Predictions and determinants of size-resolved particle infiltration factors in single-family homes in the U.S.

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Motivation: Health effects and outdoor PM

- Epidemiological studies show associations between elevated outdoor particulate matter (PM) and adverse health effects
  - $PM_{10,}$ $PM_{2.5,}$ and ultrafine particles (UFPs, < 100 nm)

Pope et al., **2002** *JAMA*; Pope and Dockery, **2006** *JAWMA*; Miller et al., **2007** *NEJM*; Stölzel et al., **2007** *JESEE*; Andersen et al., **2010** *Eur Heart J;* Brook et al. **2010** *Circulation*; and many others

- But we spend most of our time indoors

~87% of the time on average (~69% at home) Klepeis et al., **2001** *JEAEE*

- Outdoor particles can infiltrate and persist in homes with varying efficiencies

Williams et al. **2003** *AE*; Kearney et al. **2010** *AE*; Chen and Zhao **2011** *AE*; Allen et al. **2012** *EHP*; Stephens and Siegel **2012** *Indoor Air*; Baxter et al. **2013** *JESEE*; Kearney et al. **2014** *AE*; and others

- Much of our exposure to outdoor PM often occurs indoors
  - Often at home

Meng et al., **2005** *JEAEE;* Kearney et al., **2010** *AE;* Wallace and Ott **2011** *JESEE;* MacNeill et al. **2012** *AE*; Chen et al. **2012** *Epidemiology*

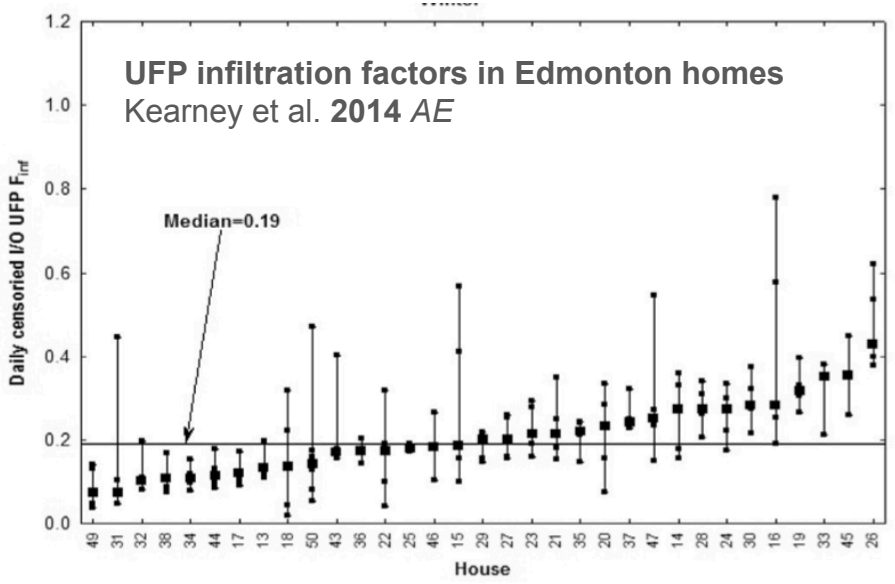
Motivation: Exposure misclassification

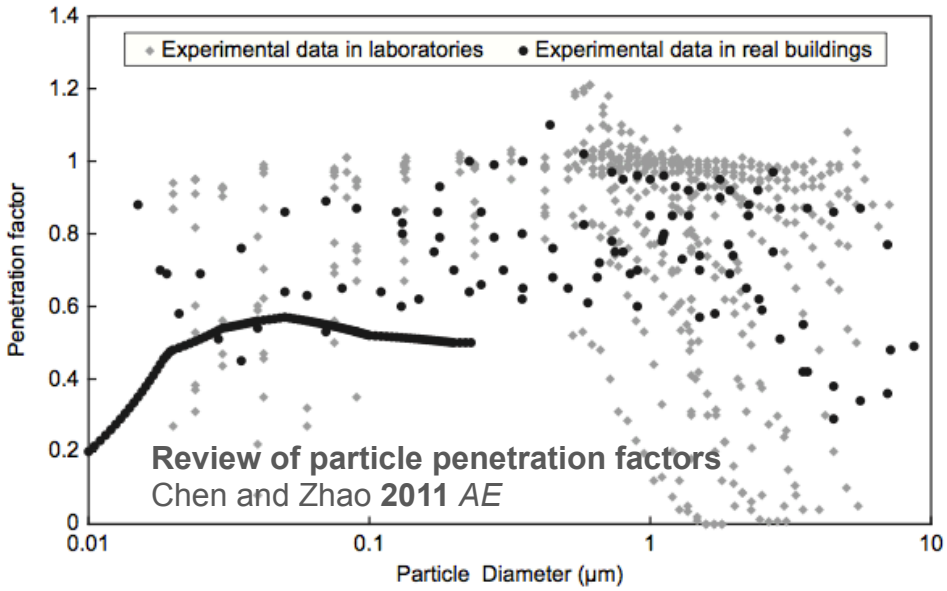
- Failing to account for differences in indoor proportions of outdoor particles can result in large exposure misclassifications

  Baxter et al. **2010** *JESEE*; Meng et al. **2005** *ES&T*; Hodas et al. **2013** *JESEE*; Baxter et al. **2013** *Air Qual Atmos Health*

- Mechanisms of particle infiltration and persistence in residences are dependent on particle size

  Liu and Nazaroff **2001** *AE*; Long et al. **2001** *ES&T;* Thatcher et al. **2003** *AS&T*; Rim et al. **2010** *ES&T*; and others



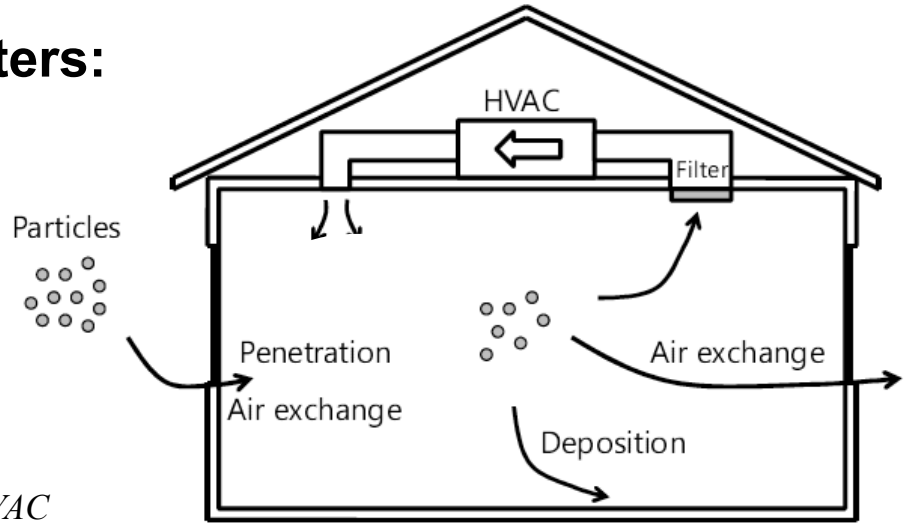


Goals of this work

- Develop and apply a Monte Carlo simulation tool to estimate the statistical distribution of long-term average size-resolved infiltration factors (F_{inf}) for particles 0.001-10 µm across the U.S. residential building stock
  - Allows for estimates of UFP and $PM_{2.5}$ as well

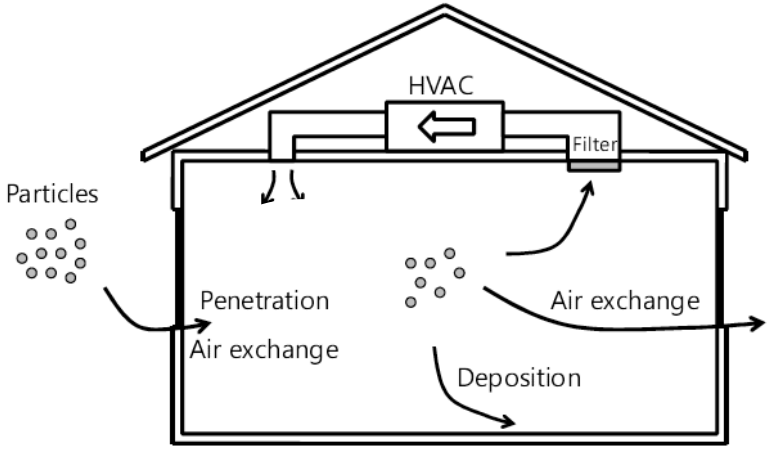
Explore influence of key parameters:

- Air exchange rate, λ
  - With and without windows open
- Particle penetration factor, P_i
  - With and without windows open
- Deposition rates, $k_{i,dep}$
- Removal by HVAC filter, $\eta_{HVAC}\lambda_{HVAC}$
  - And filter ownership
- HVAC system runtime, f_{HVAC}



$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Long-term average air exchange rates (AER, λ)

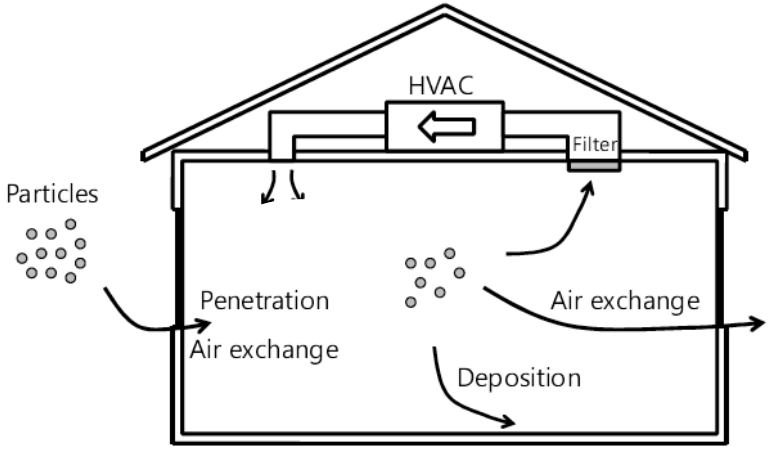
$$\lambda = \lambda_{\text{closed windows}} \left(1 - f_{\text{open windows}}\right) + \lambda_{\text{open windows}} f_{\text{open windows}}$$

$\lambda_{openwindows}$ = AER during periods of window opening (hr^{-1})

$f_{openwindows}$ = fraction of time of window opening (-)

$\lambda_{closedwindows}$ = AER during periods with closed windows (hr^{-1})

Methodology: Model framework



Long-term average size-resolved infiltration factor

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AERs with windows open

$$\lambda_{\mathrm{openwindows}} = \lambda_{\mathrm{closedwindows}} \left(\phi_{\mathrm{openwindows,low}} m_{\mathrm{openwindows,low}} + \phi_{\mathrm{openwindows,high}} m_{\mathrm{openwindows,high}} \right)$$

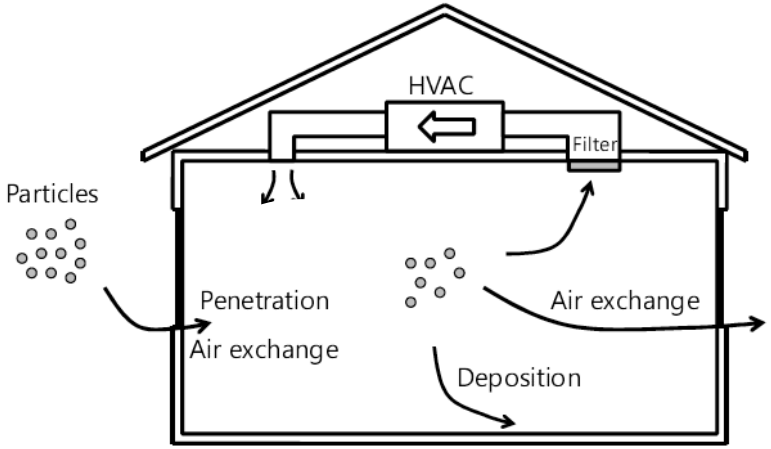
$\phi_{openwindows,low}$ = probability of low window opening (-)

$\phi_{openwindows,high}$ = probability of high window opening (-)

$m_{openwindows,low}$ = AER multiplier during low window opening (-)

$m_{openwindows,high}$ = AER multiplier during high window opening (-)

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

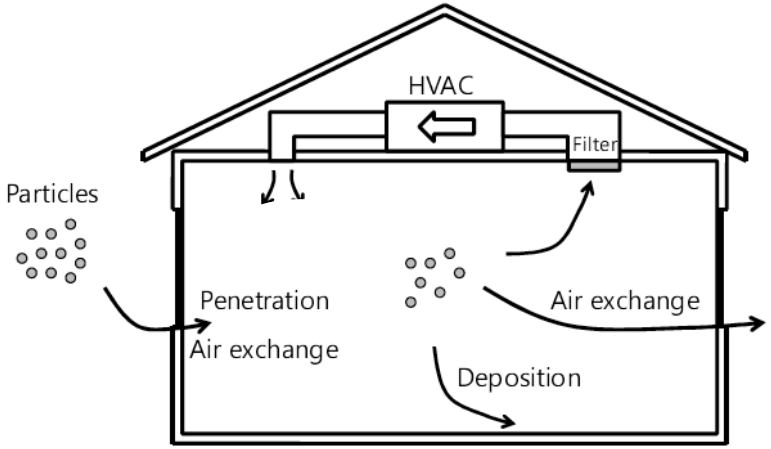
Fraction of time windows are open

$$f_{\mathrm{openwindows}} = f_{\mathrm{mild}} f_{\mathrm{openwindows,mild}}$$

f_{mild} = fraction of mild weather (-)

$f_{openwindows,mild}$ = fraction of window opening during mild weather (-)

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Long-term average size-resolved envelope penetration factors

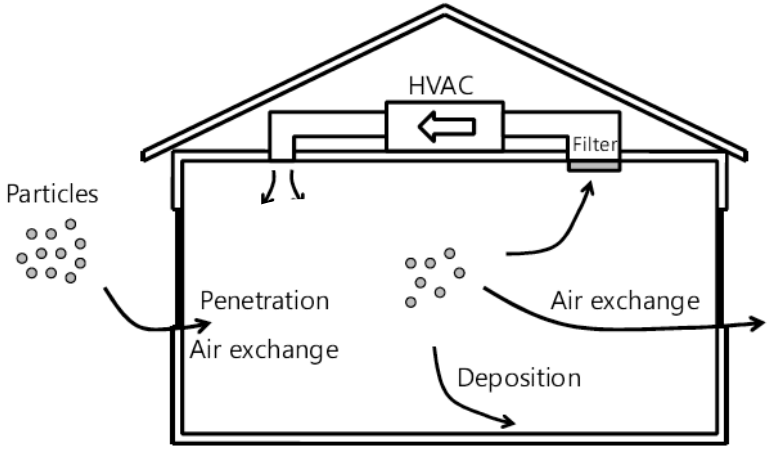
$$P_i = P_{i,\mathrm{closedwindows}} \left(1 - f_{\mathrm{openwindows}}\right) + P_{i,\mathrm{openwindows}} f_{\mathrm{openwindows}}$$

$P_{i,openwindows}$ = envelope penetration factor during periods of window opening (-)

$f_{openwindows}$ = fraction of time of window opening (-)

$P_{i,closedwindows}$ = envelope penetration factor during periods w/ closed windows (-)

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

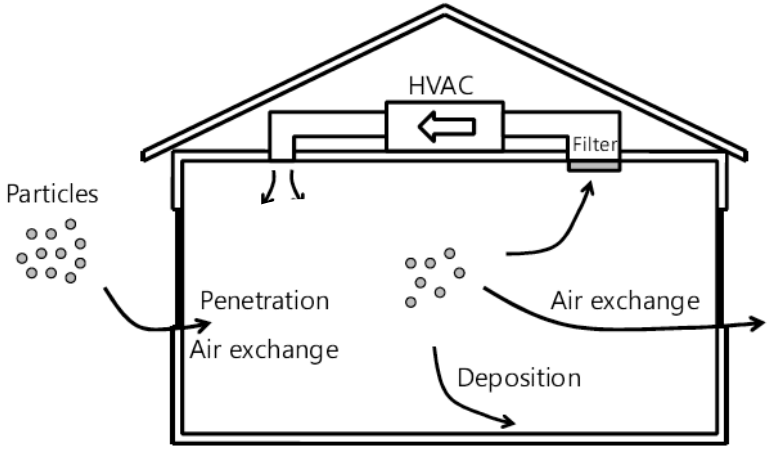
Envelope penetration factors with open windows

$$P_{i,\mathrm{openwindows}} = P_{i,\mathrm{openwindows,low}} \phi_{\mathrm{openwindows,low}} + P_{i,openwindows,high} \phi_{\mathrm{openwindows,high}}$$

$\phi_{openwindows,low}$ = probability of low window opening (-)

$\phi_{openwindows,high}$ = probability of high window opening (-)

Methodology: Model framework



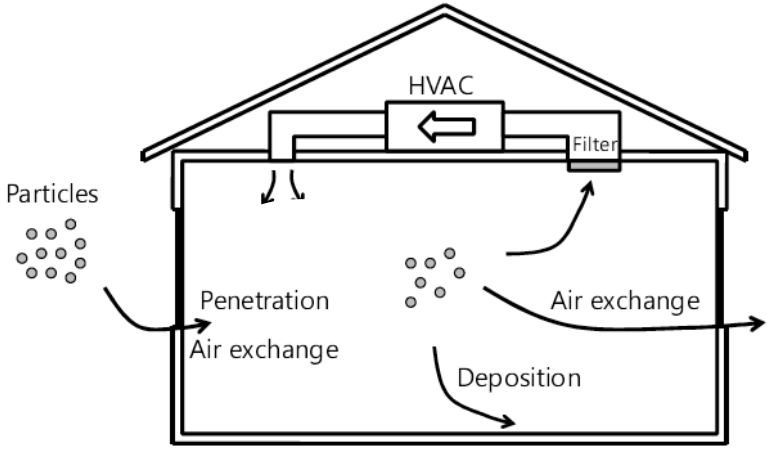
Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Envelope penetration factors with open windows (scales with AER)

$$P_{i,\mathrm{openwindows,low}} = P_{i,\mathrm{closedwindows}} \frac{\lambda_{\mathrm{closedwindows}}}{\lambda_{\mathrm{openwindows,low}}} + (1) \frac{\lambda_{\mathrm{openwindows,low}} - \lambda_{\mathrm{closedwindows}}}{\lambda_{\mathrm{openwindows,low}}}$$

Methodology: Model framework



Long-term average size-resolved infiltration factor

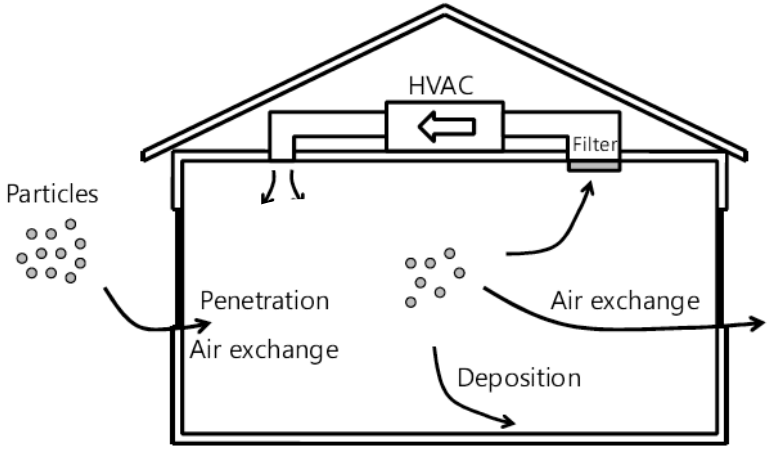
$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Long-term average size-resolved particle deposition rates

$$k_{i,\mathrm{dep}} = k_{i,\mathrm{dep,closedwindows}} \left(1 - f_{\mathrm{openwindows}}\right) + k_{i,\mathrm{dep,openwindows}} f_{\mathrm{openwindows}}$$

$$k_{i,\mathrm{dep,openwindows}} = k_{i,\mathrm{dep,openwindows,low}} \phi_{\mathrm{openwindows,low}} + k_{i,\mathrm{dep,openwindows,high}} \phi_{\mathrm{openwindows,high}}$$

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

HVAC recirculation rates, fractional operation times, and filter efficiency

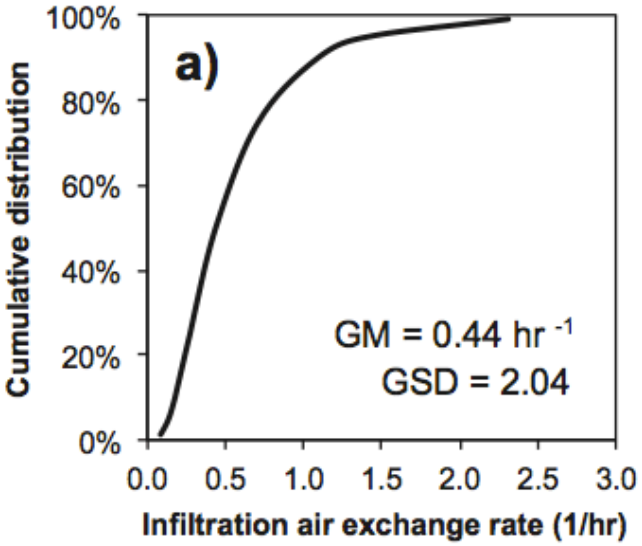
Culled directly from the literature

Methodology: Gathering input parameters

- Large literature review identified best estimates of distributions of input parameters across the US residential building stock

Infiltration AER

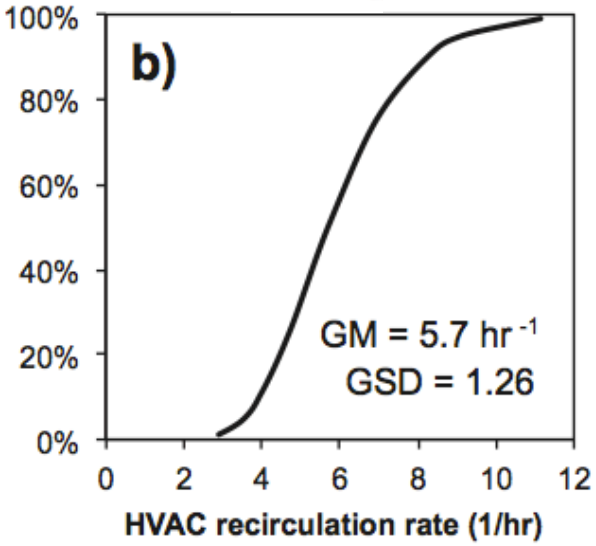
$\lambda_{closed\ windows}$



Persily et al. **2010** *Indoor Air*

Recirculation rate

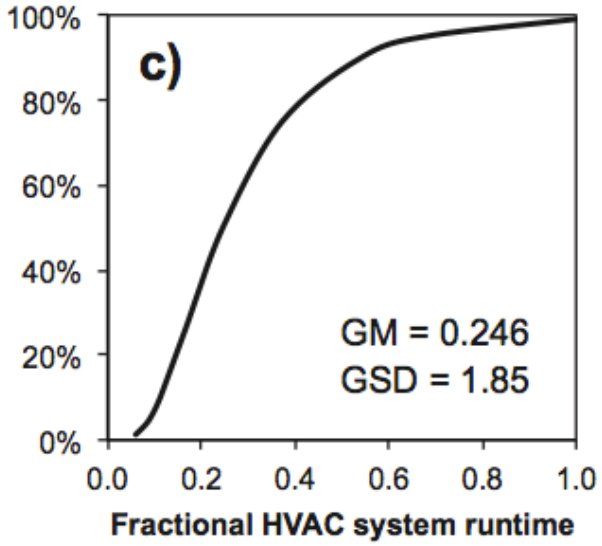
λ_{HVAC}



Stephens et al. **2011** *Build Environ*

HVAC runtime

f_{HVAC}



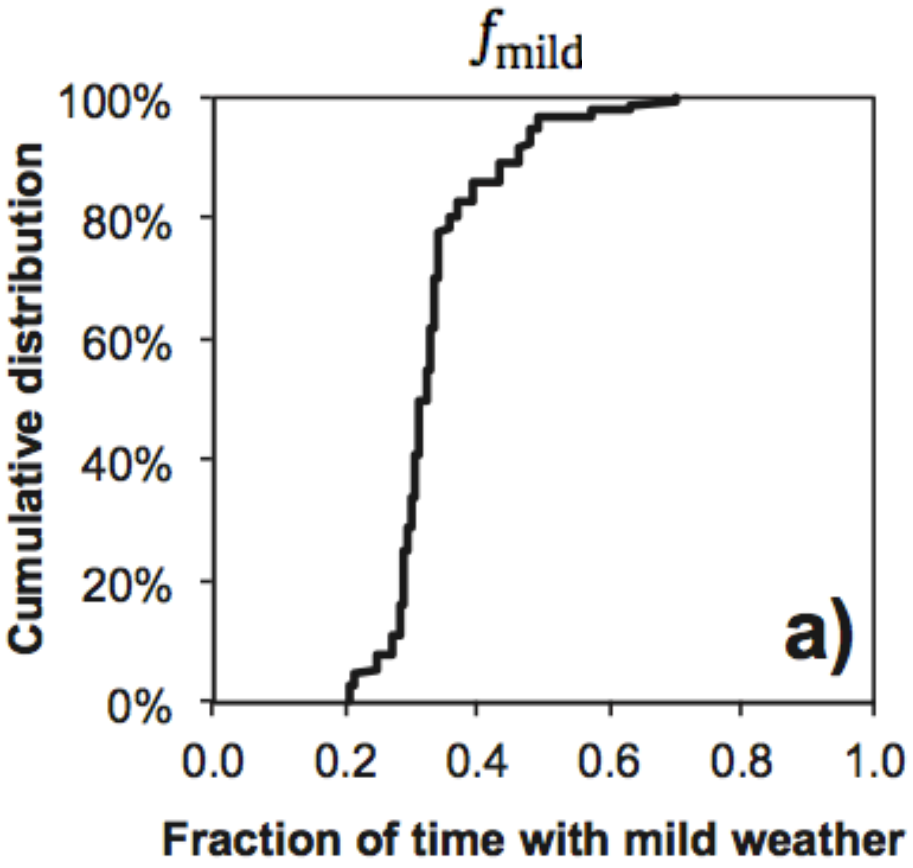
Thornburg et al. **2004** *Atmos Environ*
Stephens et al. **2011** *Build Environ*

AER multipliers:
2 when open 'low' amount
4 when open 'high' amount

Wallace et al. **2002** *JEAEE*; Marr et al. **2012** *HVAC&R Research*

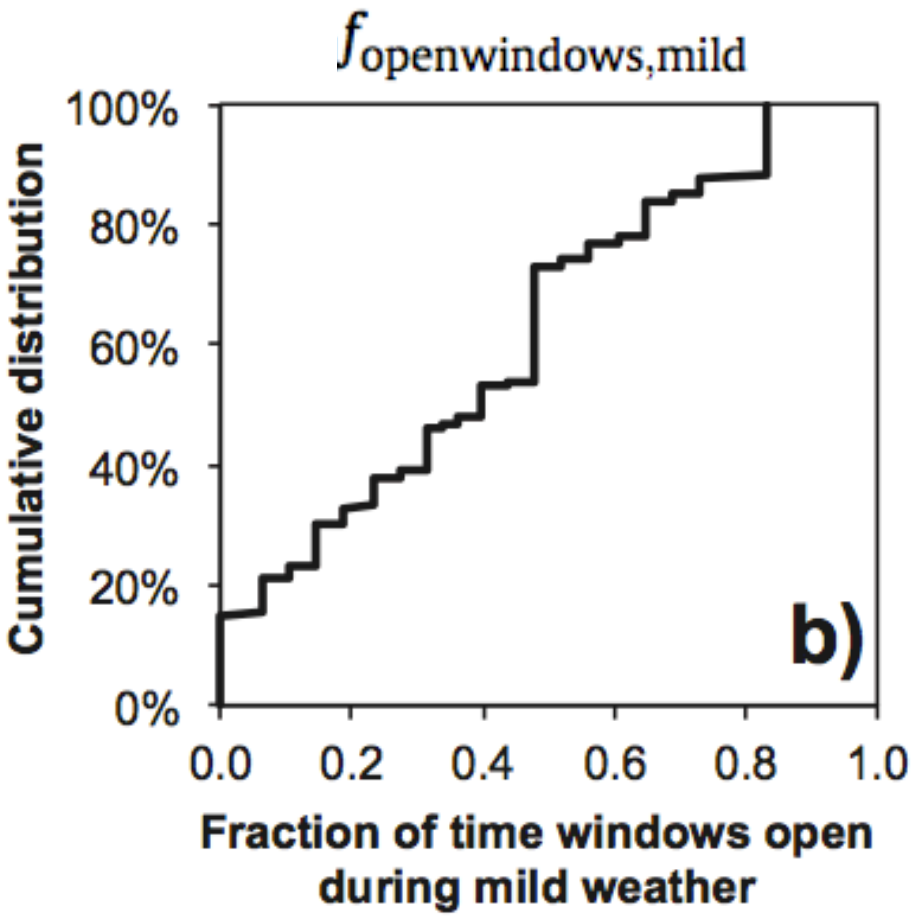
Methodology: Gathering input parameters

Fraction of mild weather



Chen et al. **2012** *Epidemiology*

Fraction of window opening during mild weather



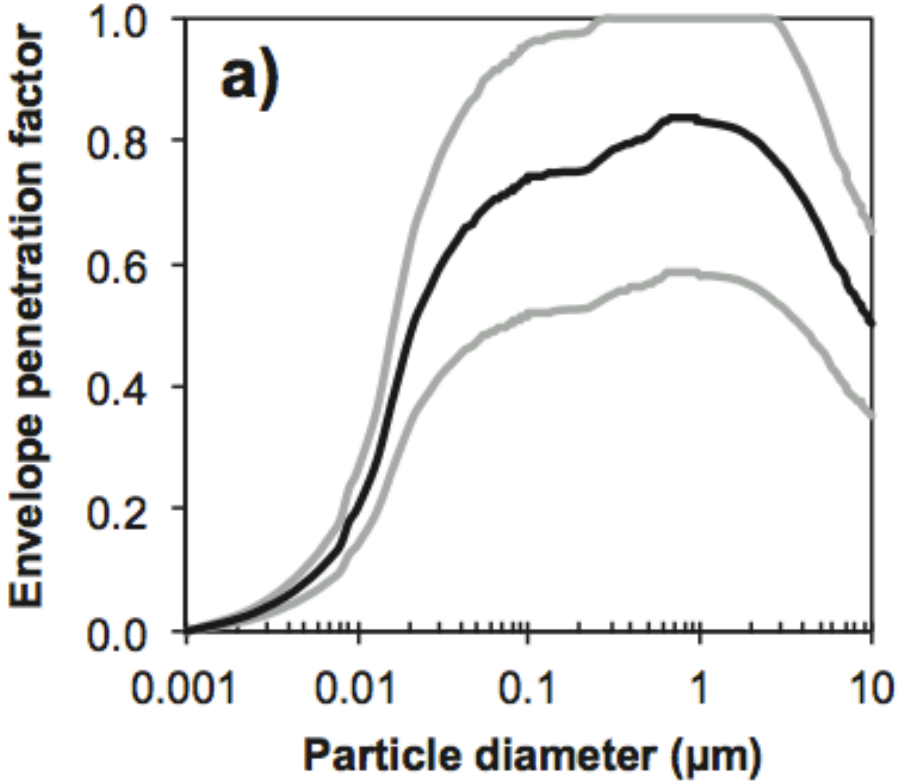
Price and Sherman **2006** *LBNL 59620*

80% open 'low' amount
20% open 'high' amount

Methodology: Gathering input parameters

Envelope penetration factor

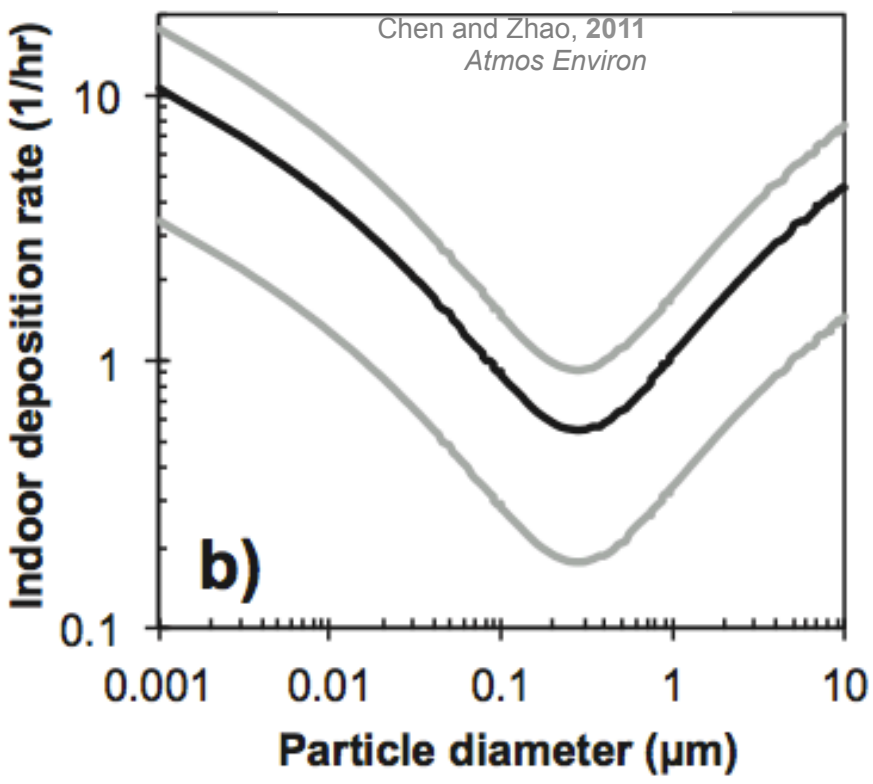
$P_{i,\text{closedwindows}}$



Chen and Zhao **2011** *Atmos Environ*
Rim et al. **2010** *Environ Sci Technol*
Stephens and Siegel **2012** *Indoor Air*
Williams et al. **2003** *Atmos Environ*

Deposition rate

$k_{i,\text{dep,closedwindows}}$



Adjusted from He et al. **2005** *Atmos Environ*

$k_{i,dep}$ multipliers:

1.2 when windows open 'low' amount

1.7 when windows open 'high' amount

He et al. **2005** & assumed to vary with AER multipliers

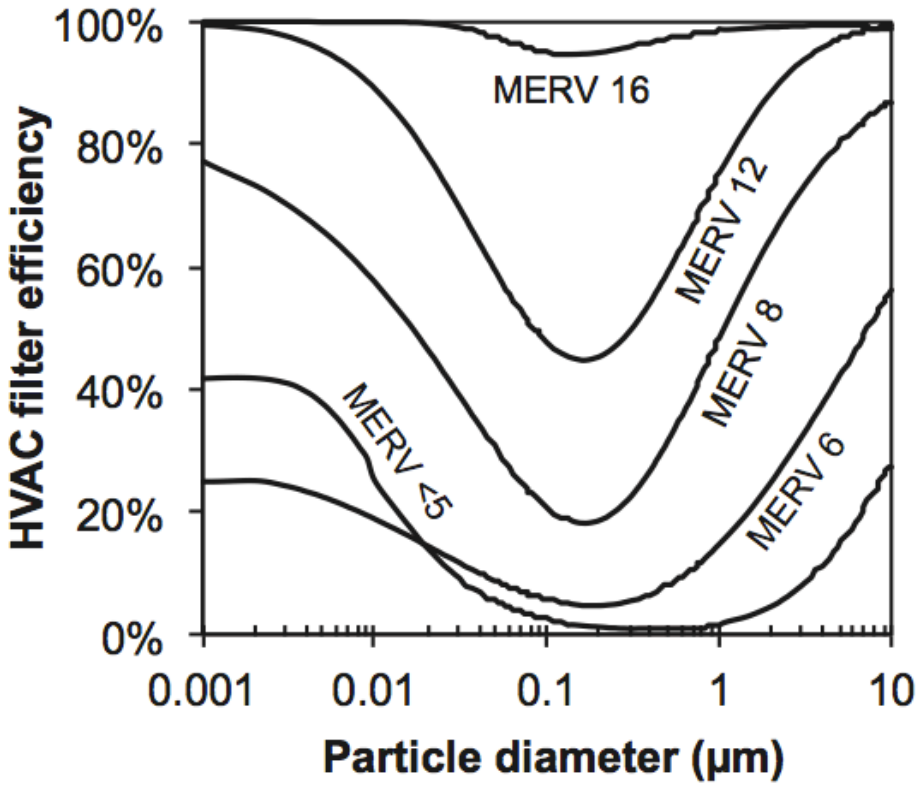
Methodology: Gathering input parameters

Estimate of HVAC filter ownership across the residential building stock (for homes with HVAC systems).

Filter type	% Ownership
MERV < 5	25%
MERV 6	30%
MERV 8	30%
MERV 12	10%
MERV 16	5%

Filter ownership

Stephens and Siegel **2012** *Indoor Air*
Offermann **2009** *CARB Report*
Anonymous filtration industry contacts



Filter efficiency

$\eta_{i,\mathrm{HVAC}}$

Hecker and Hofacre **2008** *EPA*
Waring and Siegel **2008** *Indoor Air*

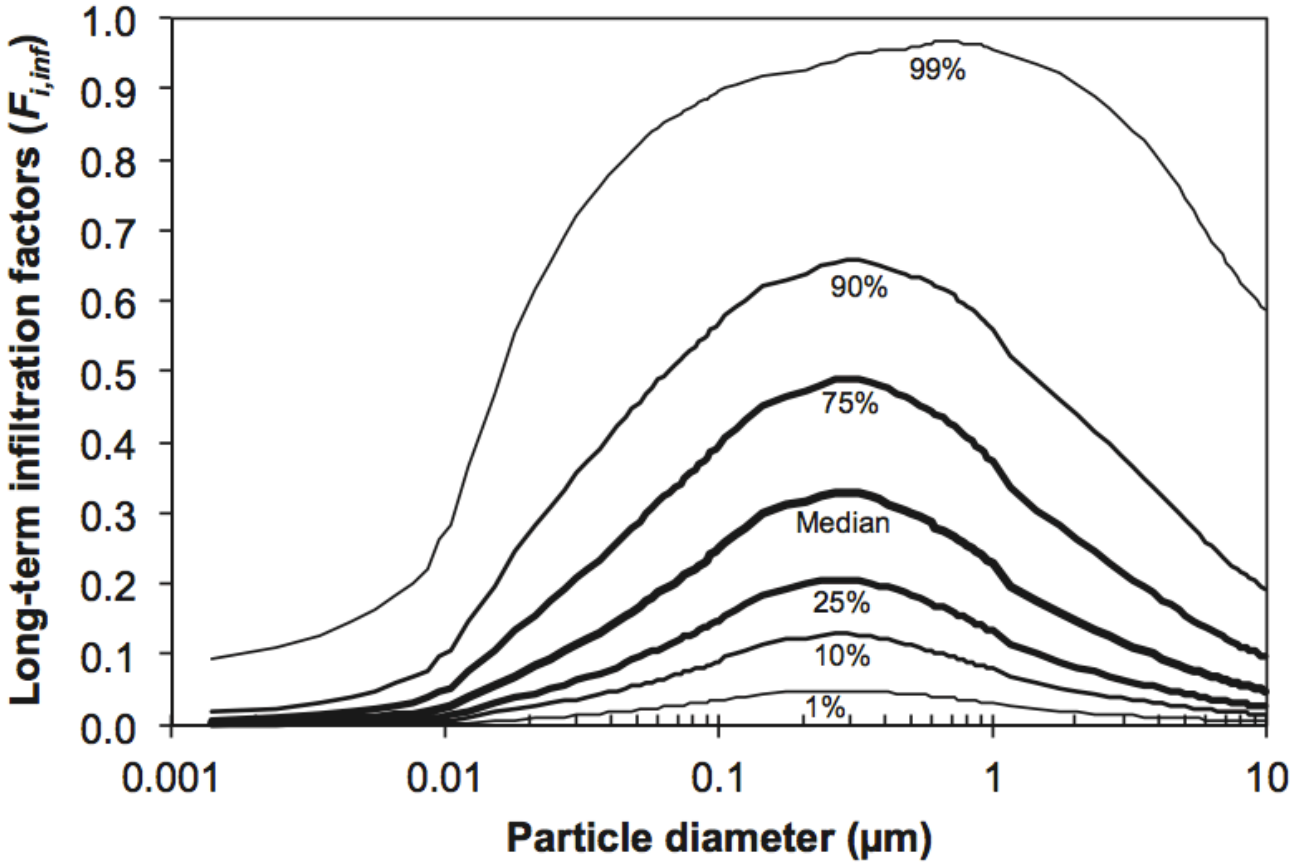
Methodology for simulations

- A Monte Carlo simulation was used to model long-term average infiltration factors for 100,000 homes across the U.S. residential building stock using these best available data for input parameters
- Long term parameters were calculated as a combination of infiltration parameters and open-window parameters
- Size-resolved simulations (0.001 to 10 μm)
- We assumed that our sample of homes was comprised of:
  - 65% of homes own HVAC systems HUD **2007**
    - Filters ranging from MERV <5 to MERV 16
  - 35% of homes without HVAC systems (no filtration) HUD **2007**

El Orch et al. **2014** *Building and Environment* 74:106–118

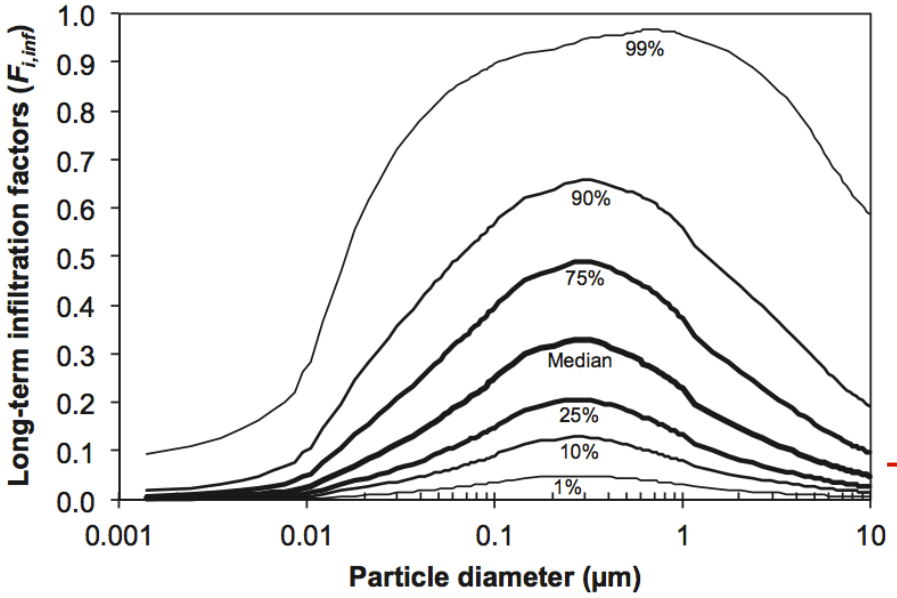
Results: Long-term average size-resolved F_{inf}

Infiltration factors were predicted to be 20-100 higher in the most protective homes (1st percentile) vs. the least protective homes (99th percentile)

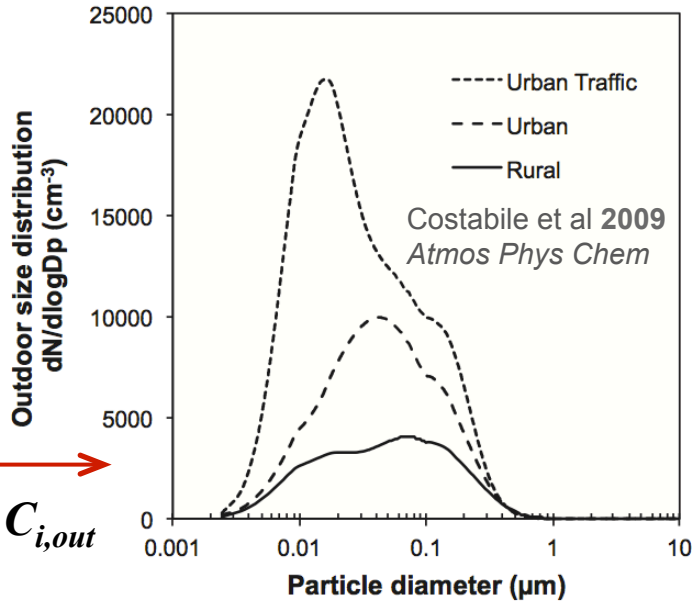


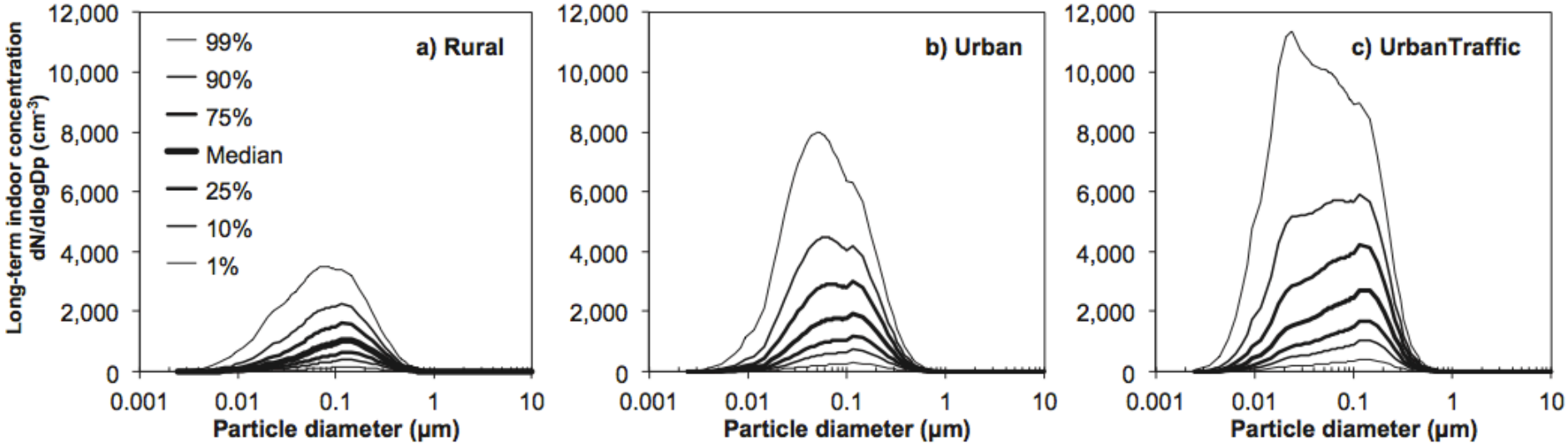
El Orch et al. **2014** *Building and Environment* 74:106–118

Results: Mapping to outdoor size distributions



$$C_{i,in} = F_{i,inf} \times C_{i,out}$$





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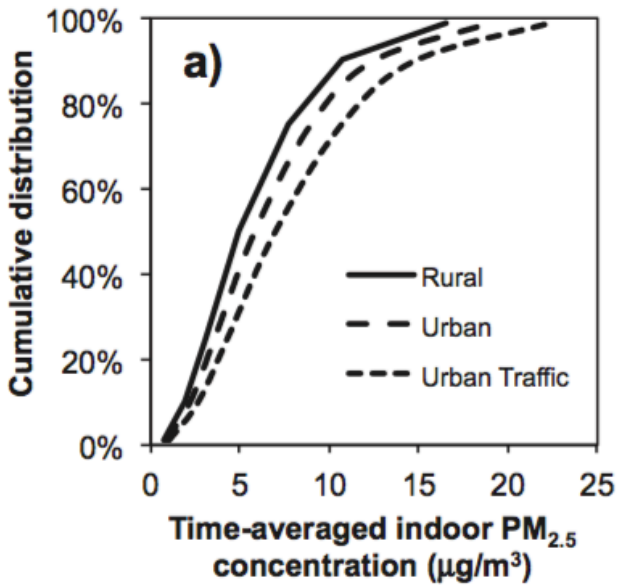
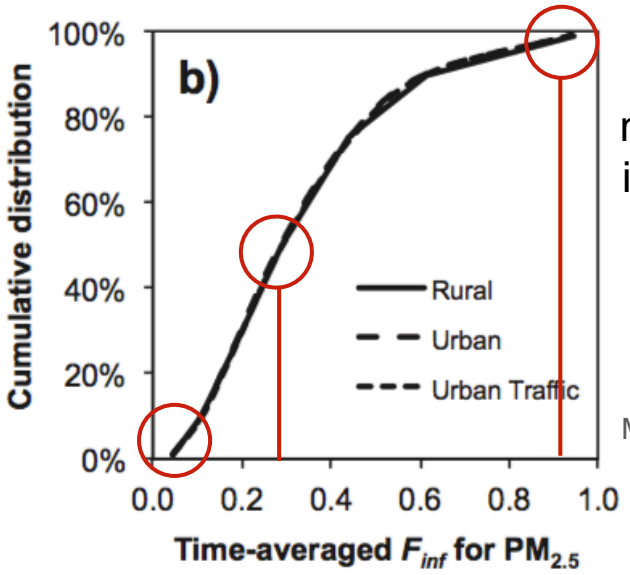
Results: Predicting CDFs of UFPs and $PM_{2.5}$

$PM_{2.5}$

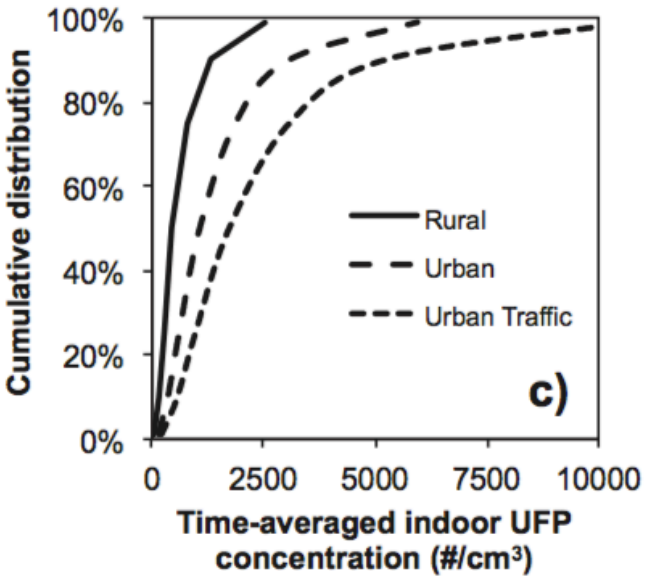


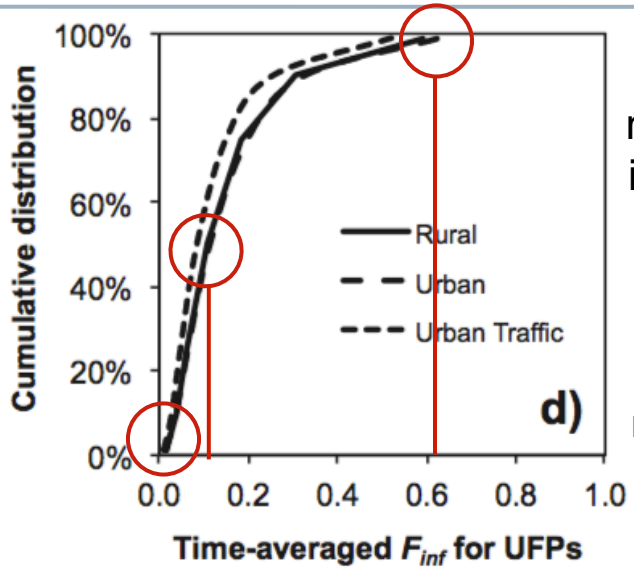


In line w/ measurements in Windsor ON
Range: 0.04-1.0
Median: 0.26-0.36

MacNeill et al. **2012** *AE*

UFPs (< 100 nm)





In line w/ measurements in Windsor ON
Range: 0.03-0.9
Median: 0.19-0.27

Kearney et al. **2011** *AE*

El Orch et al. **2014** *Building and Environment* 74:106–118

Results: Multiple linear regression for influential factors

Multiple linear regression (MLR):

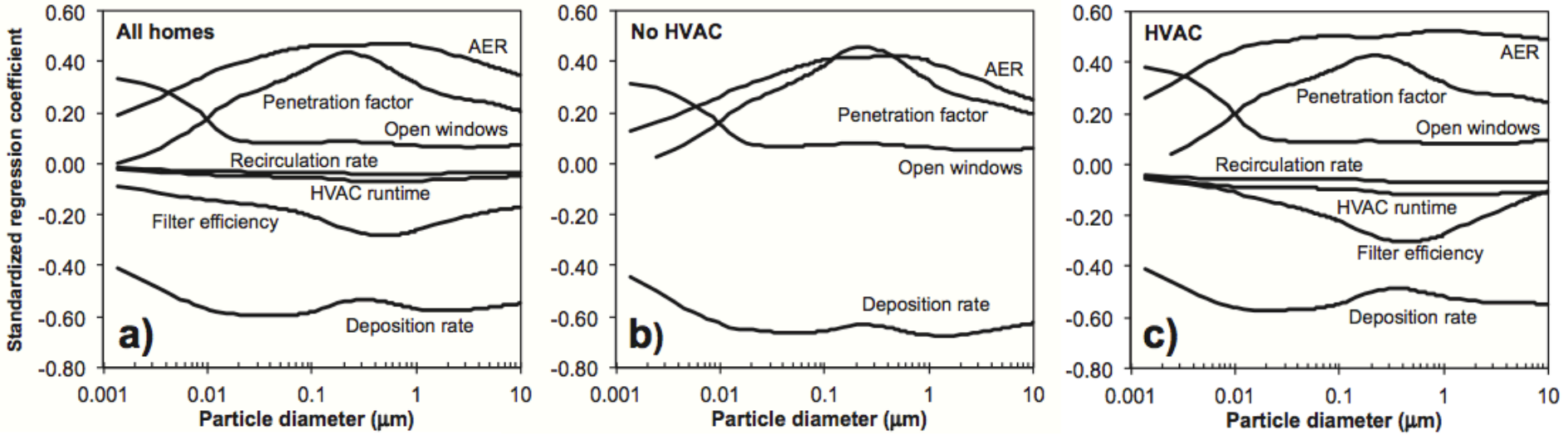
$$F_{i,\mathrm{inf}} = \beta_0 + \beta_1\lambda_{\mathrm{closedwindows}} + \beta_2 f_{\mathrm{openwindows}} + \beta_3 f_{\mathrm{HVAC}} + \beta_4\lambda_{\mathrm{HVAC}} + \beta_5\eta_{i,\mathrm{HVAC}} + \beta_6 k_{i,\mathrm{dep,closedwindows}} + \beta_7 P_{i,\mathrm{closedwindows}}$$

Largest influences

① Closed-window deposition rates
② Closed-window AER
③ Closed-window penetration factor
④ HVAC filter efficiency

Model R^2 values ranged 0.35 to 0.79 depending on particle size

Size-resolved standardized regression coefficients (SRCs):

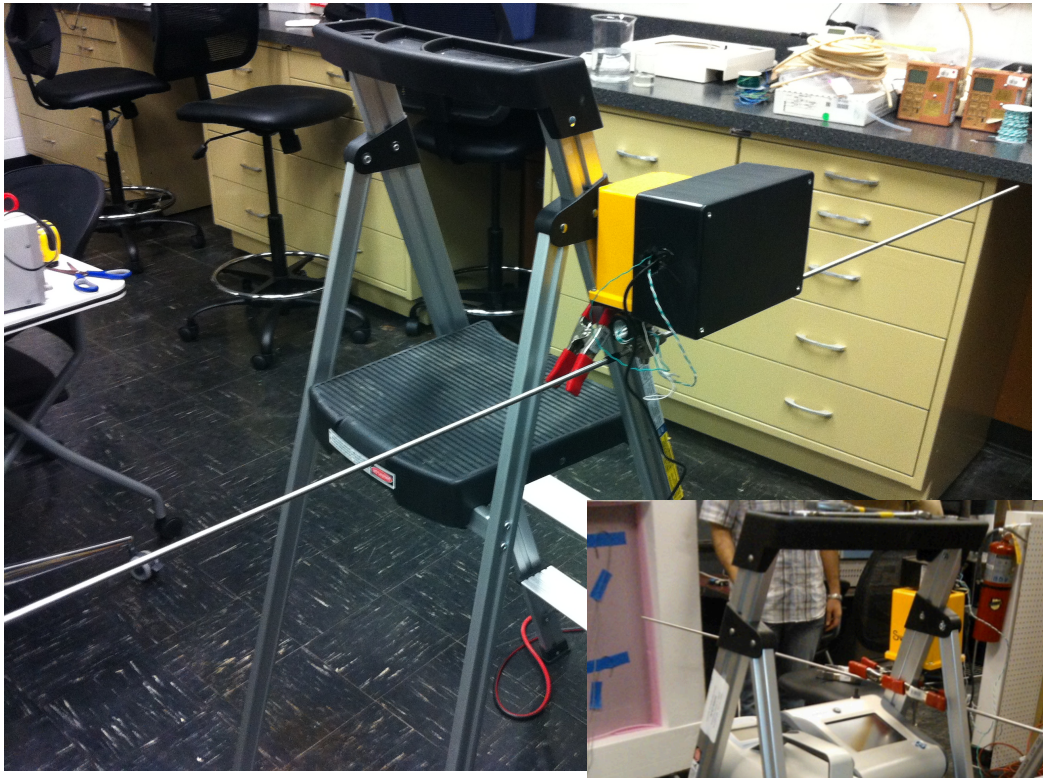


El Orch et al. **2014** *Building and Environment* 74:106–118

Limitations and future research

- Need more accurate measurements of the important predictors in a larger number and variety of buildings
  - Size-resolved deposition loss rate coefficients and penetration factors
- Need more accurate distributions of HVAC system runtimes, filter efficiencies, filter ownership, and window opening behaviors
- Need more information about U.S. outdoor particle size distributions (PSDs)
  - Although PSDs may not have a large impact on F_{inf} for UFPs/$PM_{2.5}$
- Need to incorporate indoor sources into the Monte Carlo model
  - Can also extend this approach to model inhalation exposures and doses with different individuals with different human activity patterns
- Need more information on correlations between input parameters in order to incorporate and improve this model
  - e.g. envelope penetration factors and long-term average AERs

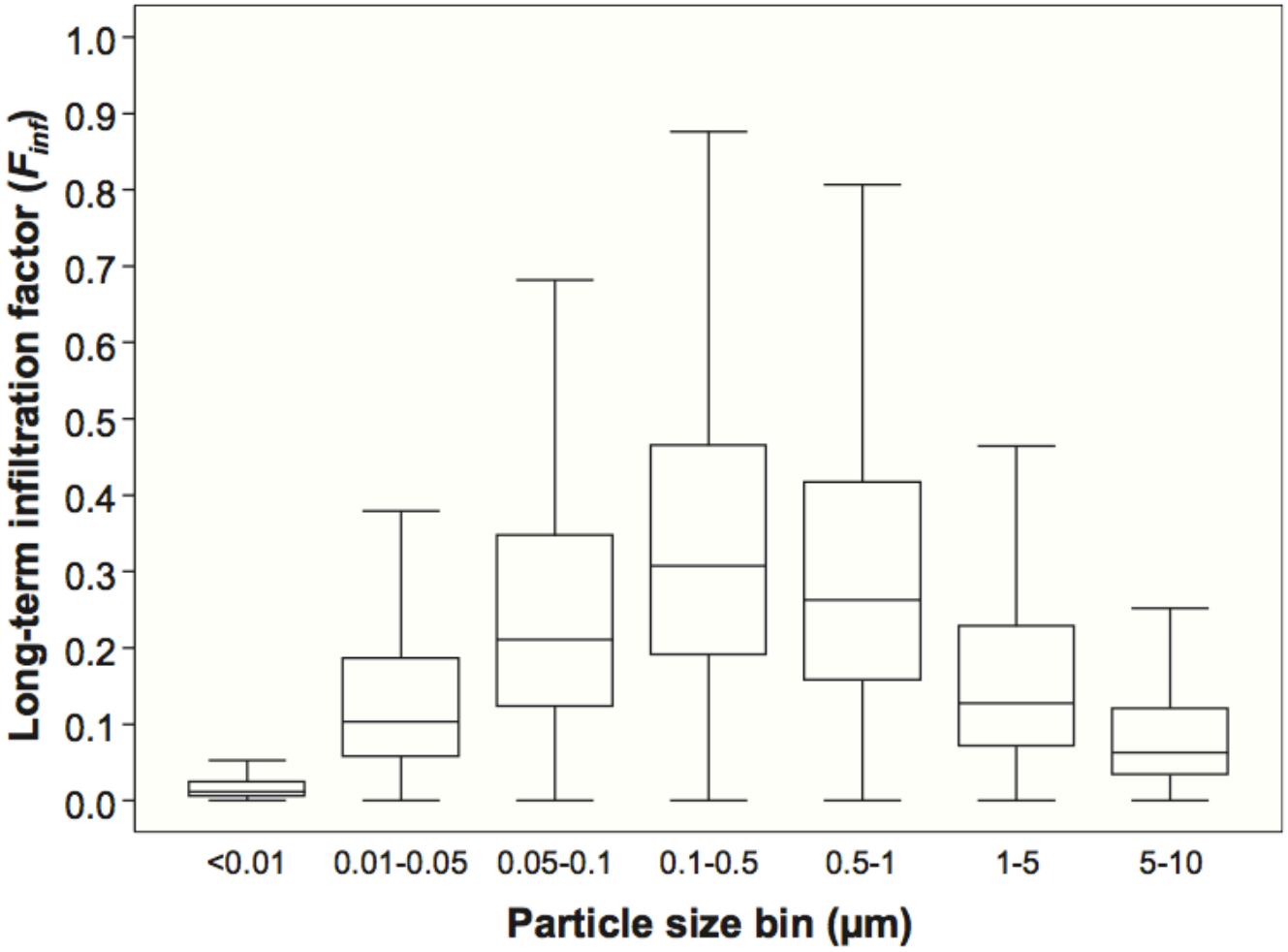
Next steps: PM infiltration measurements in Chicago



Question/comments

web: www.built-envi.com
twitter: @built_envi
email: brent@iit.edu

Results: Long-term average binned F_{inf}



UFP estimates generally in line with measurements in Kearney et al. 2011 *Atmos Environ*: 0.03-0.9, median of 0.19-0.27, and others

El Orch et al. **2014** *Building and Environment* 74:106–118