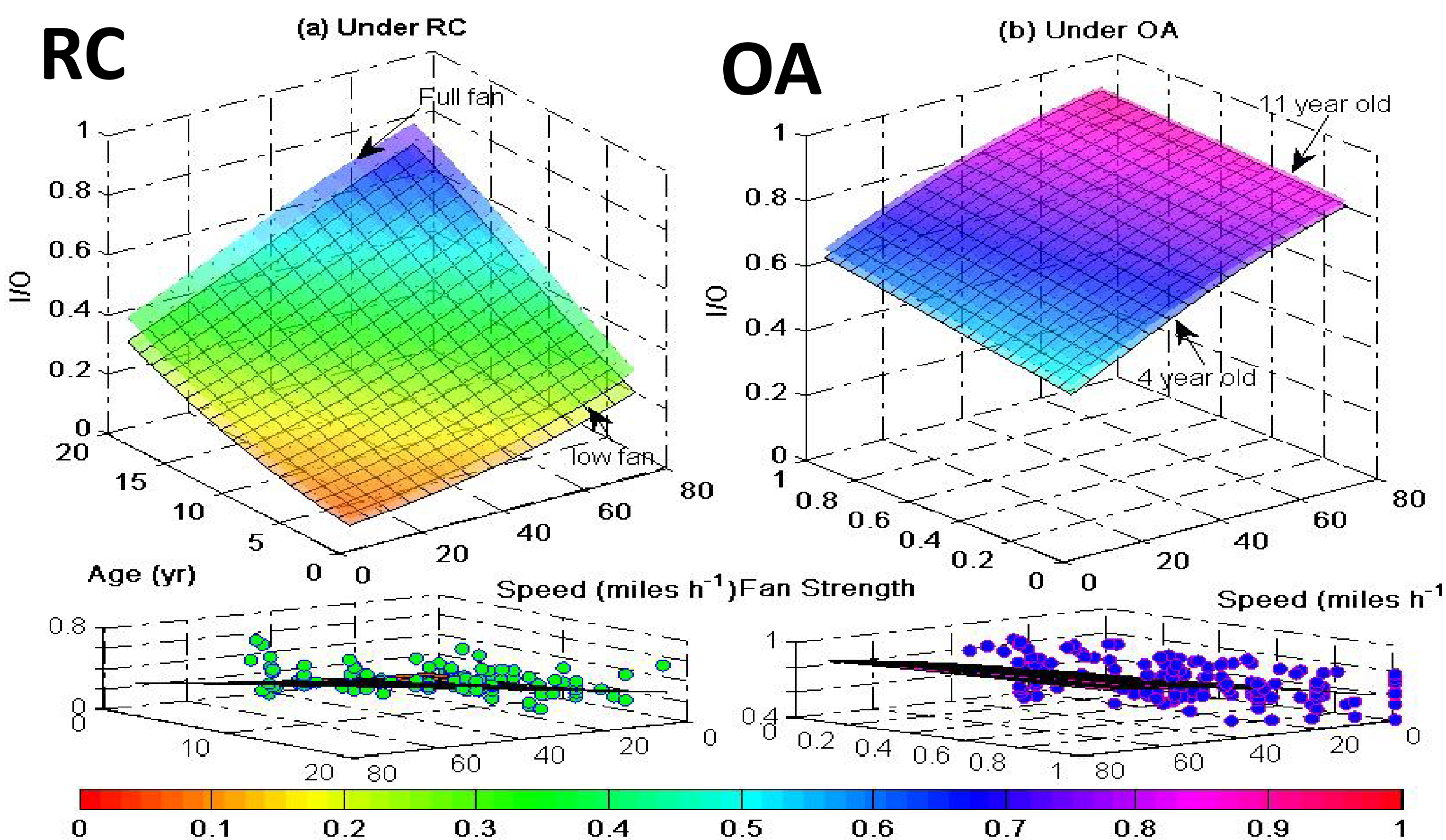
From Knibbs et al. (ES&T, 2010), I/O measurements (Sydney) added to expand the database.

UFP I/O Results vs Predicted AER



- About 66% variability in I/O can be explained by AER model predictions

Predictive I/O Models $R^2 > 0.80$

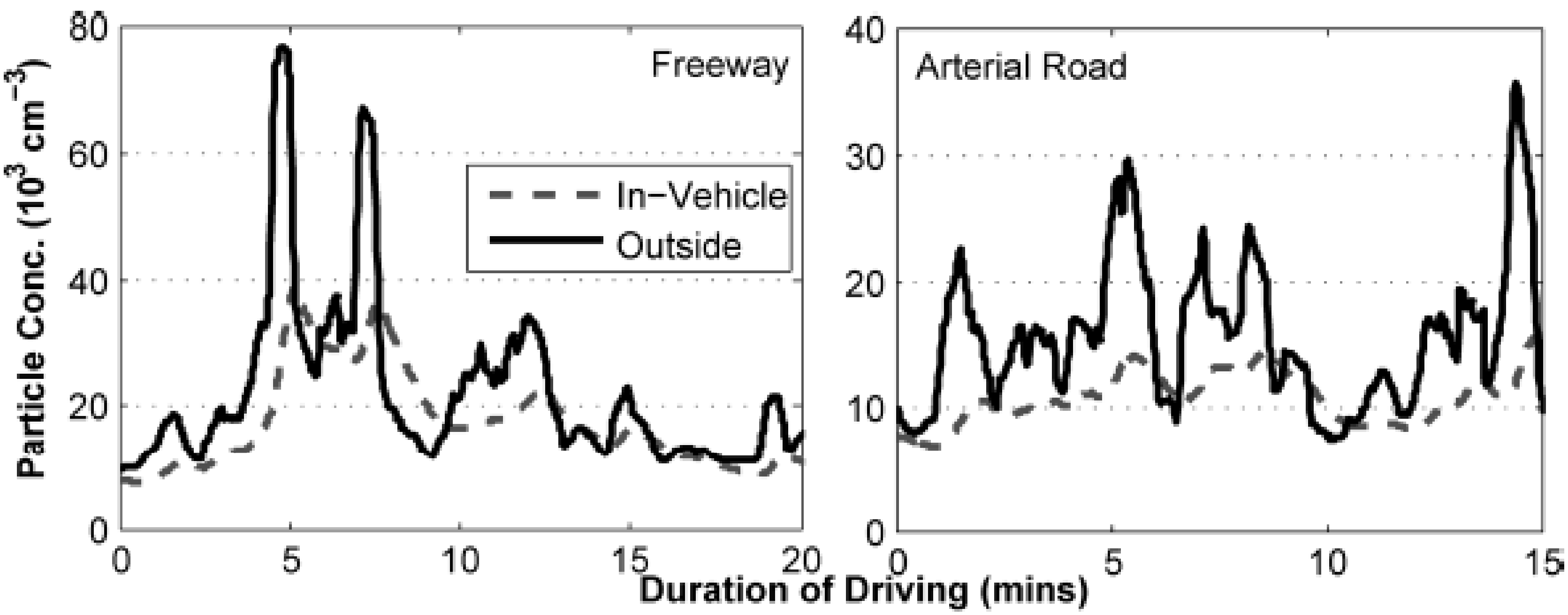


I/O mostly driven by, RC or OA

For RC: speed and age, then fan strength

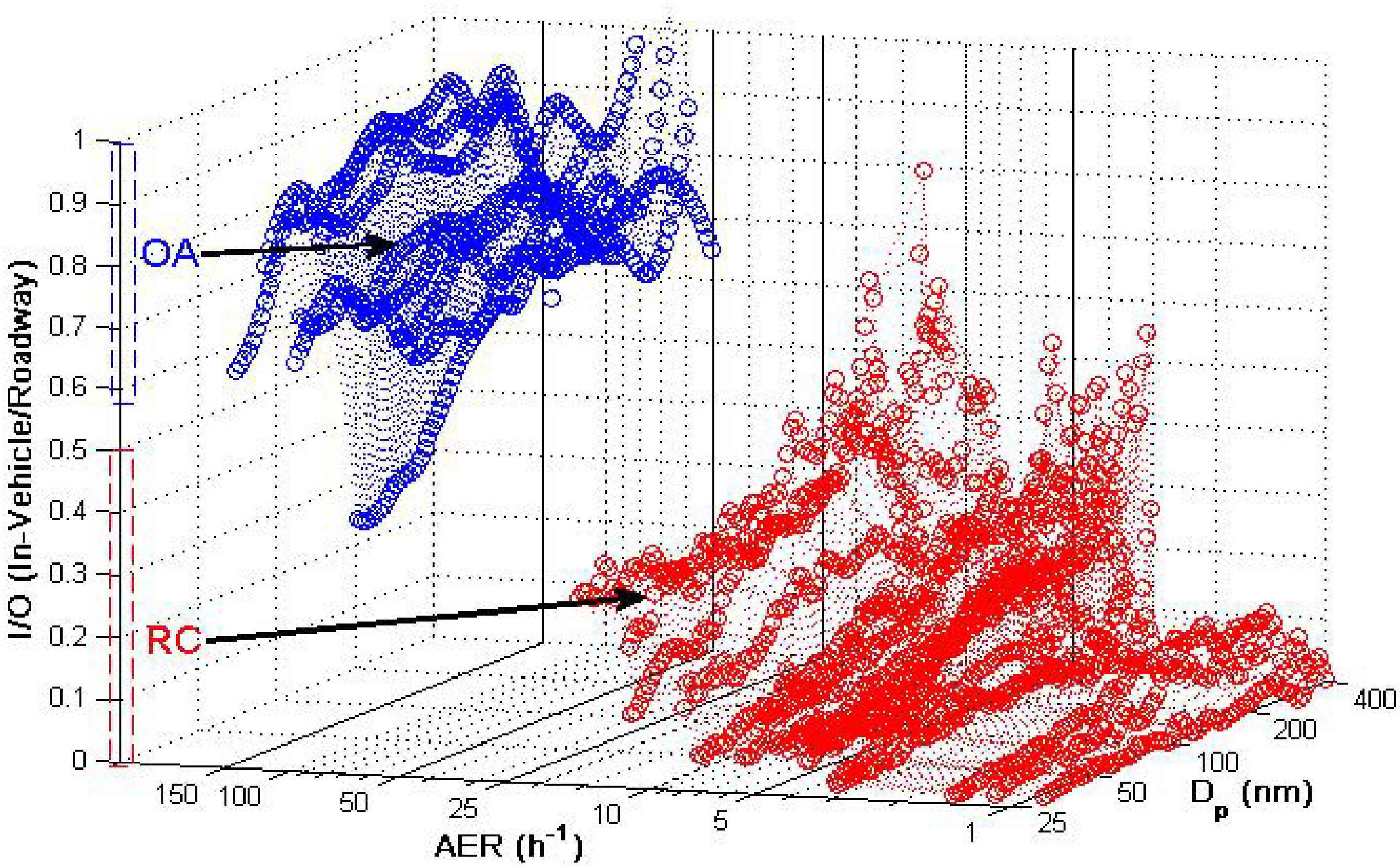
For OA: fan strength, then speed and age

Excellent Agreement for Non-Steady State Condition Tests



	Freeway	Arterial Road
Average Speed (mi h^{-1})	55	27
Average Outside Conc. (cm^{-3})	21000	16000
Average In−vehicle Conc. (cm^{-3})	16000	11000
Measured AF	**0.24±0.12**	**0.30±0.11**
Model Predicted AF	**0.22**	**0.32**

What about Particle Size?



Some increase in RC I/O as size > 0.2 um, but concs little affected.
AER far more important than size.

In-Cabin Filters

Fortunately, did not see significant difference between new, loaded or even no filter

Low efficiencies; most losses apparently due to surfaces

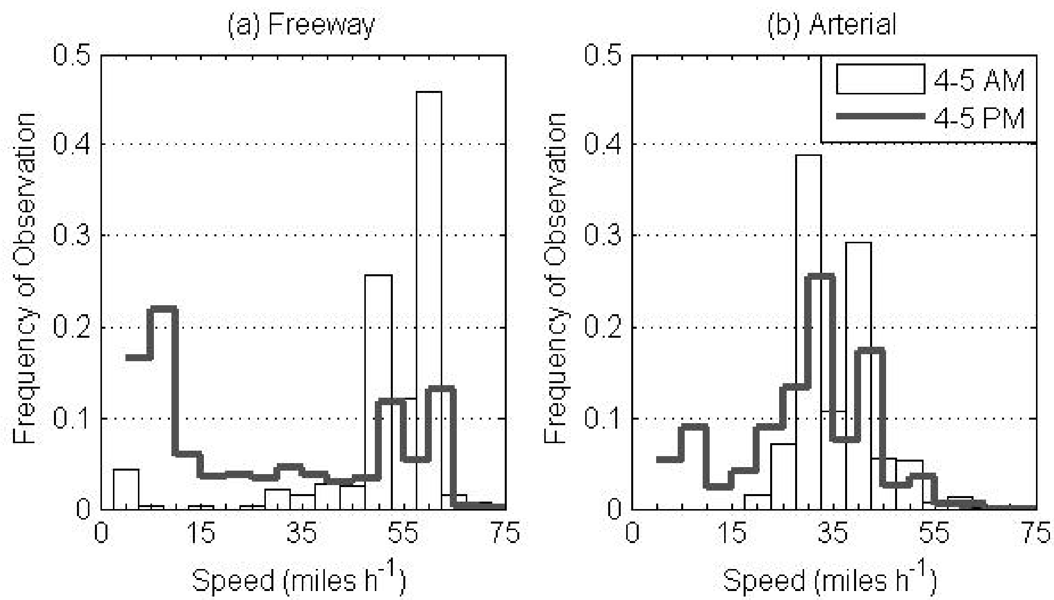
Adequate Questionnaire Info for Epi Studies

- Year, mileage, manufacturer of car
- Ventilation selection
  - Open or closed windows?
    - If closed, RC or OA?
      - If OA, what is your fan setting out of how many choices, low to high?
- Time and destination of morning commute & time of return home? (for on-road predictive models, Part II)

Fleet-wide Simulations:

What matters most when you put it all together?

- On-road concentrations measured on LA freeways and arterial roads
- Speed from EPA MOVES 2010 data for rush and non-rush times
- Vehicle characteristics (age, mileage, manuf) for U.S. fleet



❑Available as general distribution

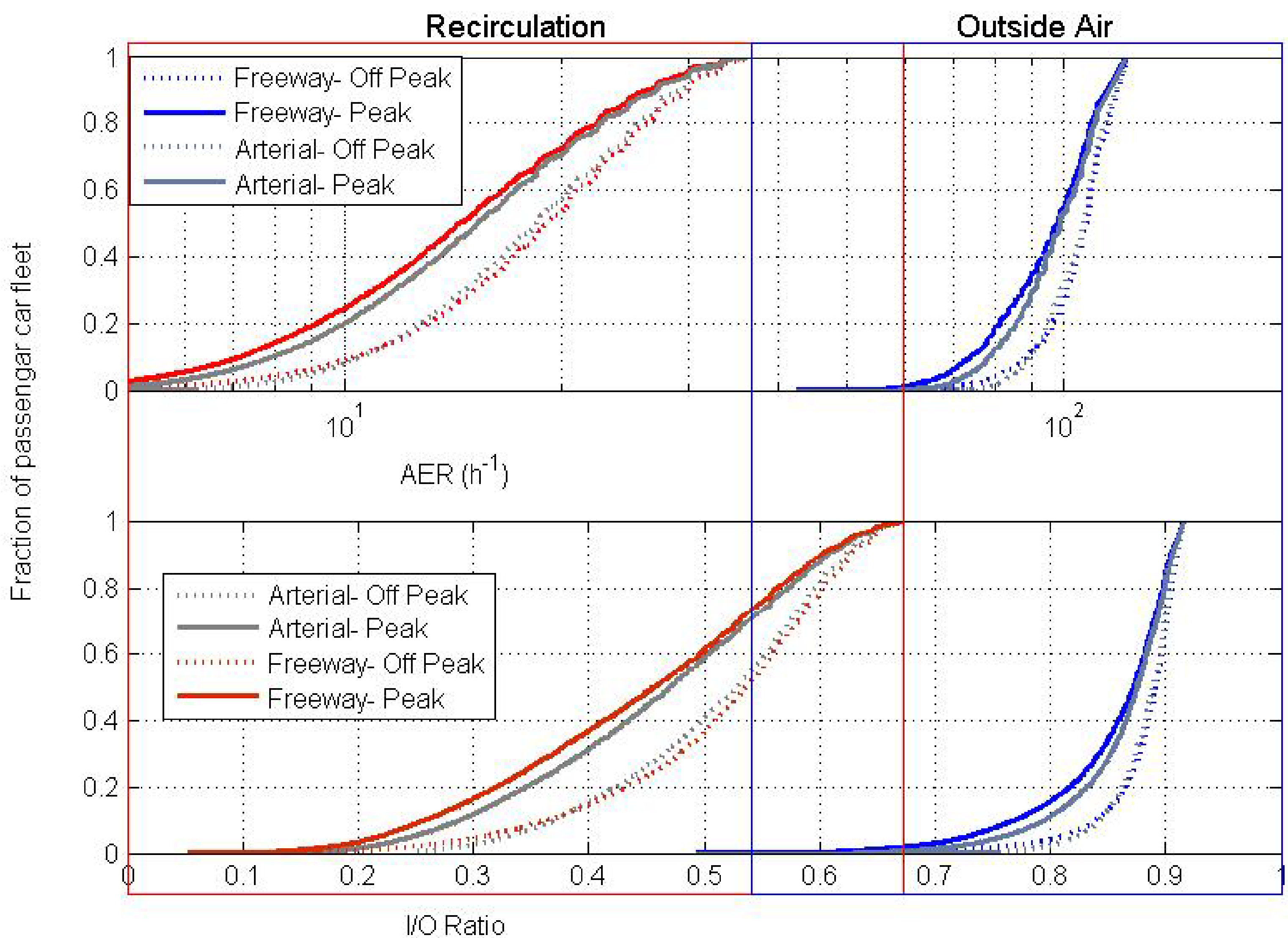
•EPA MOVES, MOBILE6

❑Route specific distribution

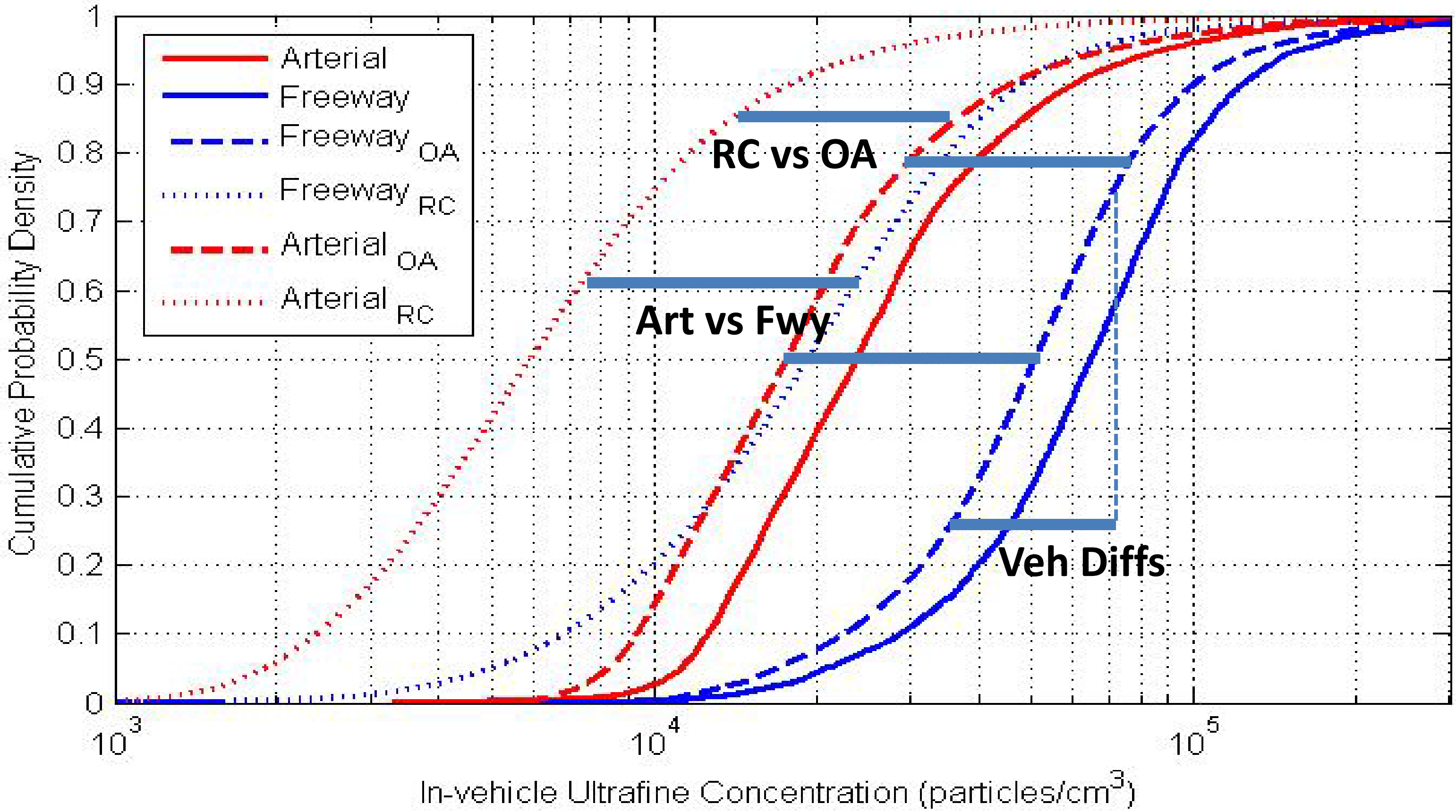
•CALTRANS Performance Measuring System

AER and I/O for U.S. Fleet Dist under LA Driving

Vent setting (RC or OA) critical, then road type (speed)



In-vehicle UFP Exposure Distribution



Summary of Differences

Similar 2 to 3x range for in-veh exposures for:

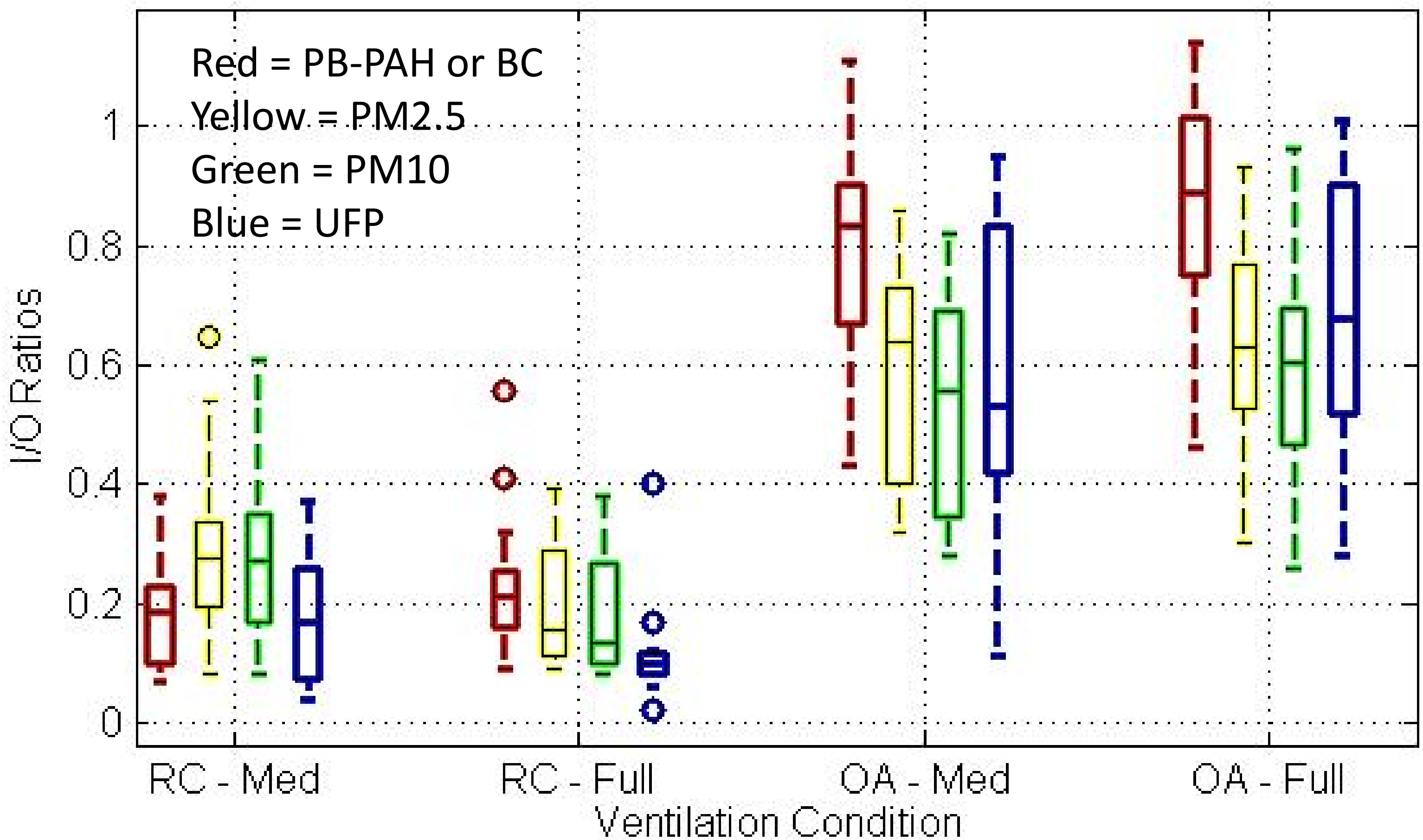
- Ventilation setting choice (RC or OA)
- Freeways versus arterial roads (conc, speed)
- 25^{th} vs 75^{th} % rank vehicle (age and size, manuf)
  - **25^{th} age = 4 years 75^{th} = 11 years**

~10x exposure difference (25^{th} to 75^{th})

- RC on arterial roads: 4,000 to 10,000 #/cm^3
- OA on freeways: 35,000 to 90,000 #/cm^3

75^{th} % freeway OA commuter probably getting more than half of daily exposure from commute

Other Pollutant I/O Ratios



PART II:
Modeling the Concentrations of On-Road Air Pollutants in Southern California

Part II slides courtesy of Jun Wu (modified)

STUDY AIMS

- **Part II aimed to develop predictive models to estimate on-road concentrations of traffic-related air pollutants using temporal, traffic and meteorological variables.**

- **These predictions, multiplied by I/O ratios, give exposure**

Methods

- **The roadways covered the metropolitan Los Angeles area including both Los Angeles and Orange counties.**
  - Over 210 miles of roads (approximately 75% on freeways and 25% on surface streets) during 20 days ranging from March 25 to June 16, 2011
- **On-road concentrations were measured at 10 second intervals, average to 60 seconds:**
  - PB-PAH, particle number, nitrogen oxides (NOx), and PM2.5

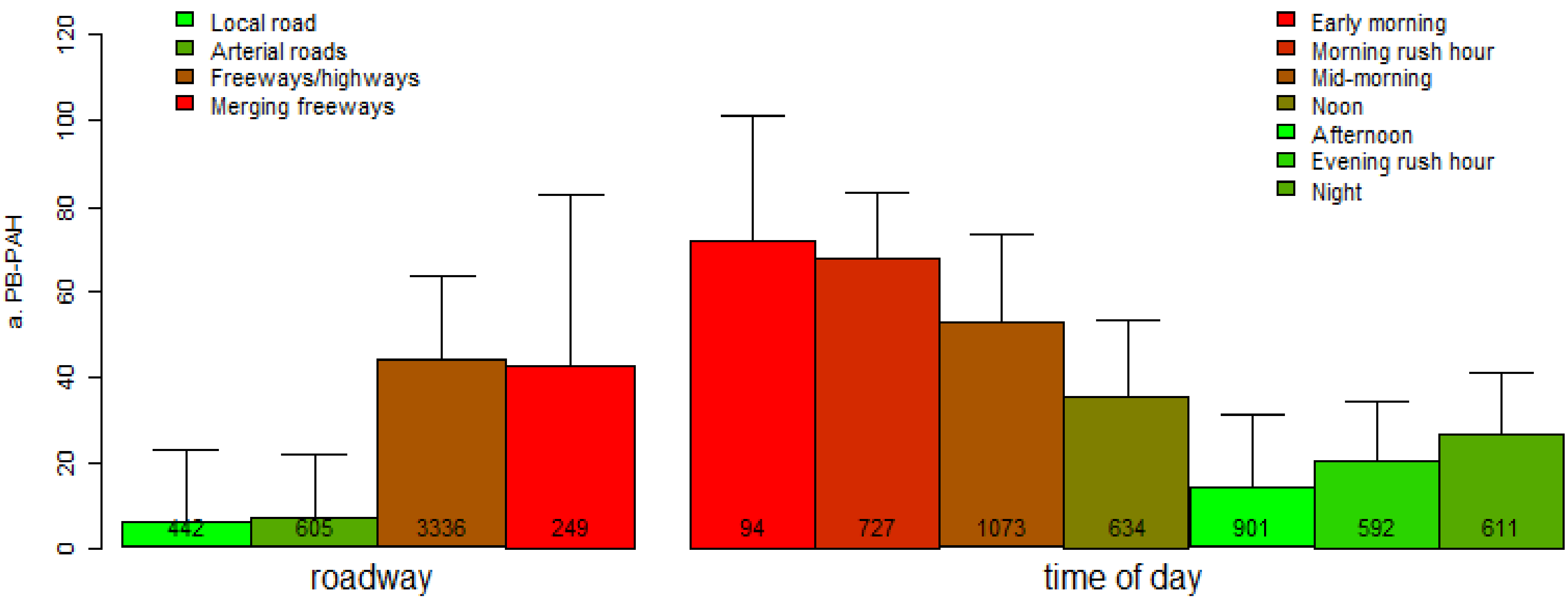
Study region and routes of on-road pollutant measurements

Method – cont.

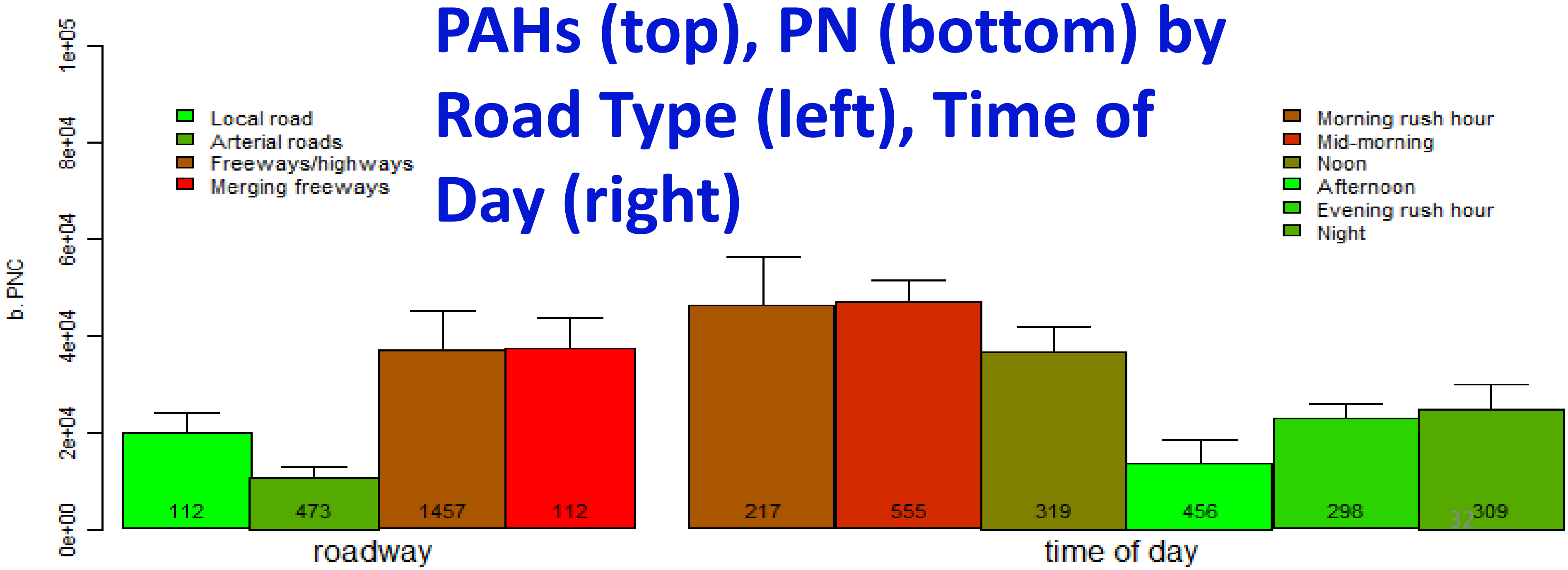
- **Three types of models were developed**
  - Linear regression model
  - Non-linear generalized additive model s, with and without accounting for autocorrelation
    - (can incorporate both continuous and categorical variables, as well as linear and non-linear relationships)
- **Covariates**
  - time of day
  - roadway type
  - vehicle speed
  - traffic counts
  - meteorological parameters

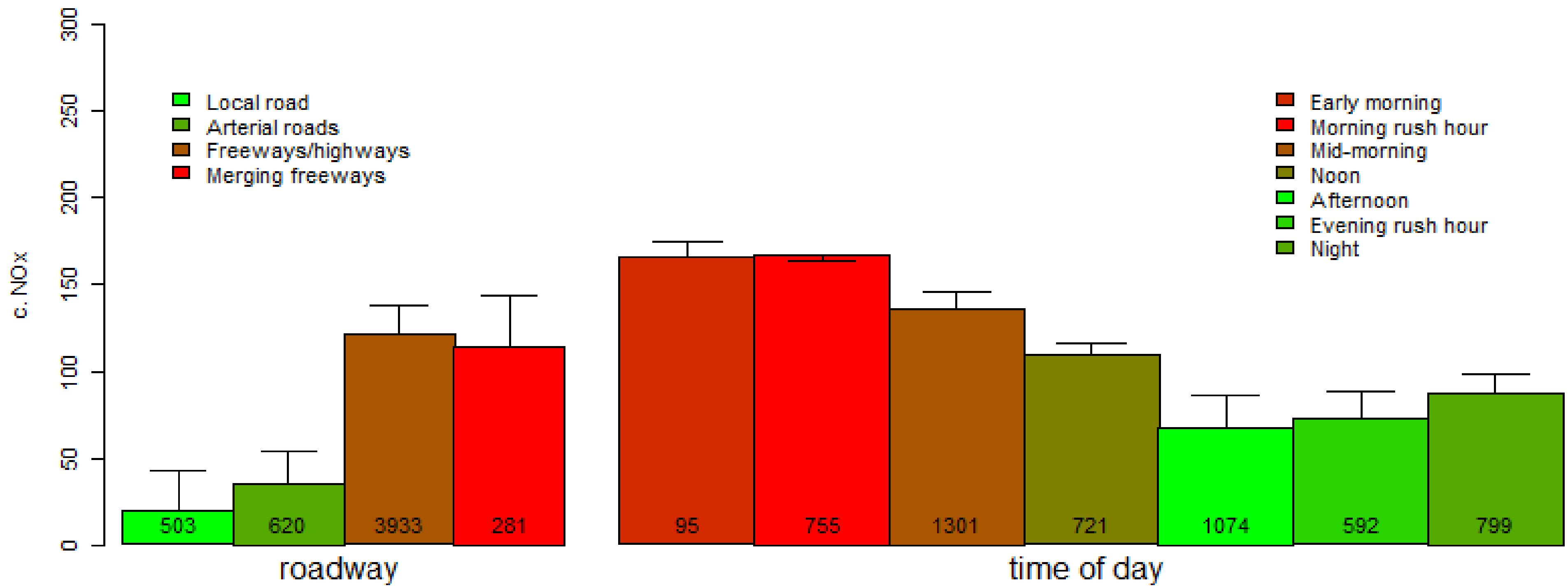
Summary Statistics for the One-Minute Average On-Road Air Pollutants

Pollutant	Samples	Interquartile range (IQR)	Mean	Median
PB-PAH (ng/m^3)	4632	62.6	55.5	31.9
PNC (particles /cm^3)	2154	34500	36830	28570
NO_X (ppb)	5337	124	119	99.1
$PM_{2.5}$ (g/m^3)	3992	10.3	25.0	19.8

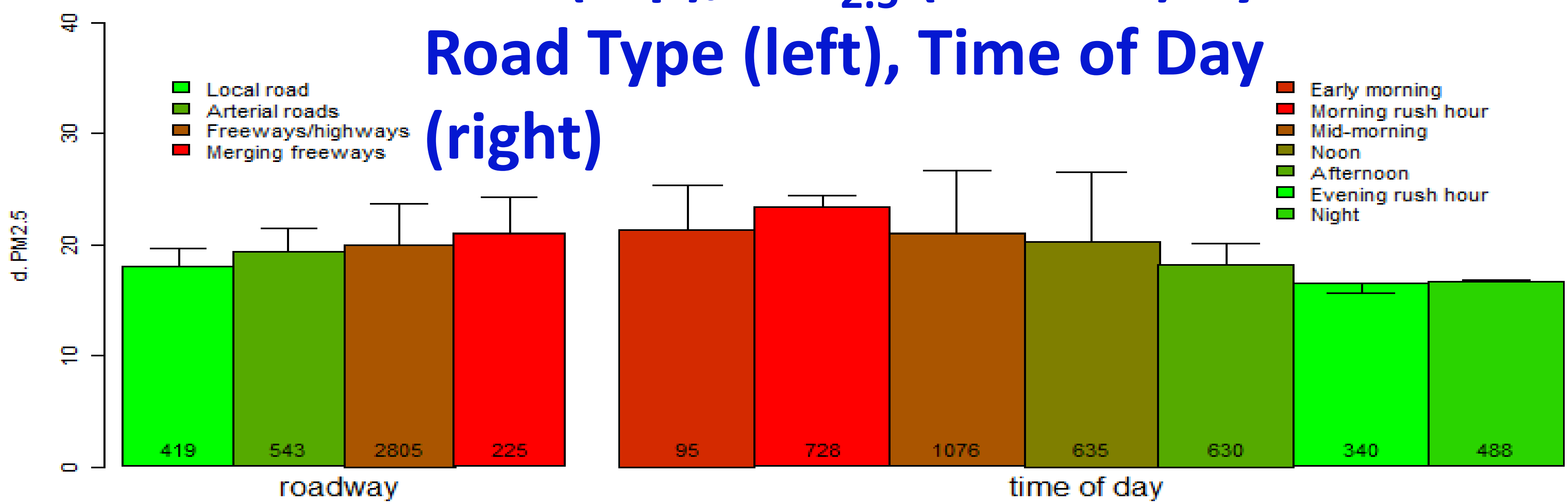


PAHs (top), PN (bottom) by Road Type (left), Time of Day (right)





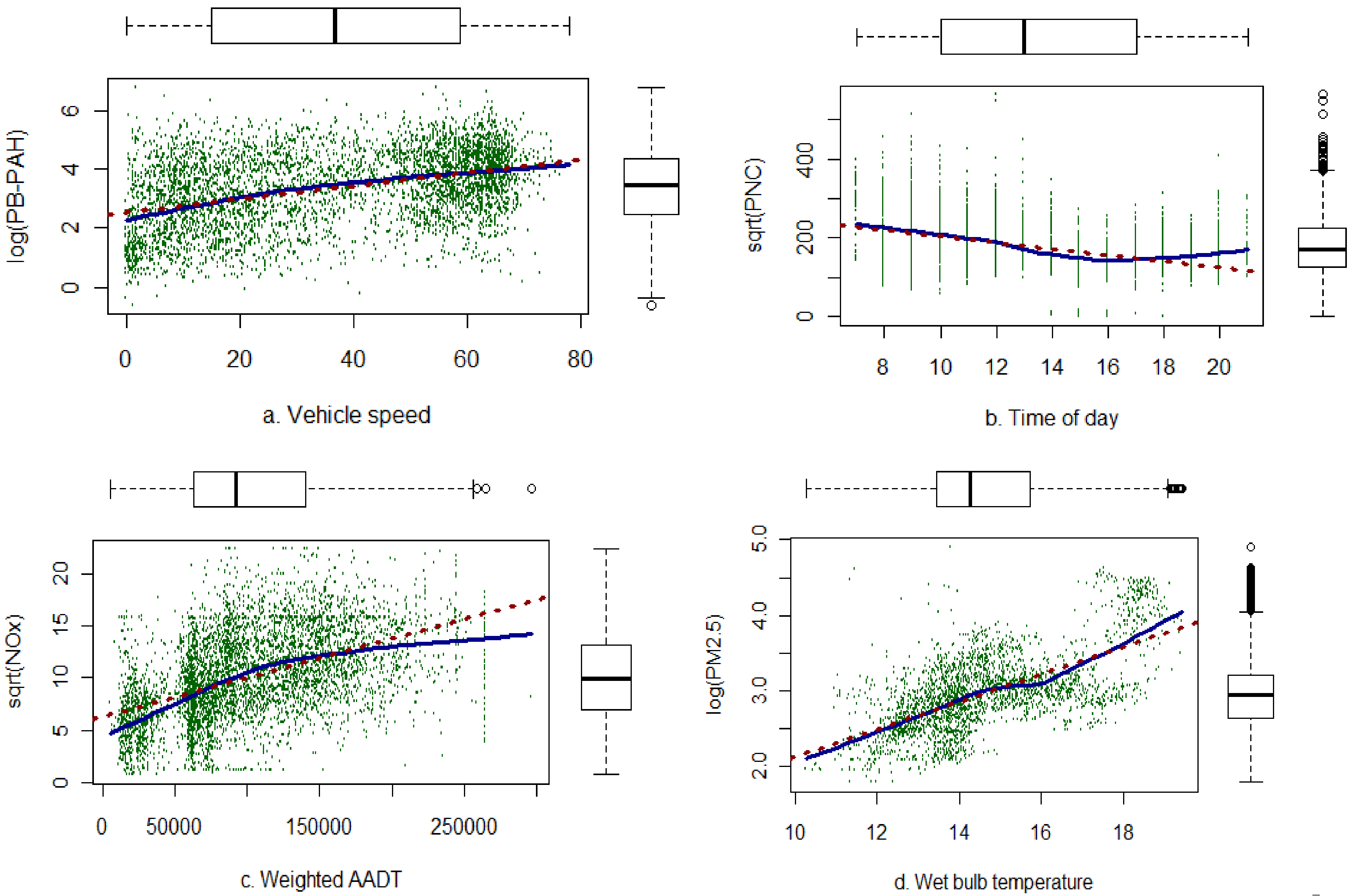
NOx (top), $PM_{2.5}$ (bottom) by Road Type (left), Time of Day (right)



Variance Explained in Linear Regression (LR) or GAM for Selected Variables

		Vehicle speed (miles/hour)	Weighted AADT	N lanes	Ambient temperature (°C)	On-road wet bulb temperature (°C)	Wind speed (m/s)	Time of day	Roadway type	Total variance explained
PB-PAH (ng/m^3)	LR	15.6%	8.8%	2.23%	0.1%	-	-	7.3%	9.1%	43.1%
	GAM	1.9%	2.4%	1.4%	5.7%	-	-	23.0%	17.2%	51.7%
PNC ($\#particles/cm^3$)	LR	16.3%	10.4%	-	-	-	-	17.8%	3.9%	48.3%
	GAM	2.7%	4.3%	-	13.6%	-	-	26.8%	16.1%	63.6%
NO_x (ppb)	LR	16.2%	8.3%	-	0.008%	-	0.2%	5.2%	10.3%	40.0%
	GAM	2.3%	4.6%	-	6.5%	-	6.7%	17.3%	11.5%	48.9%
$PM_{2.5}$ ($\mu g/m^3$)	LR	-	-	-	34.3%	11.84%	0.9%	20.6%	-	67.7%
	GAM	-	1.0%	-	7.8%	31.1%	2.6%	30.3%	-	72.8%

Examples of Decent Predictors



1/4 Holdout and 4 fold Cross Validation for Linear Regression and GAM

		Linear regression			Generalized additive model		
		General	4 fold CV	1/4 test	General	4 fold CV	1/4 test
PB-PAH	Samples	3874	3874	2916 vs. 958	3874	3874	2916 vs. 958
	R^2	0.42	0.42	0.39	0.52	0.49	0.49
PNC	Samples	1784	1784	1195 vs. 589	1784	1784	1195 vs. 589
	R^2	0.48	0.47	0.48	0.63	0.59	0.59
NO_x	Samples	4446	4446	2974 vs. 1472	4446	4446	2974 vs. 1472
	R^2	0.41	0.40	0.41	0.50	0.46	0.48
$PM_{2.5}$	Samples	2062	2062	1385 vs. 677	2062	2062	1385 vs. 677
	R^2	0.68	0.65	0.67	0.73	0.71	0.71

Note: General: no cross validation; 4 times CV: 4 times 4-fold cross validation; 1/4 test: three fourths used for training and one fourth used for test.

Model “Weaknesses”

- Data quantity not adequate for grouping data by hour (used 2-3 hour bins); wind direction used only four bins
- Truck activity not included.
  - Much of truck fraction effect “soaked up” by road type variable
- Lots of PN data missing

Part II Conclusions

- **<u>Time of day</u> accounted for 17-30% of variance, reflecting diurnal variations in emissions or meteorological factors.**
- **<u>Traffic predictors</u> (speed, traffic volume, road type) were statistically significant for PB-PAH, PNC, and NOx, but not for PM2.5, and explained 19-34% of variability.**
  - <u>Temperature</u> a critical predictor for PM2.5.
- **The non-linear GAM explained 5-10% more variance than the linear regression models.**
- **Autocorrelation regression models performed best, explaining 60, 72, 75 and 89% of the variance in PB-PAH, PNC, NOx, and PM2.5 concentrations, respectively.**

Part III:
Mobile Monitoring: a Better Tool to Measure Vehicle Emission Factors?

Value of Measuring EF

- Fleet-wide emission factor (EF) trends important in evaluating efficacy of regulations
  - Big drop in HDD emission standards for 2007 and newer vehicles, though HDD fleet turnover slow
  - Additional CA and LA freight movement regulations and voluntary commitments
    - Programs of accelerated truck turnover
    - Bans of older trucks, esp. short haul; retrofits of pre-97
    - Other voluntary programs

Recent CA Fleet Trends

- Light duty (gasoline) vehicle emissions have come down 2 orders of magnitude since 1960s, but downward trends continue…
  - From 2000 to 2010, CO dropped 60% in CA (ARB, 2009) (LEV II standards)
- During same time period, growing HDD vehicle miles and relatively unimproved emissions rates came to dominate freeway emissions
- After 2010 or 2011, HDDs emissions appear to be dropping rapidly.

EF Measurement Method Options

	Advantages	Disadvantages
Dyna-mo-meters	Accurate Can modify driving cycle	•High cost per test • Procurement difficult for HDD; representativeness a challenge
Tunnel Studies	Good sample numbers Representative of fleet	~~•Fleet averages only~~ •Fixed or limited driving conditions (e.g., grade) •Expensive to set up
Remote Sensing	Good sample numbers	•Snapshot in time and space, so need large numbers of locations, driving conditions

Motivation/Goal

- Is there a lower-cost alternative that efficiently allows capturing:
  - Both fleet-wide and individual vehicle EFs, (mean and variability)?
    - A large representative vehicle sample?
    - A representative mix of different driving speeds, acceleration and grade?
    - Multiple pollutants including PM species like black carbon (BC)(diesel PM)

Our Approach: On-Road Mobile Platform

Hybrid between individual plume EF determination (very labor intensive) and tunnel-style averages:

- Large analysis savings if freeway segment averages used, but distributional spread of EFs appears to be maintained
- Allows larger data set

Methods

1. Need baseline distribution of light-duty (LD), gasoline-only EFs from a truck-restricted freeway
2. Calculate HDD EFs from pollutant concentration change per unit CO_2 above the LD baseline and background concentrations (1^{st} percentile values) for each mile
3. Use freeway segment-specific truck count, traffic volume and speed (CalTrans PeMS sensors)

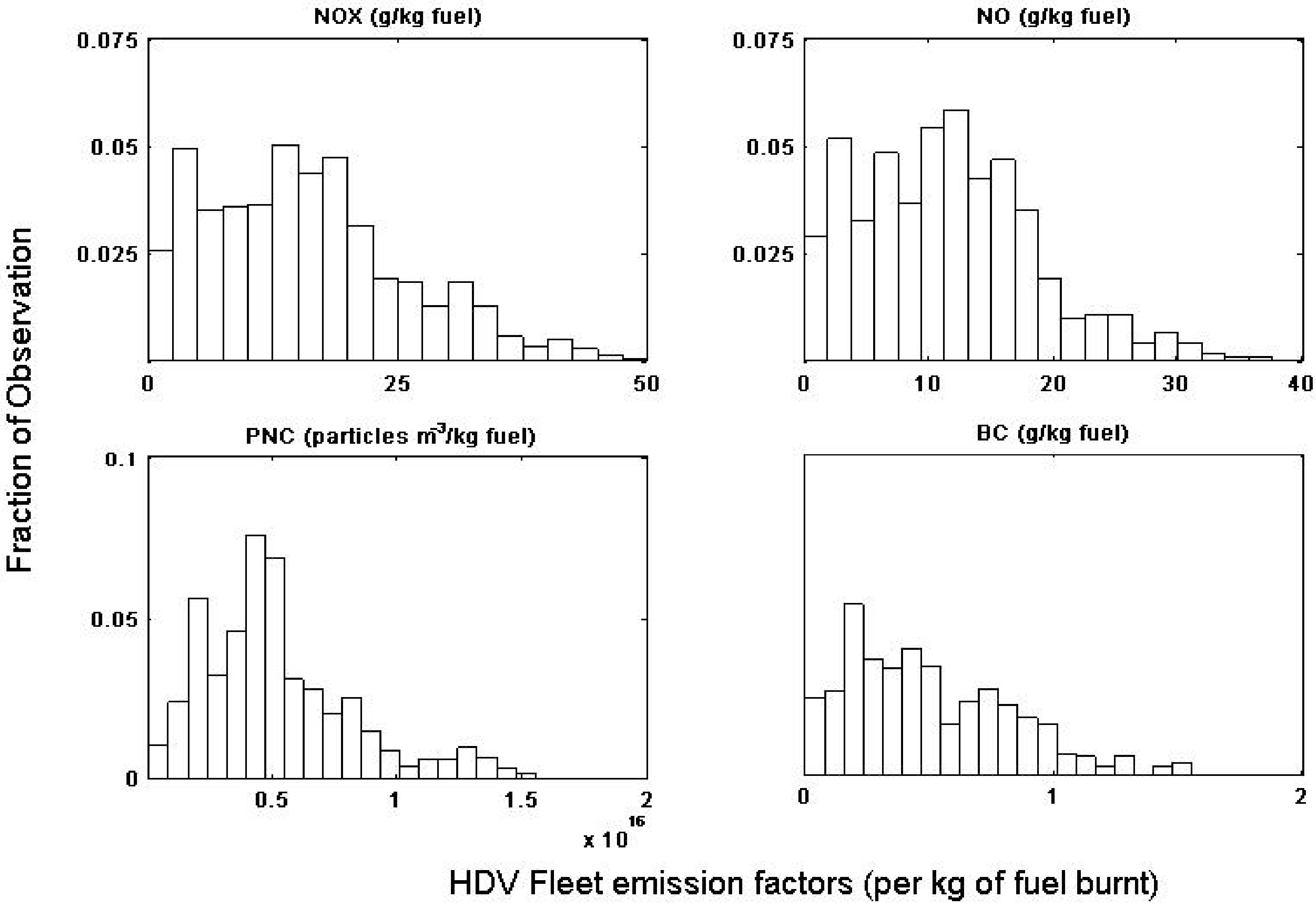
Sampling

- Routes selected to cover:
  - Freeway segments of differing HDD and LDV mix (3-12%) and LDV only (110) (EFs should agree)
  - Range of roadway grades (EFs should vary)
- Times of day selected to cover different driving conditions (can further sort by speed, acceleration, etc. to verify representativeness)

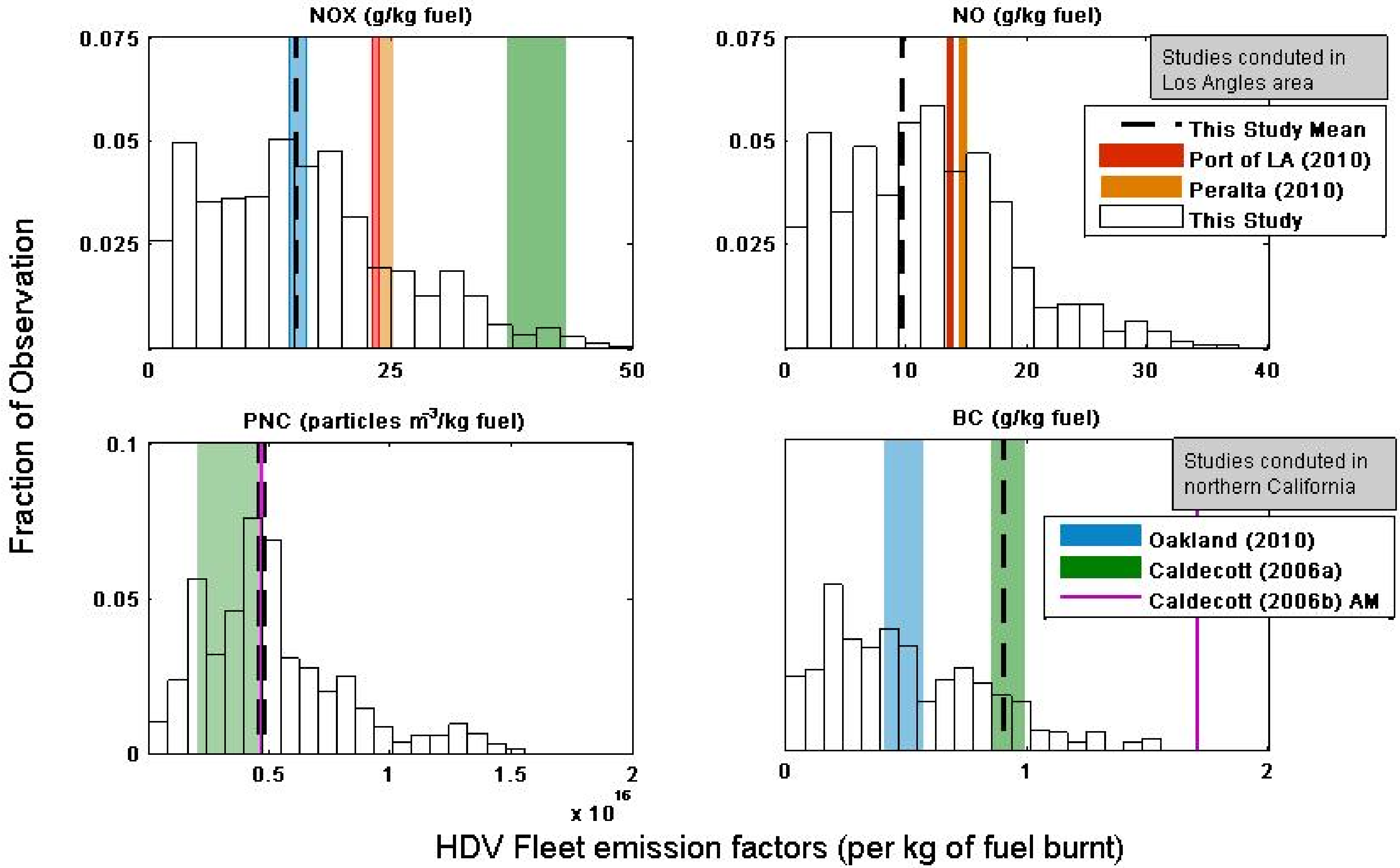
Rough Cost Comparison, Mobile vs Tunnel Sampling

- Initially investment of equipment and vehicle ~ ~ 100k
- On-road sampling per day: <$1000
- Analysis: 5-10 hrs per data hour
- Tunnel equivalent data collection ~ ~ 10k
- Tunnel equivalent analysis ~ ~ 25k

HDD EF Distributions by Pollutant (excludes largest freight route, I-710)



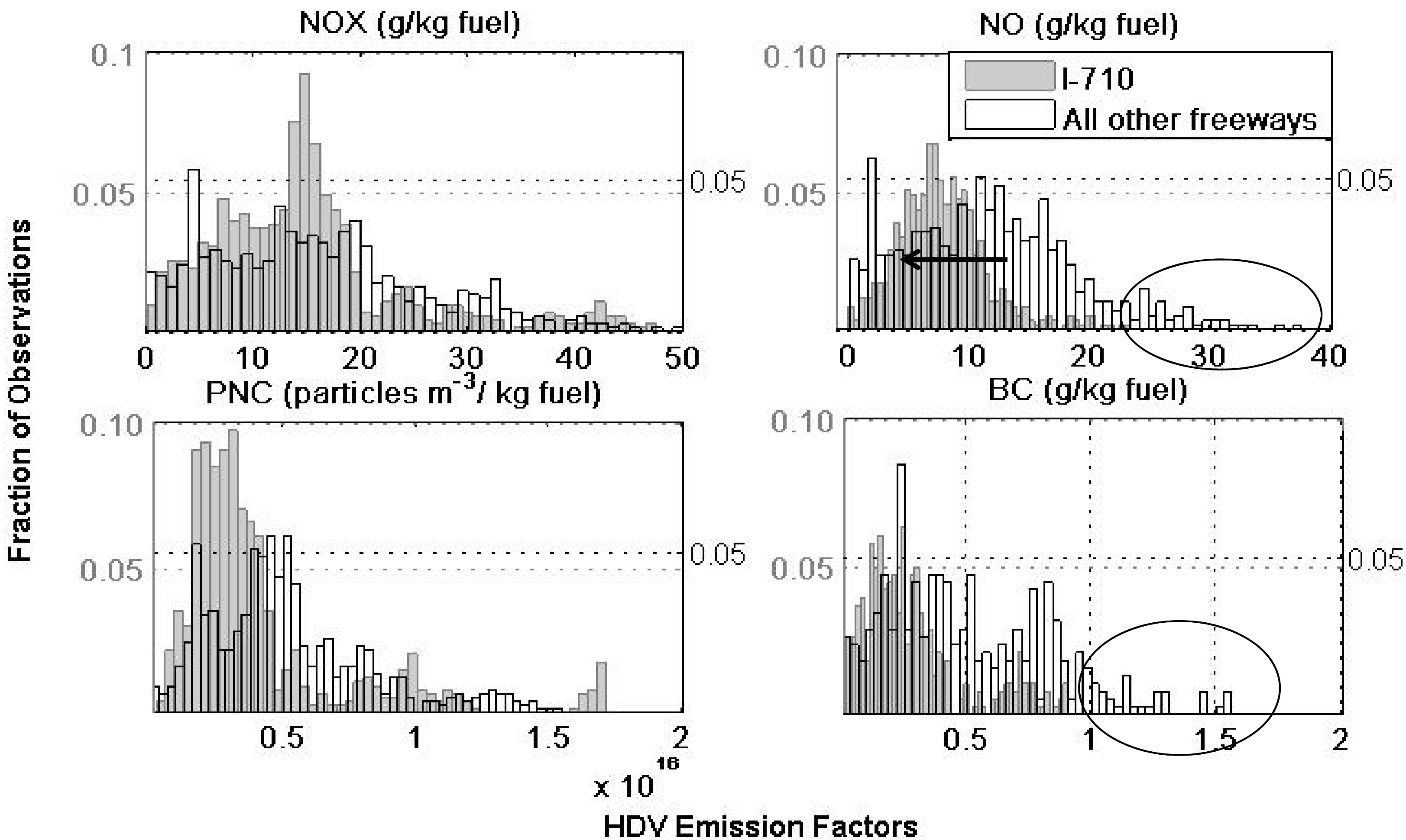
Comparison between Different Methods: Means



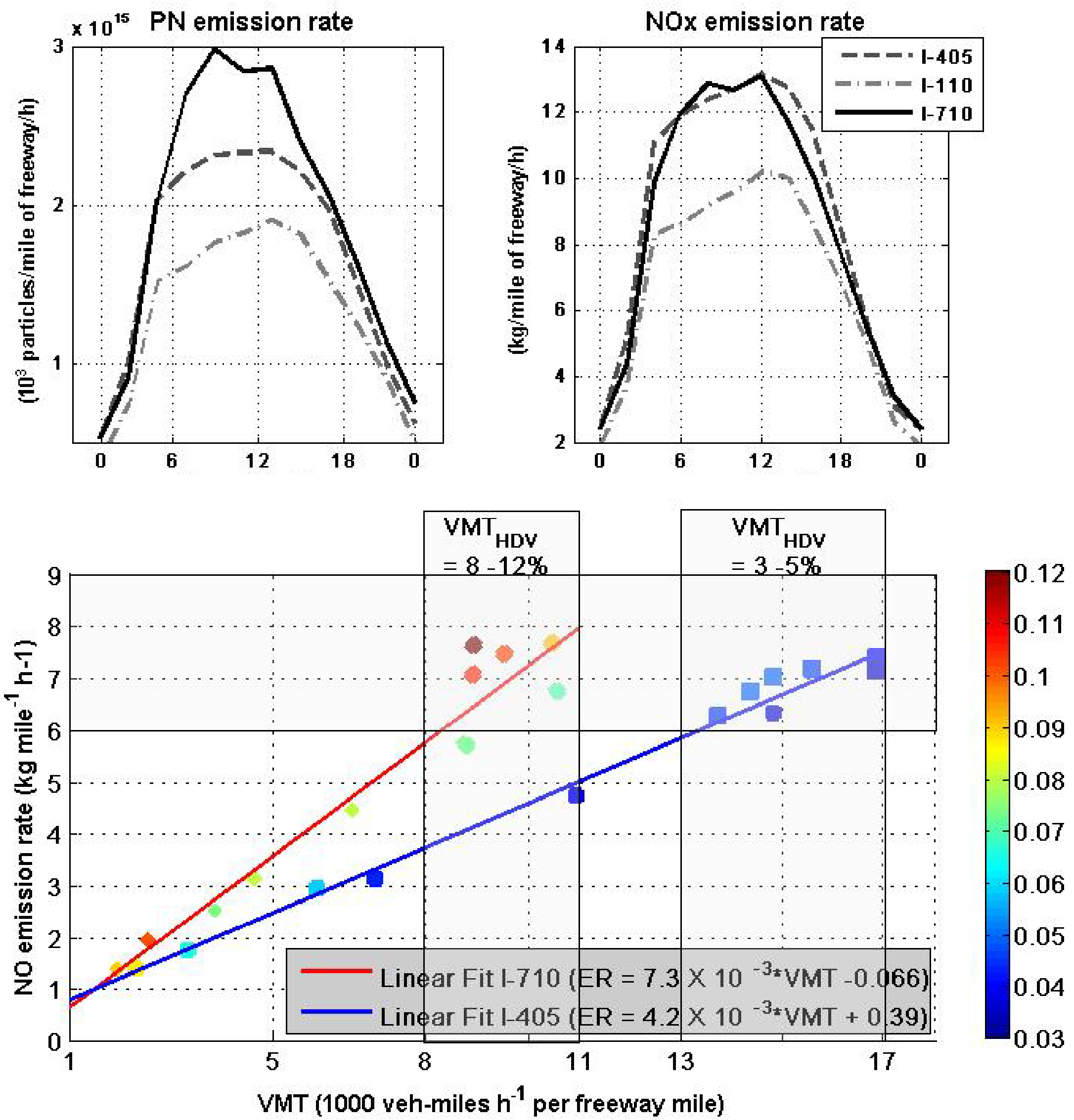
I-710 in Los Angeles

- Historically most polluted LA freeway
- Recent regulations
  - State-wide regulations
    - Drayage (short trip) truck regulations – retrofitting with DPF; pre-1994 engines banned
    - Expected to reduce 1994-2006 truck emissions by 85% by 2013
  - (San Pedro Bay) Ports Clean Air Action Plan
    - Progressively only allows HDDs meeting 2007 federal emission standards after Jan 1, 2012
    - Expected to eliminate 72% of diesel particulate matter and 22% of NOx

Evaluating the efficacy of recent regulations



Total Freeway Emissions



Part III Conclusions

1. **Light duty vehicle air pollution fraction contributions are increasing as HDD EFs rapidly come down**

Part III Conclusions

2. **Mobile platform measured fleet EFs**

- **Means agree well with tunnel studies**
- **Distributional spreads appear to have also been captured compared to individual plume studies**
- **Potentially far lower cost per campaign**

Part III Conclusions

3. I-710, a major freight cargo route, with high HDD fraction—formerly far higher concentrations of BC, ultrafine PM, and NO--now seems comparable to other LA freeways.
   - Especially large drop in 710 HDD EFs in last 1-2 years
   - Accelerated turnover programs at ports appear to be working as planned
     - Going after high emitters appears to have been very effective for BC

Overall Conclusions

- Vehicle AER drives I/O ratios for traffic-related pollutants in predictable ways
  - Model R2s 0.7 to 0.8
- On-road predictive models reasonably good, but need further improvements
  - Recent downward trends in HDD emissions will require period re-calibration of models
- Mobile measurements can serve “double duty” by providing data to serve both on-road models and EF trends

What Next?

- Better arterial on-road models (Part II)
- Characterizing RC vs OA (or open window) choice (weather?)
- Characterizing relationship between AER and I/O for other particulate pollutants (PM2.5, coarse PM, particle-bound PAHs, black carbon…)
- Commuter health study (n of several hundred)

Acknowledgements

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Thank you for your attention

Questions?