Impact of High-Efficiency Filtration Combined with High Ventilation Rates on Particulate Matter Concentrations in U.S. Offices

NAFA Annual Convention 2017
Annapolis, MD
September 20, 2017

Michael S. Waring*, Tom Ben-David, Sheng Wang

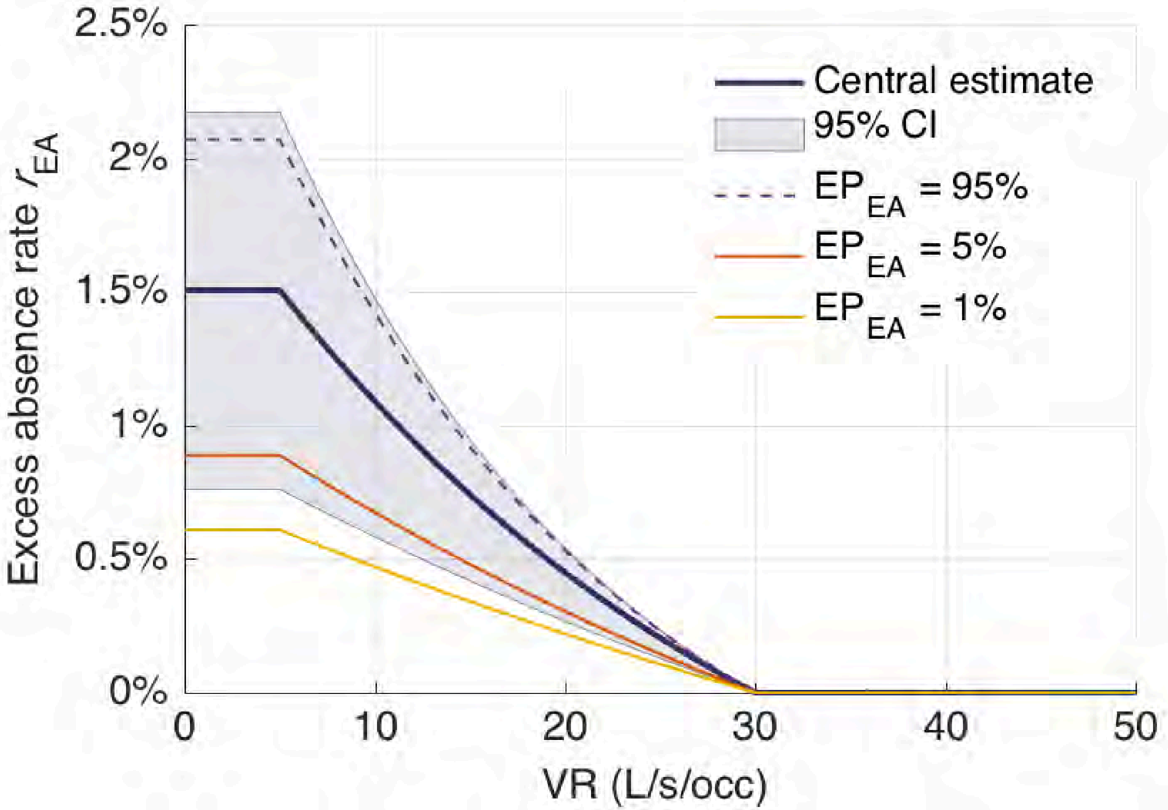
*Associate Professor
Civil, Architectural and Environmental Engineering
Drexel University, Philadelphia, PA
Indoor Environment Research Group (http://www.indoor-envi.com/)
Drexel Air Resources Research Laboratory (DARRL)
Building Science & Engineering Group (BSEG)
msw59@drexel.edu

Introduction

- Maintaining a healthy indoor environment is vital for our wellbeing
  - Americans spend 90% of time indoors (Klepeis et al., 2001)
  - Exposure to pollutants of outdoor origin occurs more indoors
- Most common way to improve indoor air quality (IAQ) in commercial buildings is with **ventilatio**n (Wei et al., 2015)
  - Studies show that higher ventilation = better IAQ
    (Carrer et al., 2015; Seppänen et al., 2006; Sundell et al., 2011)

Introduction

- Higher ventilation rates (VR) yield positive impacts, such as:
  - Improved work performance (Seppänen et al., 2006; Fisk et al., 2012)
  - Reduced absenteeism (Milton et al., 2000; Fisk et al., 2012)



Introduction

- However, higher ventilation introduces harmful pollutants indoors:
  - Particulate matter (PM), Ozone (O_3), etc.

- Filtration can mitigate one strong negative impact of ventilation by removing PM from airstream

- Removing PM is important because:
  - PM is most significant pollutant of outdoor origin (Ben-David et al., 2017)
  - Exposure to PM can lead to acute health effects, chronic cardiopulmonary diseases, and even premature mortality (Burnett et al., 1999; Dutton et al., 2013; Pope et al., 2002, 2009)

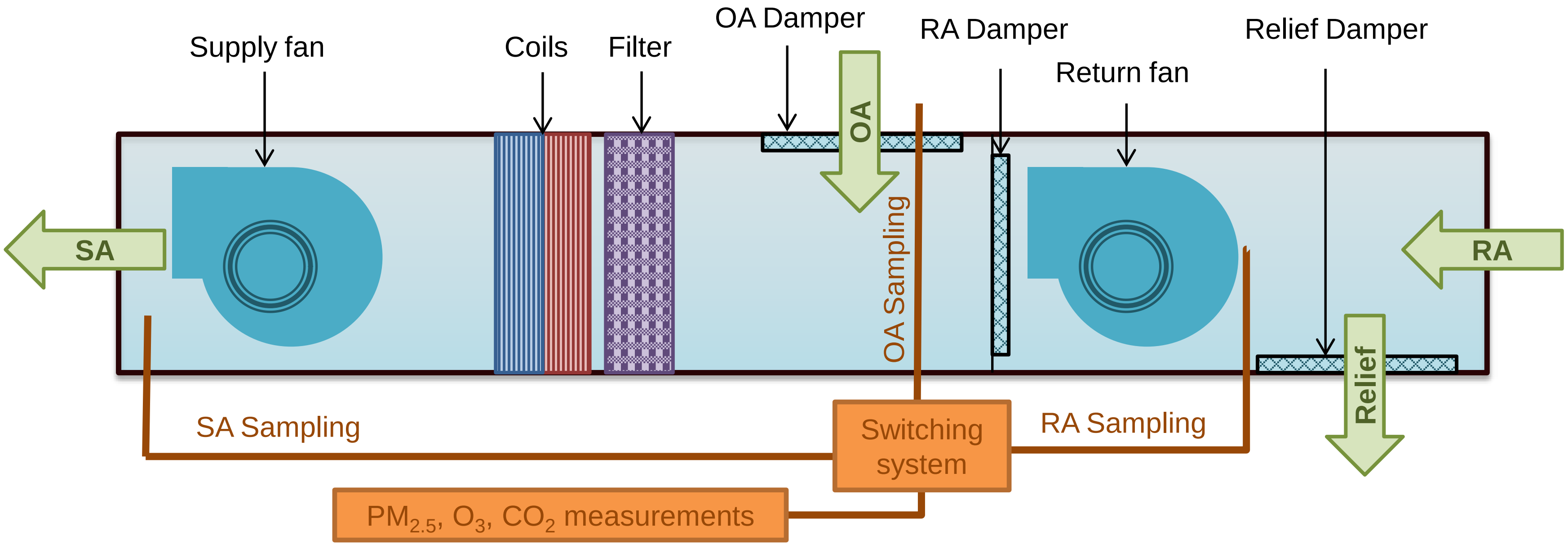
- Therefore, mitigating indoor PM concentrations is essential to create a healthy building with satisfactory IAQ

Research Objectives

- Using different filters, a series of office experiments was conducted to determine:
  1. How well can filters be used to control indoor PM, over a series of lower to higher ventilation rates?
  2. What are the real time removal efficiencies for a range of MERV filters?
  3. Does filter removal efficiency correlate with environmental or fan parameters?

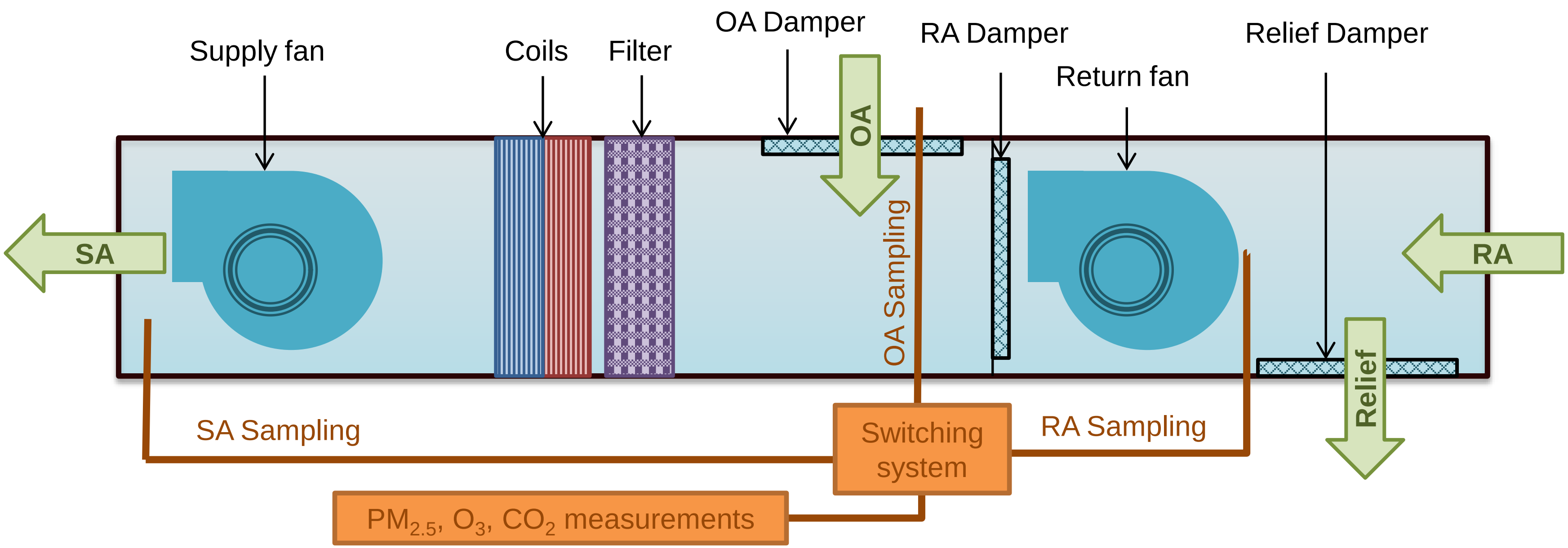
Methodology

- Experiments were conducted in an active office building:
  - Stratton Hall at Drexel University, Philadelphia, PA
  - Third floor, lightly occupied, independent air handling unit
  - CAV operation, with supply air (SA) of ~5.4 h^{-1} or ~0.9 CFM/ft^2
  - 6 ft. × 6 ft. filter bank, RA fan at 25% of SA fan power



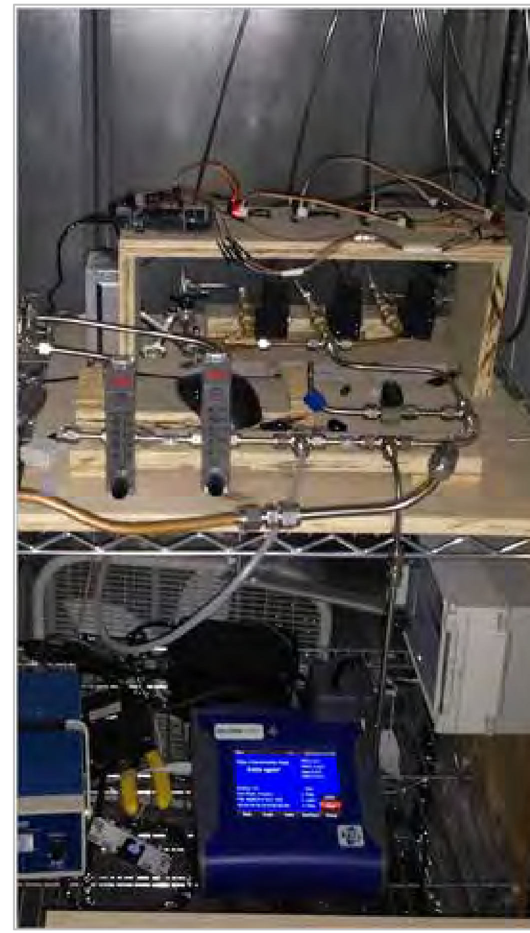
Methodology

- The following real-time measurements were taken:
  - Flow rates in outdoor (OA), supply (SA), and return (RA) airstreams
  - Temperature and relative humidity (RH) in OA, SA, RA
  - SA and RA fan power (from installed HOBO data loggers)
  - $PM_{2.5}$, O_3, and CO_2 concentrations from OA, SA, RA (indoor surrogate)



Methodology

- Sampling system for measuring OA, SA, and RA concentrations:
  - Custom valve switching system
  - Sampled each air stream for 2-min
  - 30 ft., 0.25 in. OD stainless steel tubing for OA, SA, RA pollutant sampling



- Instrumentation:
  - $PM_{2.5}$ with TSI DustTrak DRX 8533, auto-zero capability, sample every 1 s
  - O_3 with 2B Technologies 205, 1 ppb accuracy, sample every 10 s
  - CO_2 with PP Systems WMA-4, auto-zero capability, 1% accuracy, sample every 2 s

Methodology

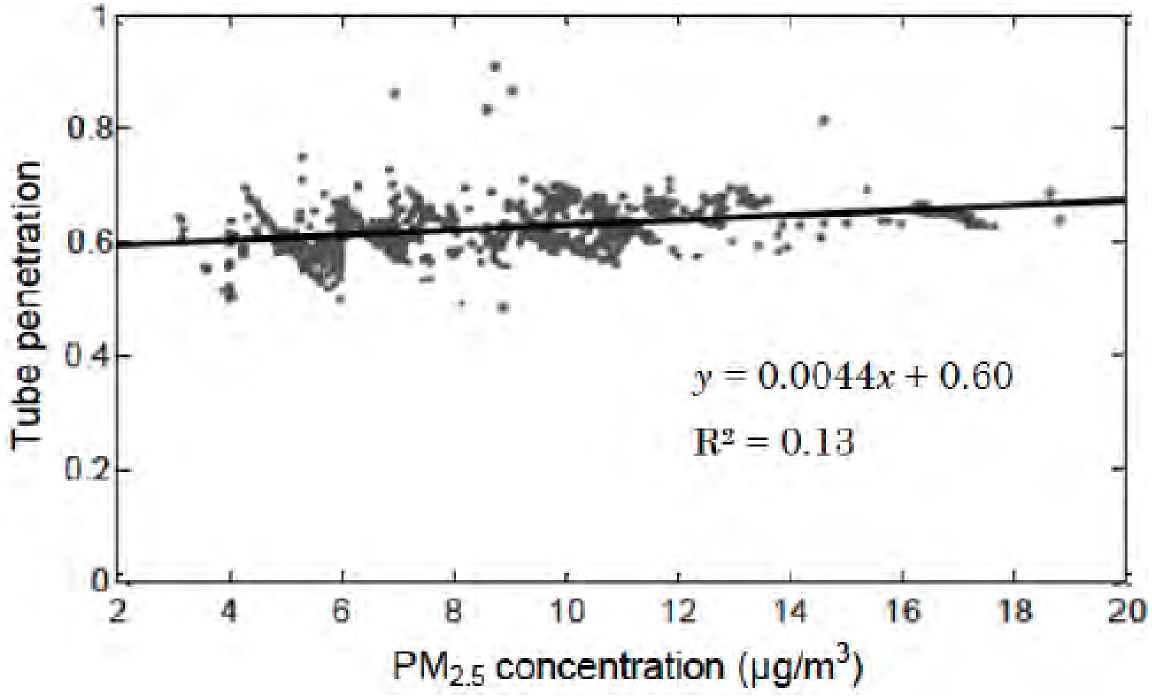
- Experiments on 66 days over January to December 2016
  - All measurements from ~8 AM to ~5 PM

- In experimental matrix, we parametrically varied:
  - Ventilation rate by varying OA fraction:
    - Nominal ventilation rates were 1.2, 2.3, or 5.4 h^{-1}
    - Nominal supply rates were 5.4 h^{-1}
    - CAV system, so higher ventilation meant less recirculation air
  - Filtration efficiency, one of three filters:
    - MERV 8; pleated; 24 in. × 24 in. width; 2 in. depth
    - MERV 14; synthetic V-cell; 24 in. × 24 in. width; 12 in. depth
    - MERV 15; glass V-cell; 24 in. × 24 in. width; 12 in. depth

Methodology

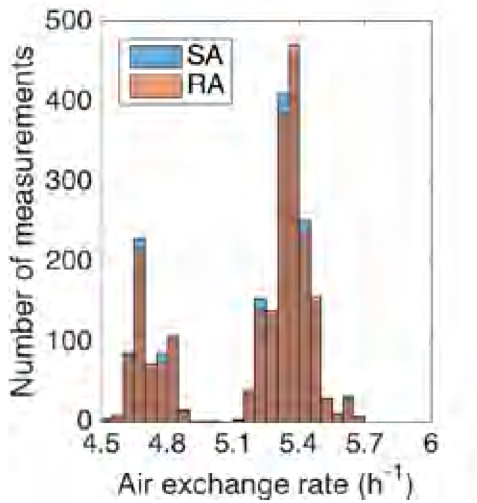
- $PM_{2.5}$ corrected for losses in valve and tubing (30 ft.):
  - Valve penetration of 98.4%
  - Tube penetration of 62.4%

→ Combined penetration = 61.4%

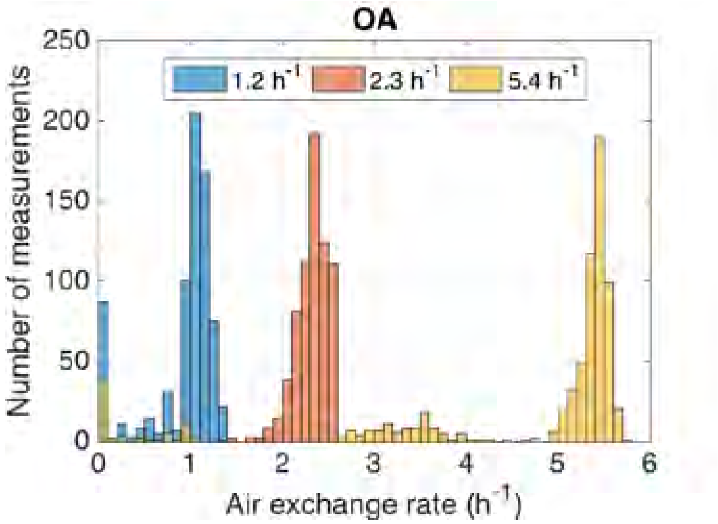


Results: Flow measurements

- SA and RA flow were almost identical:
  - Target 5.4 h^{-1}; resulting median = 5.3 h^{-1}
  - Correlation coefficient = 0.98
  - During August and September measurements, lower flow rates were measured
    - No relation to filter or ventilation flow rate



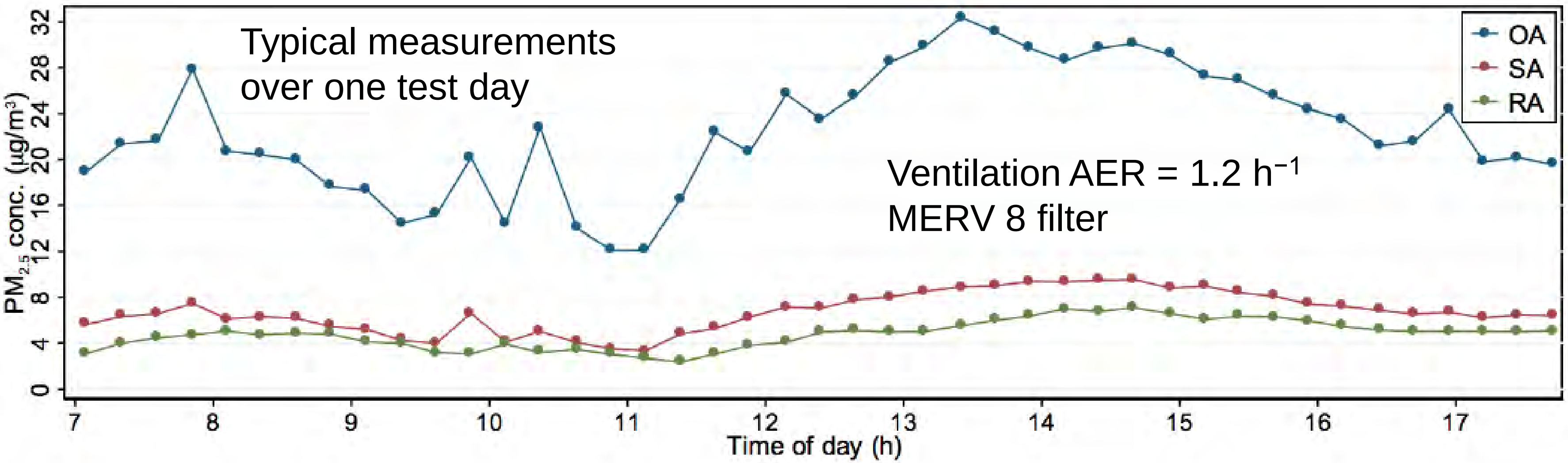
- OA ventilation flow measurements corresponded to control values:
  - @ 1.2 h^{-1}, median = 1.0 h^{-1}, cov = 0.42
  - @ 2.3 h^{-1}, median = 2.4 h^{-1}, cov = 0.08
  - @ 5.4 h^{-1}, median = 5.4 h^{-1}, cov = 0.34

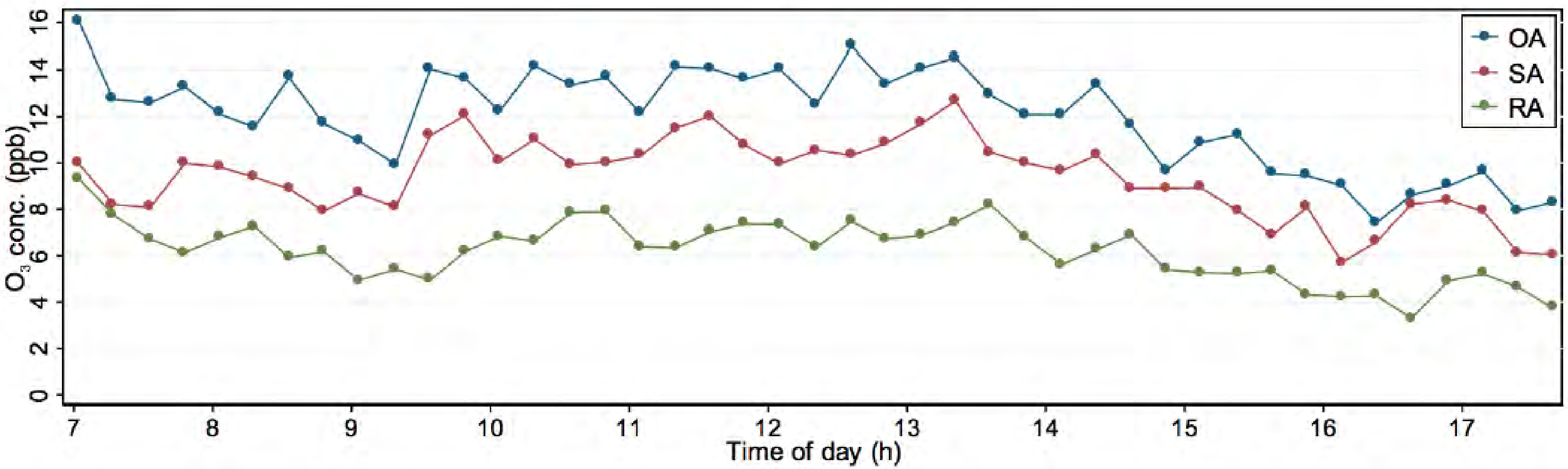


Research Objective 1:

How well can filters be used to control indoor PM, over a series of lower to higher ventilation rates?

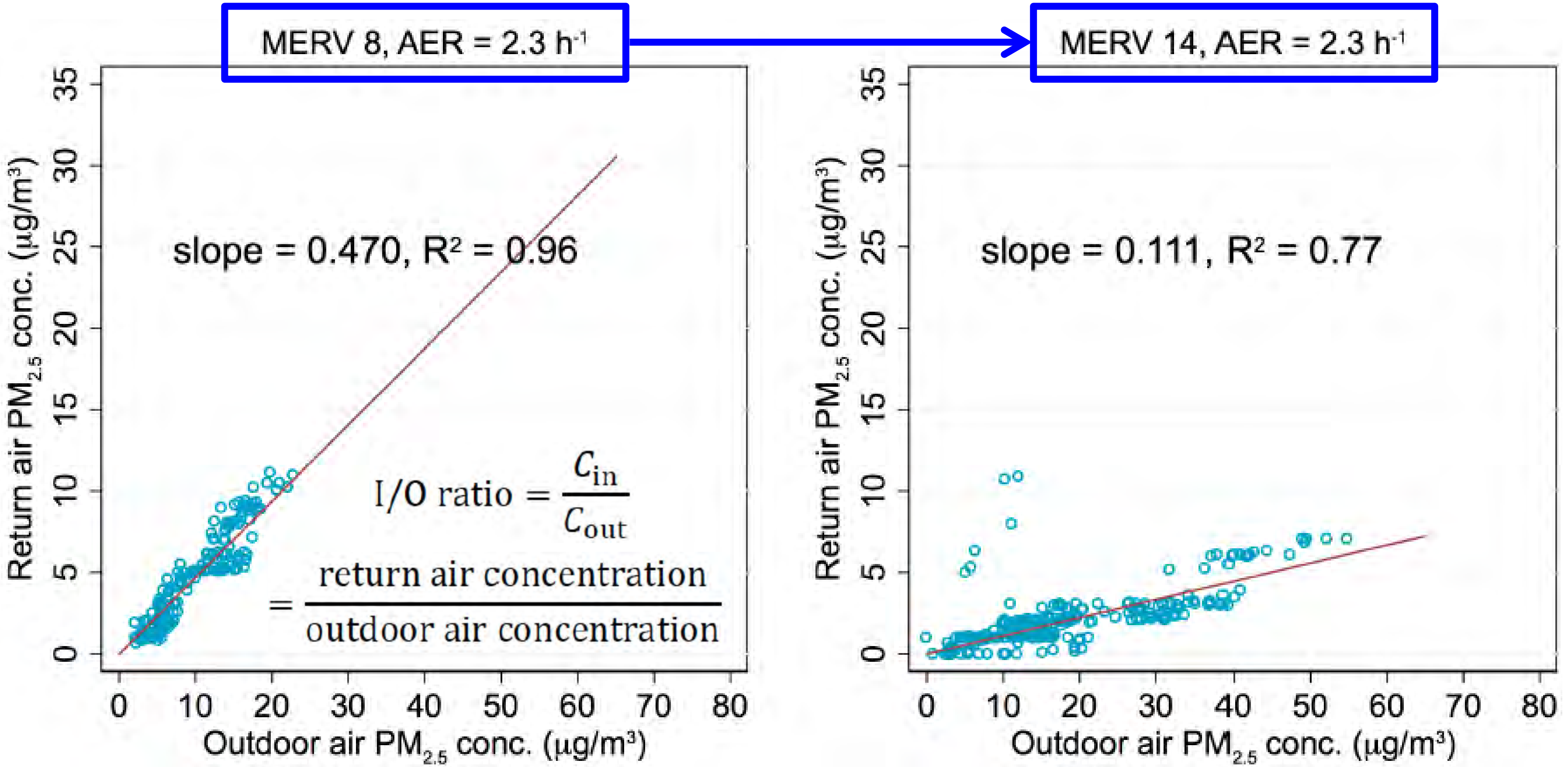
Results: Pollutant measurements





Results: $PM_{2.5}$ I/O ratios

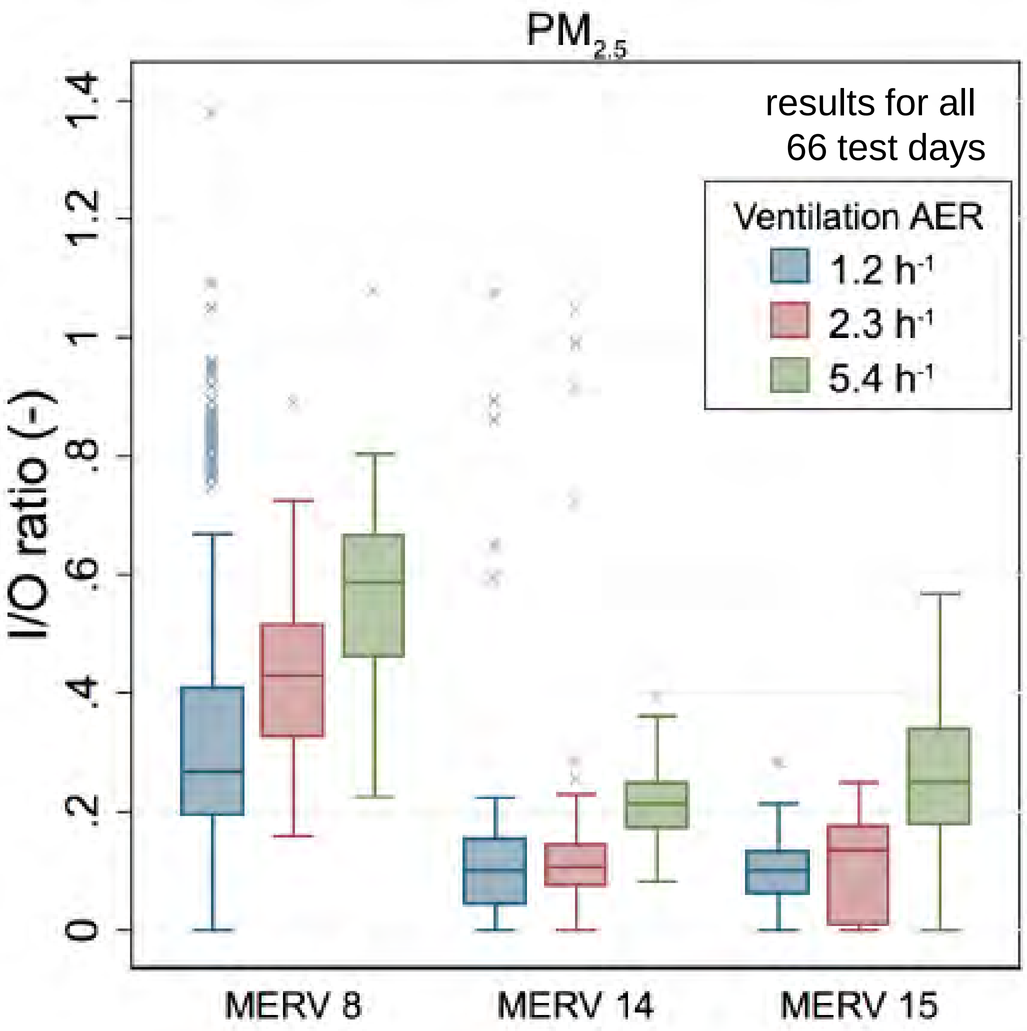
- $PM_{2.5}$ concentrations in the RA (indoor) and OA airstreams:
  - Slope is the overall indoor/outdoor (I/O) ratio of particles



Results: $PM_{2.5}$ I/O ratios

- Real-time $PM_{2.5}$ I/O ratios:
  - Affected by ventilation and filtration efficiency
  - Filtration dominant driver of $PM_{2.5}$ I/O ratios
  - MERV 8 had higher I/O ratios than MERV 14, 15
- Calculation:

$$\text{I/O ratio} = \frac{C_{\text{in}}}{C_{\text{out}}} = \frac{\text{return air concentration}}{\text{outdoor air concentration}}$$

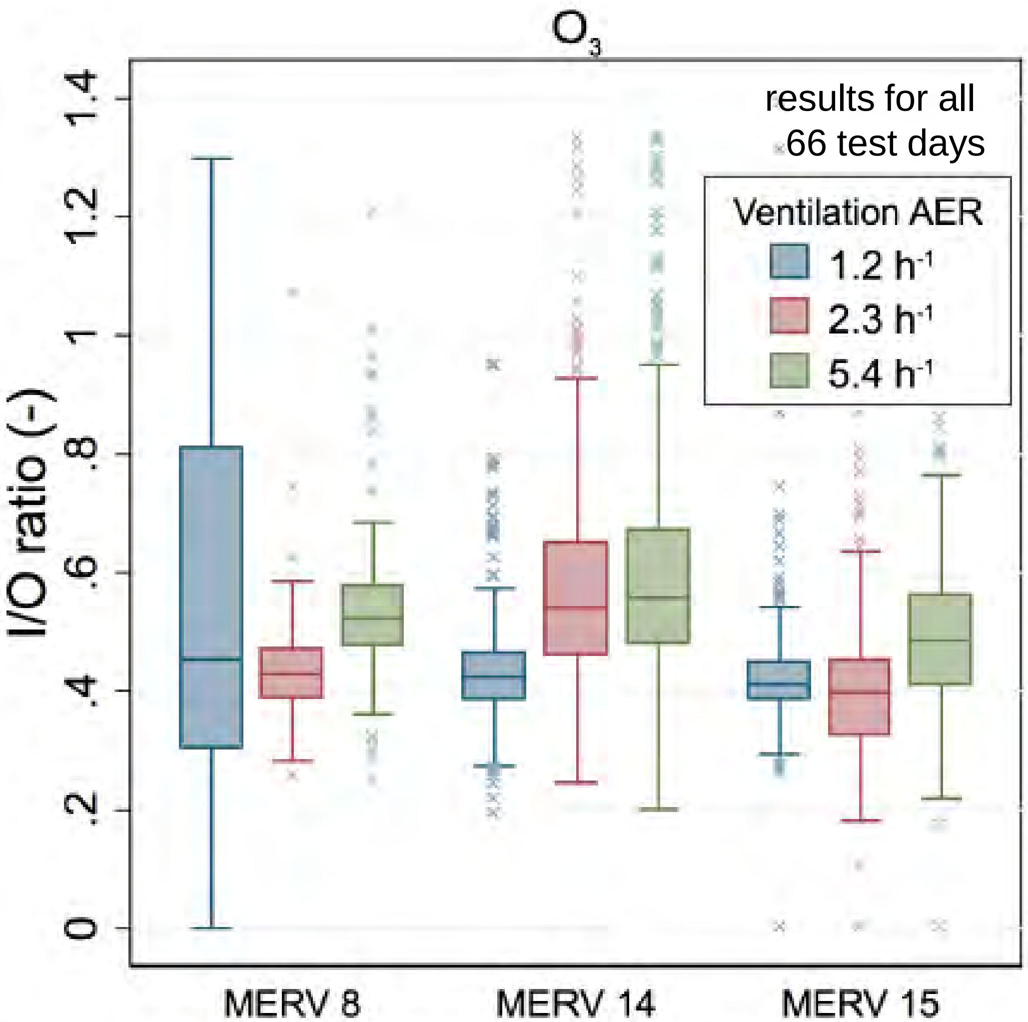


Results: Ozone I/O ratios

- Real-time O_3 I/O ratios:
  - Medians of ~0.4–0.5
  - Increased slightly with ventilation rate
  - Slightly smaller for MERV 15 filters

- Calculation:

$$\text{I/O ratio} = \frac{C_{\text{in}}}{C_{\text{out}}} = \frac{\text{return air concentration}}{\text{outdoor air concentration}}$$



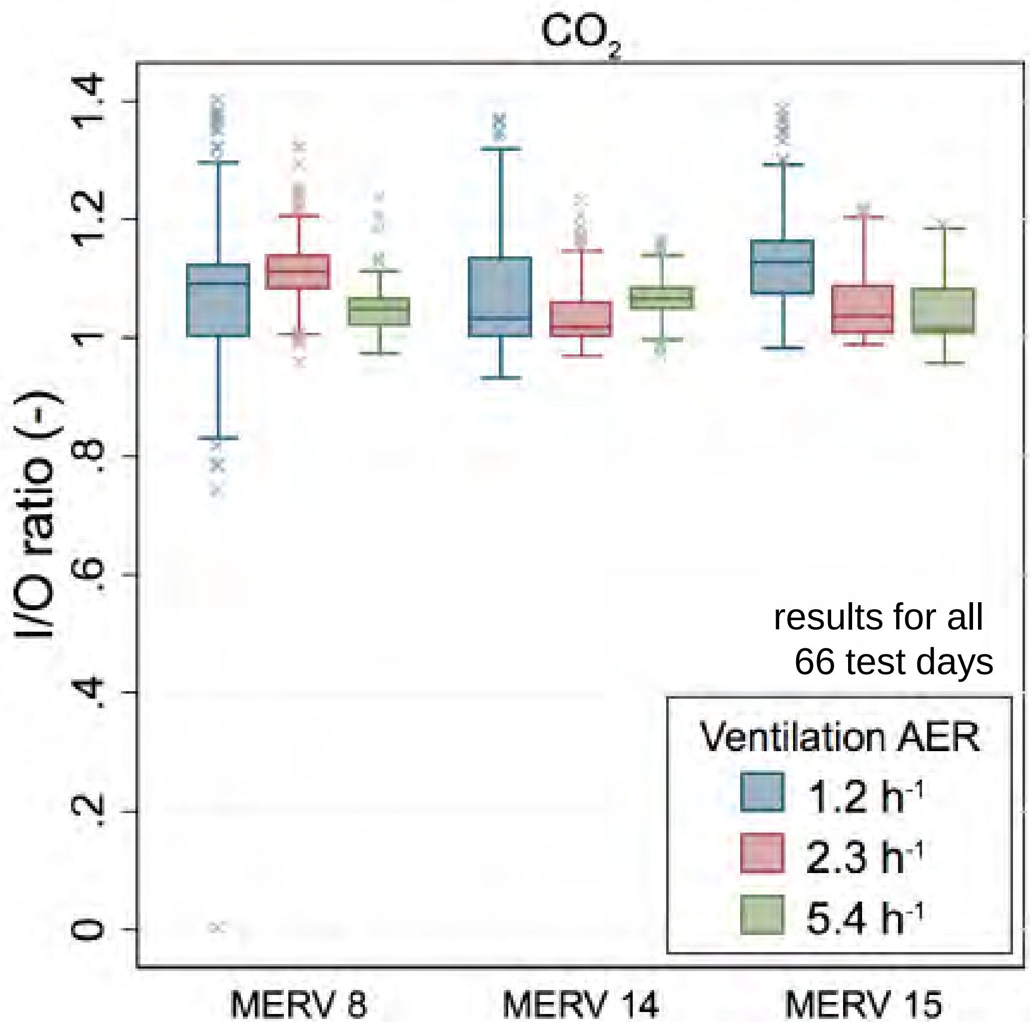
Results: CO_2 I/O ratios

- Real-time CO_2 I/O ratios:
  - Little variation with ventilation due to low and changing occupancy
  - No filtration effect

- Calculation:

$$\mathrm{I/O\ ratio} = \frac{C_{\mathrm{in}}}{C_{\mathrm{out}}}$$

$$= \frac{\text{return air concentration}}{\text{outdoor air concentration}}$$



Results: I/O ratios summary

- Trends for $PM_{2.5}$ I/O ratios:
  - When VR increases:
    - I/O ratio increases
    - I/O ratio becomes less scattered (not shown)
  - When filter efficiency increases:
    - I/O ratio strongly decreases, and can compensate for VR increases
  - Pairing high efficiency filter with high VR allows for effective control of indoor PM concentrations due to outdoor-to-indoor transport

- Trends for O_3 I/O ratios:
  - Higher when VR increases
  - Filter had little impact

- Trends for CO_2 I/O ratios
  - No strong trends
  - Occupancy low and varied

Research Objective 2:

What are the real time removal efficiencies for a range of MERV filters?

Results: Filter efficiency

- Efficiency estimated with mass balance and measured parameters*:

$$\underbrace{(\lambda_{OA}C_{OA}}_{\text{OA exchange rate} \times \text{OA concentration}} + \underbrace{(\lambda_{RA}-\lambda_{OA})C_{RA})}_{\text{Recirculated air exchange rate (RA − OA)} \times \text{RA concentration}}\underbrace{(1-\eta_v)}_{\text{Fraction of PM not filtered, (1 – efficiency)}} = \underbrace{\lambda_{SA}C_{SA}}_{\text{SA flow rate} \times \text{SA concentration}}$$

OA exchange rate × OA concentration

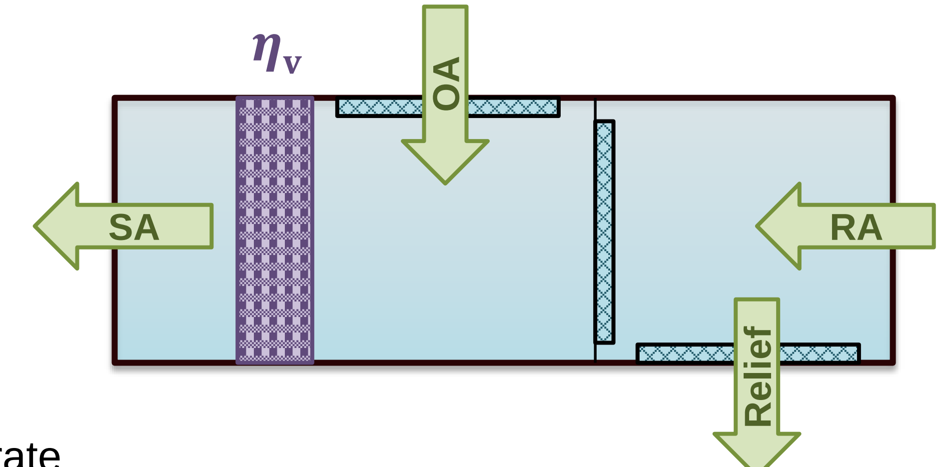
Recirculated air exchange rate (RA − OA) × RA concentration

Fraction of PM not filtered, (1 – efficiency)

SA flow rate × SA concentration

Filter removal efficiency (**η_v**) can be calculated using measured values:

$$\eta_v = 1 - \frac{\lambda_{SA}C_{SA}}{\lambda_{OA}C_{OA} + (\lambda_{RA}-\lambda_{OA})C_{RA}}$$

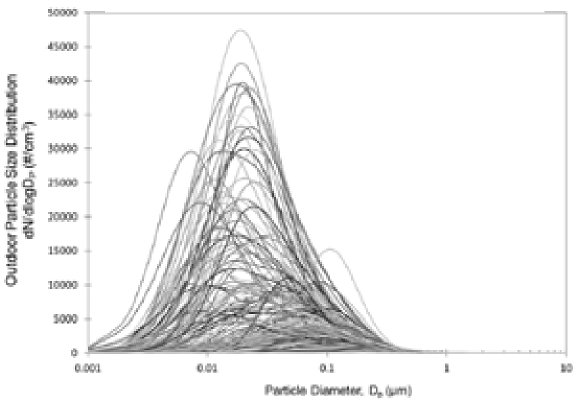


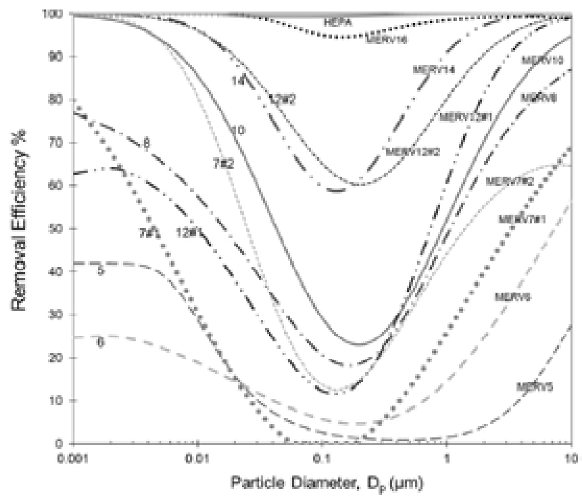
*Relief flow rate was assumed to equal OA flow rate

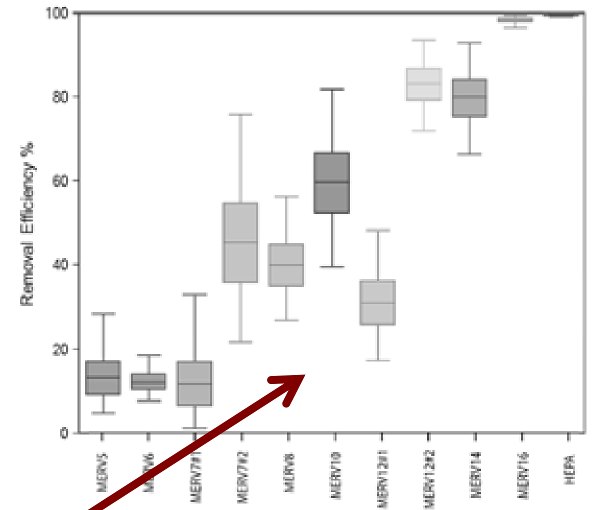
Results: Filter efficiency

- We compared our PM efficiency results against Azimi et al. (2014)
  - Azimi et al. (2014) combined outdoor PM size distributions with size-resolved efficiency filter curves to compute $PM_{2.5}$ removal efficiency

PM size distribution + Size-resolved removal efficiency = $PM_{2.5}$ removal efficiency







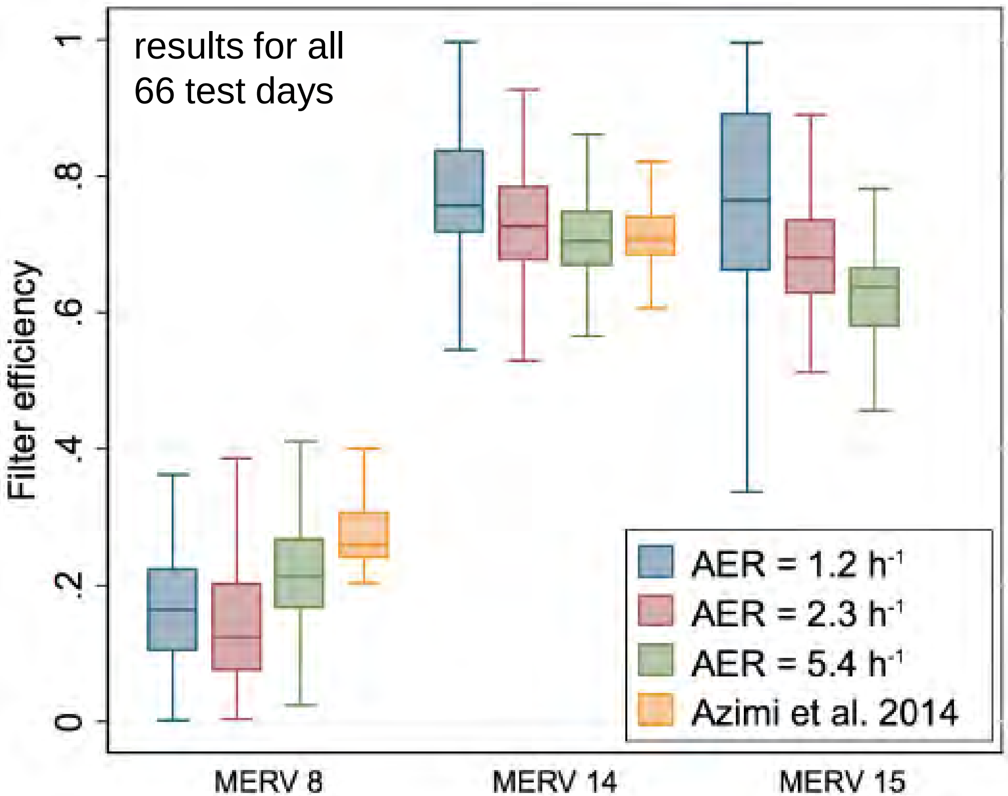
So, we compared our measured results against

Azimi, P., Zhao, D., & Stephens, B. (2014). Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. Atmospheric Environment, 98, 337-346.

Results: Filter efficiency, $PM_{2.5}$

- $PM_{2.5}$ filter efficiency calculated at each time step for each filter
  - MERV 8 and MERV 14 were compared to estimated in Azimi et al. (2014)
  - Plot of efficiency by filter, for VRs individually:

- Observations:
  - Our MERV 8 had lower efficiency and wider spread compared with Azimi et al. (2014)
  - Our MERV 14 had similar or higher efficiency and wider spread compared with Azimi et al. (2014)



Results: Filter efficiency, $PM_{2.5}$

- $PM_{2.5}$ filter efficiency calculated at each time step for each filter
  - MERV 8 and MERV 14 were compared to estimated in Azimi et al. (2014)
  - Table of efficiency by filter, for VRs individually:

MERV	Ventilation AER (h^{-1})	N_{net}	N_{net}	μ_A	σ_A	R^2 normal	GM	GSD	R^2 LN	p5	p10	p25	p50	p75	p90	p95
8	All	677	555	0.18	0.096	1.00	0.14	2.3	0.91	0.024	0.052	0.11	0.17	0.24	0.30	0.34
	1.2	265	211	0.16	0.089	1.00	0.13	2.6	0.86	0.011	0.037	0.10	0.17	0.22	0.28	0.31
	2.3	188	168	0.15	0.11	0.93	0.11	2.4	0.98	0.024	0.040	0.074	0.12	0.20	0.34	0.40
	5.4	224	176	0.22	0.073	1.00	0.20	1.6	0.95	0.10	0.12	0.17	0.21	0.27	0.30	0.32
	Azimi et. al									0.22	0.23	0.24	0.26	0.30	0.34	0.39
14	All	771	655	0.74	0.090	0.98	0.73	1.1	0.99	0.61	0.64	0.68	0.73	0.78	0.86	0.93
	1.2	254	155	0.78	0.11	0.97	0.77	1.2	0.98	0.63	0.66	0.72	0.76	0.84	0.93	0.98
	2.3	271	256	0.74	0.092	0.98	0.74	1.1	0.99	0.62	0.64	0.68	0.73	0.78	0.87	0.96
	5.4	246	244	0.71	0.064	0.99	0.71	1.1	1.00	0.61	0.63	0.67	0.70	0.75	0.80	0.82
	Azimi et. al									0.65	0.66	0.68	0.71	0.74	0.78	0.81
15	All	692	589	0.68	0.14	0.97	0.66	1.3	0.96	0.40	0.49	0.61	0.70	0.76	0.89	0.97
	1.2	242	185	0.75	0.17	0.99	0.73	1.3	0.95	0.42	0.49	0.66	0.77	0.89	0.97	0.99
	2.3	220	205	0.69	0.11	0.98	0.68	1.2	0.98	0.55	0.57	0.63	0.68	0.73	0.83	0.90
	5.4	230	199	0.60	0.11	0.89	0.59	1.2	0.82	0.36	0.40	0.59	0.64	0.66	0.70	0.73

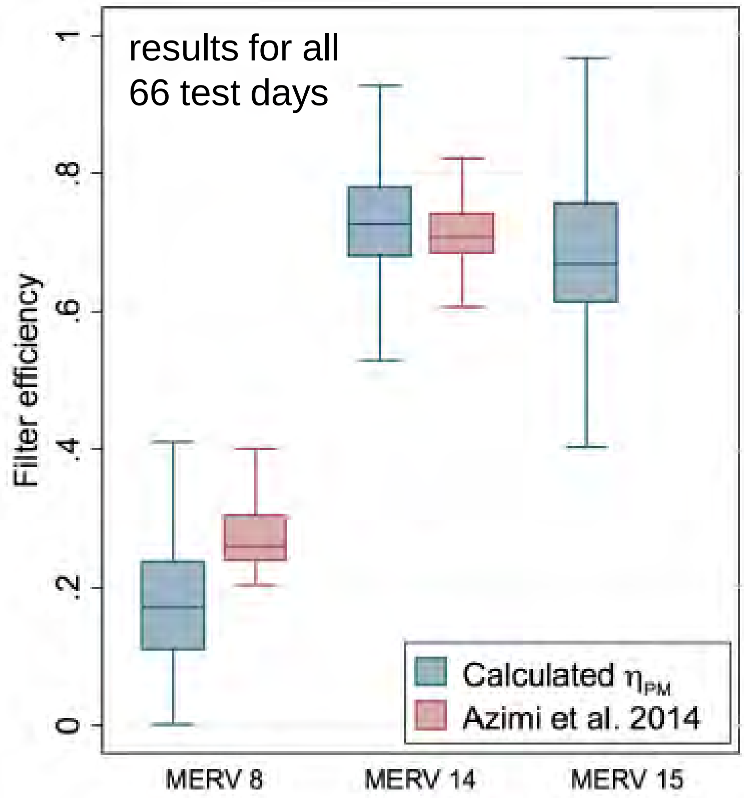
Definitions: μ_A = arithmetic mean; σ_A = arithmetic standard deviation; GM = geometric mean; GSD = geometric standard deviation; LN = lognormal; N_{tot} = total number of observations; N_{net} = number of observations after removing outliers; p5 – p95 = 5^{th} – 95^{th} percentiles

Results: Filter efficiency, $PM_{2.5}$

- $PM_{2.5}$ filter efficiency calculated at each time step for each filter
  - MERV 8 and MERV 14 were compared to estimated in Azimi et al. (2014)
  - Table and plot of efficiency by filter, over all VRs together:

Efficiency followed a normal distribution:

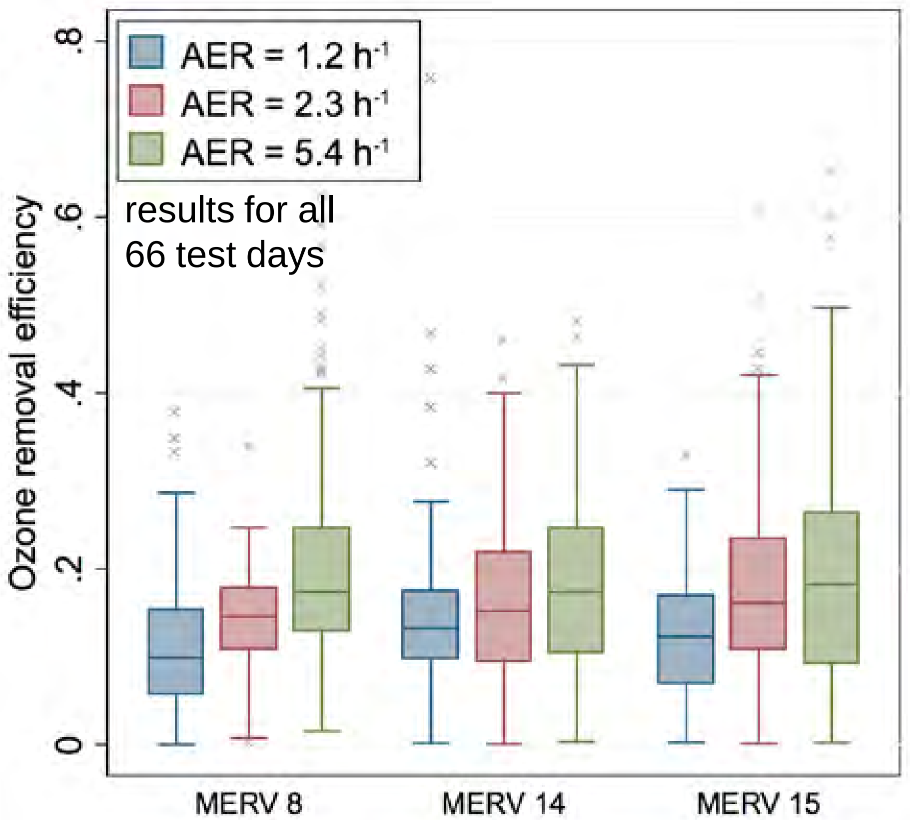
Filter	Mean	SD	Median
MERV 8	0.18	0.096	0.17
MERV 14	0.74	0.090	0.73
MERV 15	0.68	0.14	0.70



Results: Filter efficiency, O_3

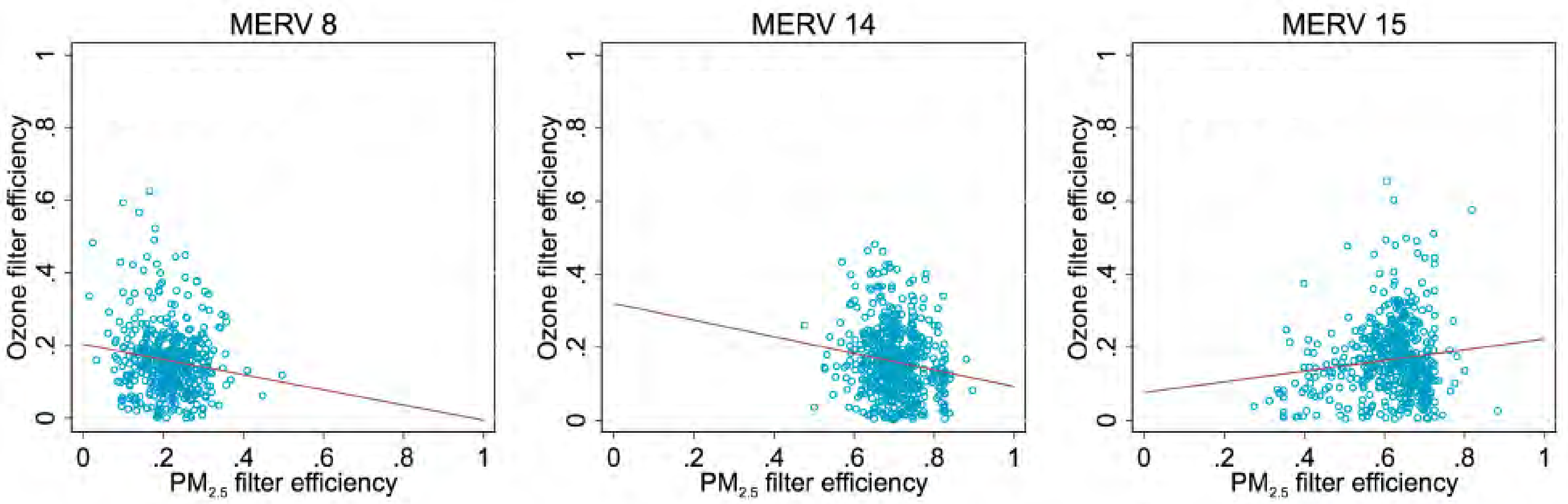
- O_3 filter efficiency calculated at each time step for each filter
  - Plot of efficiency by filter, for VRs individually:

- Observations:
  - Removal efficiency independent of filter MERV
  - Removal efficiency slightly increases with ventilation
  - Efficiency followed a normal distribution, with:
    - Mean = 0.16, SD = 0.099



Results: Filter efficiency, O_3 vs. $PM_{2.5}$

- $PM_{2.5}$ and O_3 filter removal efficiency were compared:



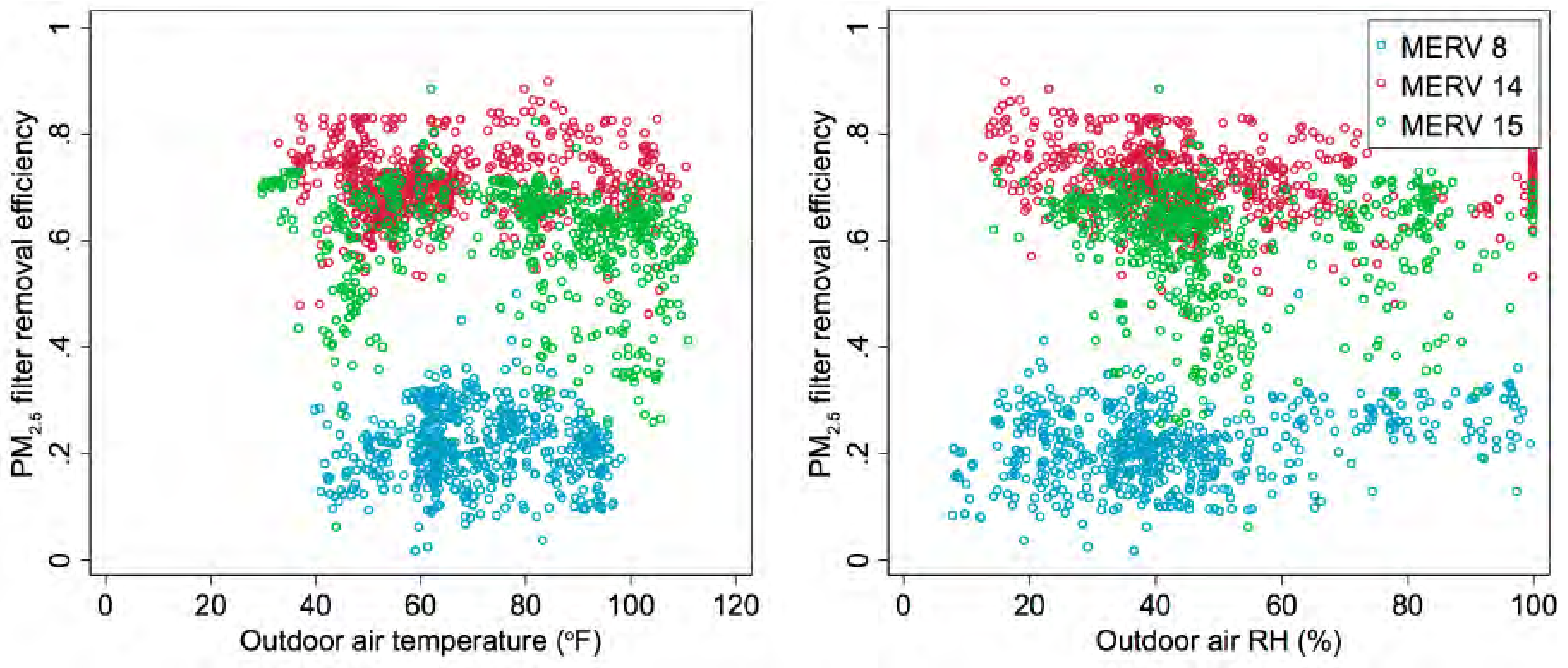
Ozone removal and $PM_{2.5}$ filter removal efficiency appear to be mostly independent of each other

Research Objective 3:

Does filter removal efficiency correlate with environmental or fan parameters?

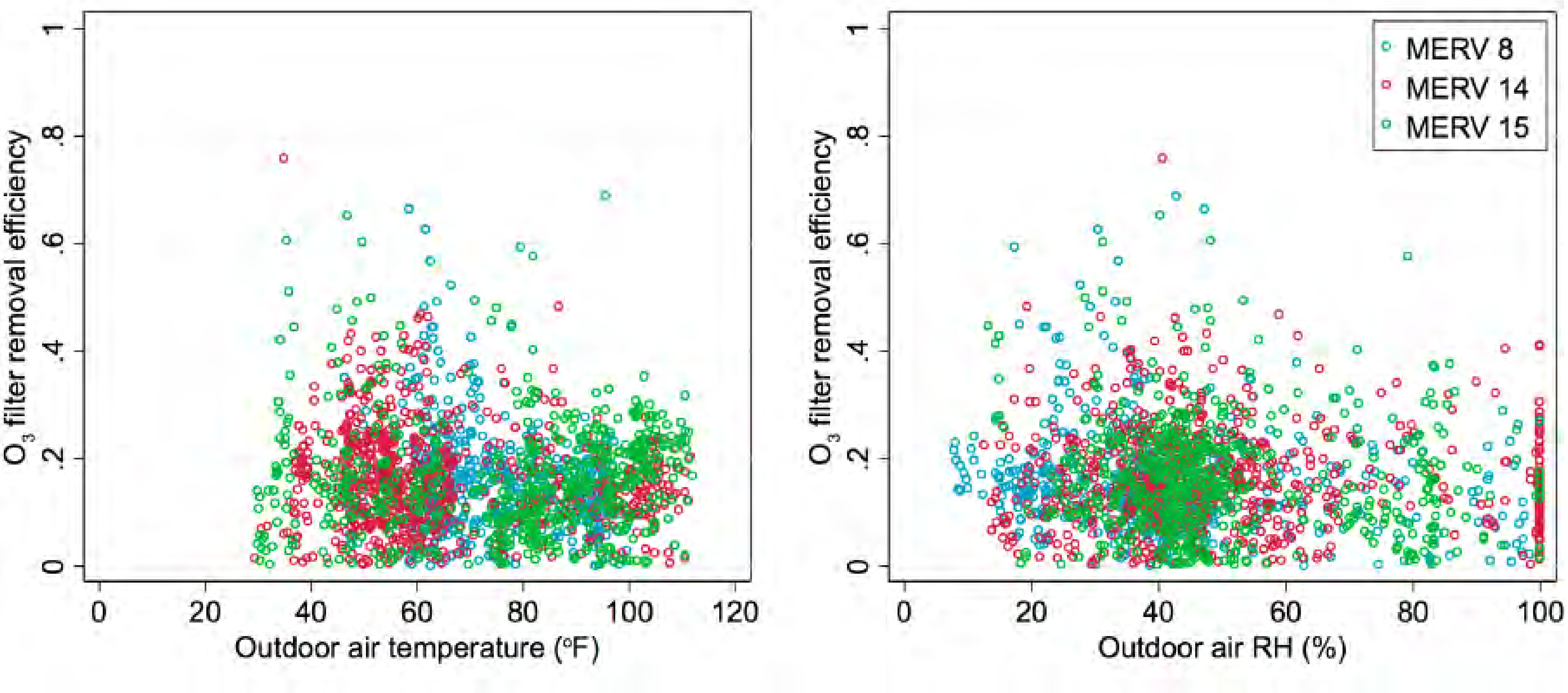
Results: Efficiency dependence

- $PM_{2.5}$ filter efficiency did NOT depend on OA temperature or RH:



Results: Efficiency dependence

- O_3 filter efficiency did NOT depend on OA temperature or RH:



Results: Efficiency dependence

- Fan power did NOT depend on filter MERV:

	SA fan power (kW)		RA fan power (kW)	
	Mean	SD	Mean	SD
MERV 8	3.93	0.626	0.999	0.0919
MERV 14	3.97	0.300	0.994	0.0601
MERV 15	3.92	0.249	0.982	0.0509

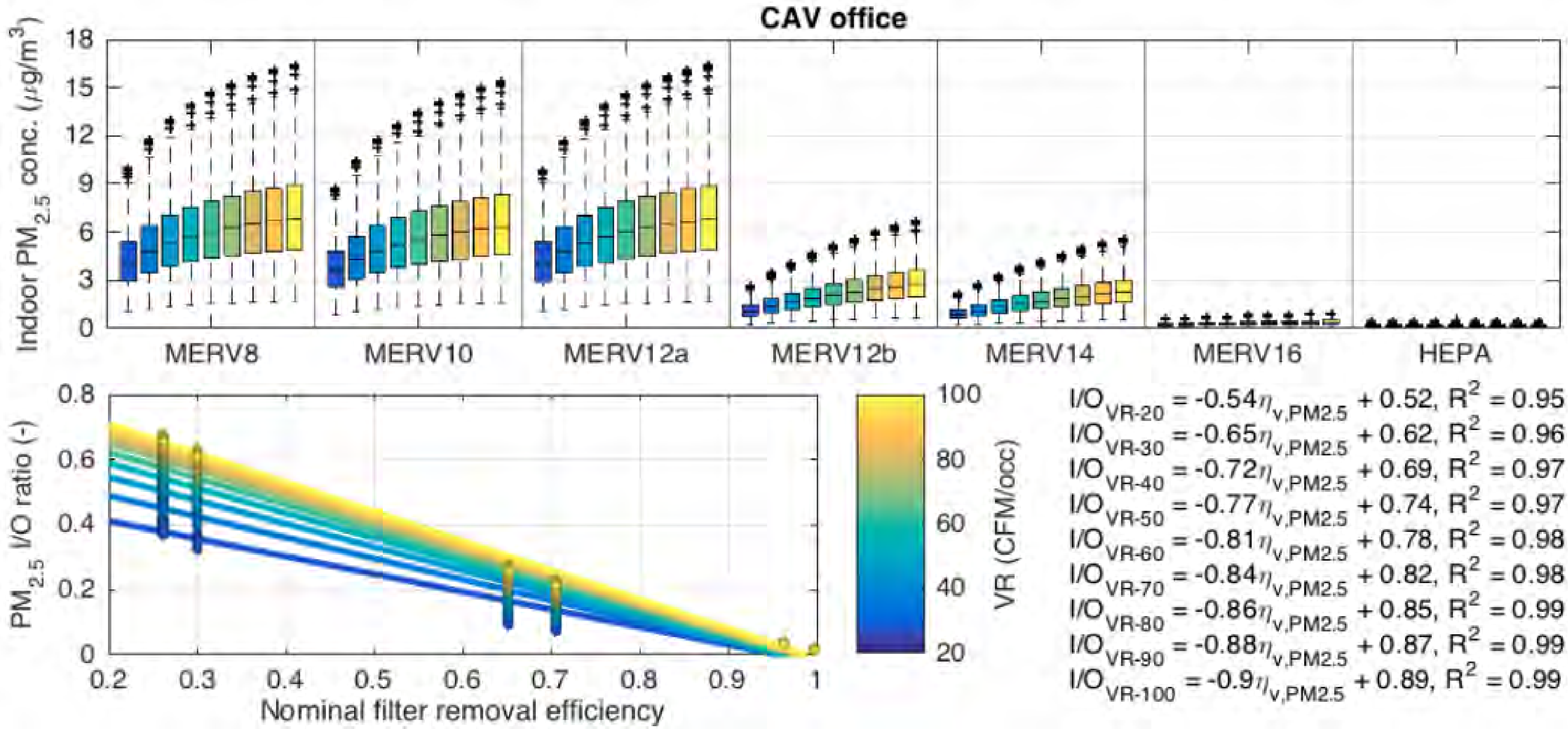
- Also, there was no association with flow rates and MERV (not shown)

Modeling Research:

Similar questions were investigated with a simulation study

Simulation Summary

- Quantified **ventilation and filtration impact** on $PM_{2.5}$ concentration
  - Office simulated in 15 locations with differing pollution and climate
  - Seven different filters: MERV 8, 10, 12a, 12b, 14, 16, HEPA
  - Nine different VRs: 20 to 100 L/s/person



Simulation Summary

- A cost function was developed that accounted for costs of:
  - Ventilation and fan energy use
  - Health impacts due to IAQ exposures
  - Filter replacement and installation

- Results showed that:
  - Cost of filter and due to pressure drop were minimal comparatively
  - IAQ exposure costs ($PM_{2.5}$) were much higher than ventilation costs
  - Improving filtration had a significant reducing effect on cost function
  - At higher VRs, filtration appeared to become more efficacious
  - When paired together, high ventilation rates and high filter efficiency can work together to provide good IAQ

Comparison of results

- Measured I/O ratios were compared to simulated results:

Pollutants	Ventilation	Measured	Simulated
PM under MERV 8	1.2 h^{-1}	0.354	0.503
	2.3 h^{-1}	0.425	0.611
PM under MERV 14	1.2 h^{-1}	0.117	0.119
	2.3 h^{-1}	0.210	0.176
Ozone	1.2 h^{-1}	0.485	0.263
	2.3 h^{-1}	0.501	0.396

  - MERV 8, measured $PM_{2.5}$ I/O ratio is a factor of 0.70 of simulated
  - MERV 14, measured $PM_{2.5}$ I/O ratio is a factor of 1.1 of simulated
  - Measured O_3 I/O ratio is a factor of 1.6 of simulated

Major conclusions

- Filters protect against $PM_{2.5}$ in high ventilation rate (VR) buildings:
  - High efficiency filters led to low $PM_{2.5}$ I/O ratios at high VRs
  - MERV 14 and 15 I/O ratios at highest VR < MERV 8 I/O ratios at lowest VR
- Real-time efficiency values behave as expected; e.g. for $PM_{2.5}$:

Filter	Mean	SD	Median
MERV 8	0.18	0.096	0.17
MERV 14	0.74	0.090	0.73
MERV 15	0.68	0.14	0.70

Similar to Azimi et al. (2014) calculated efficiency values

- Correlations:
  - $PM_{2.5}$ and O_3 filter efficiencies had no correlation
  - $PM_{2.5}$ and O_3 filter efficiencies did not correlate with OA temperature or RH
  - O_3 removal efficiency was independent of the filter

References

- Azimi, P. and Stephens, B. (2013) HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs, *Build. Environ.*, 70, 150–160.
- Azimi, P., Zhao, D. and Stephens, B. (2014) Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin, *Atmos. Environ.*, 98, 337–346.
- Ben-David, T., Rackes, A. and Waring, M.S. (2017) Alternative ventilation strategies in U.S. offices: Saving energy while enhancing work performance, reducing absenteeism, and considering outdoor pollutant exposure tradeoffs, *Build. Environ.*, 116, 140–157.
- Burnett, R.T., Cakmak, S., Brook, J.R. and Krewski, D. (1997) The role of particulate size and chemistry in the association between summertime ambient air pollution and hospitalization for cardiorespiratory diseases., *Environ. Health Perspect.*, 105, 614.
- Carrer, P., Wargocki, P., Fanetti, A., Bischof, W., De Oliveira Fernandes, E., Hartmann, T., Kephalopoulos, S., Palkonen, S. and Seppänen, O. (2015) What does the scientific literature tell us about the ventilation–health relationship in public and residential buildings?, *Build. Environ.*, 94, Part 1, 273–286.
- Dutton, S.M., Banks, D., Brunswick, S.L. and Fisk, W.J. (2013) Health and economic implications of natural ventilation in California offices, *Build. Environ.*, 67, 34–45.

References

- Jenkins, P.L., Phillips, T.J., Mulberg, E.J. and Hui, S.P. (1992) Fifth International Conference on Indoor Air Quality and Climate Indoor Air '90: Characterization of Indoor Air Activity patterns of Californians: Use of and proximity to indoor pollutant sources, *Atmospheric Environ. Part Gen. Top.*, **26**, 2141–2148.
- Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C. and Engelmann, W.H. (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, *J. Expo. Anal. Environ. Epidemiol.*, **11**, 231–252.
- Pope, Burnett, Thun and et al (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *JAMA*, **287**, 1132–1141.
- Pope, C.A., Burnett, R.T., Krewski, D., Jerrett, M., Shi, Y., Calle, E.E. and Thun, M.J. (2009) Cardiovascular Mortality and Exposure to Airborne Fine Particulate Matter and Cigarette Smoke Shape of the Exposure-Response Relationship, *Circulation*, **120**, 941–948.
- Seppänen, O., Fisk, W.J. and Lei, Q.H. (2006) Ventilation and performance in office work, *Indoor Air*, **16**, 28–36.
- Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T. and Weschler, C.J. (2011) Ventilation rates and health: multidisciplinary review of the scientific literature, *Indoor Air*, **21**, 191–204.
- Wei, W., Ramalho, O. and Mandin, C. (2015) Indoor air quality requirements in green building certifications, *Build. Environ.*, **92**, 10–19.

Acknowledgments

- Co-authors and research assistants:

Tom Ben-David

Sheng Wang

- Special thanks to National Air Filtration Association (NAFA) for funding this research project

Questions?