Workshop on Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches

The Utility, Use, and Misuse of Low-Cost Consumer Indoor Particulate Matter Sensors

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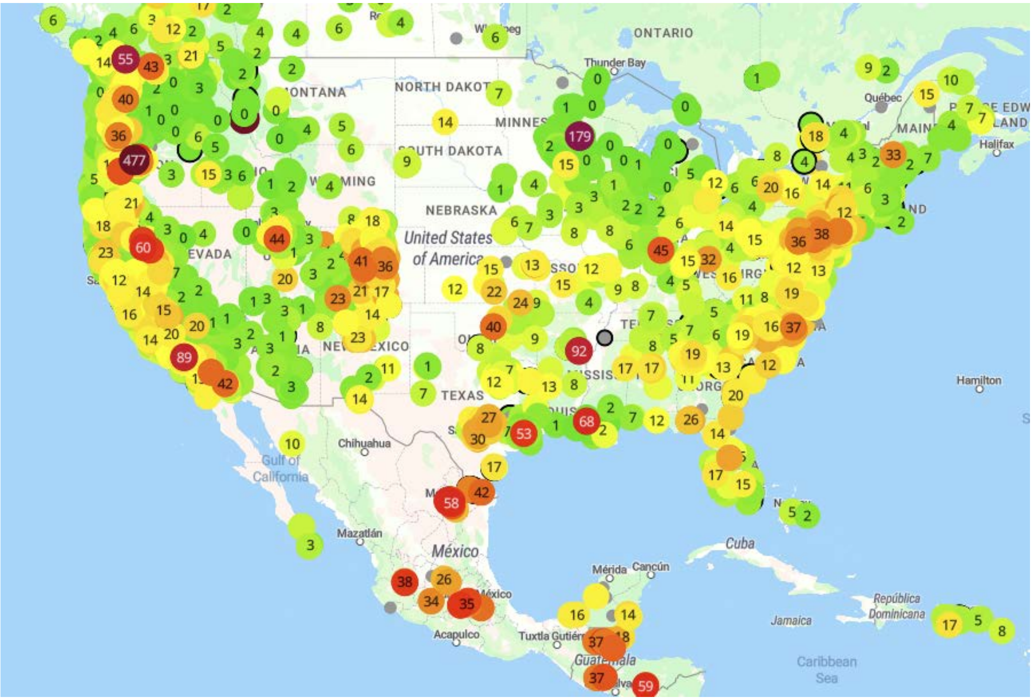
Human-Oriented Built Environment Lab
Website: hobel.epfl.ch
Twitter: @licinadusan

Asst. Prof. Dusan Licina, Ph.D.
School of Architecture, Civil and Environmental Engineering
École polytechnique fédérale de Lausanne
dusan.licina@epfl.ch

A few (important) caveats on low-cost sensing of indoor PM

- Recent & rapidly growing field (majority of papers dates from the past 5 years)
- More research available for low cost sensors for outdoor PM monitoring
- PM monitoring networks primarily established for outdoors



www.purpleair.com

Snapshot of $PM_{2.5}$ concentration in the US ($\mu g/m^3$)

Definitions

- **Reference instrument**: associated with a reference method (FRM, FEM), but can also be a “lab-grade” instrument

- **Monitor**: an integrated device that comprises at least sensor other supporting components needed to create a fully functional air quality data collection system

airmet.com.au

- **Sensor**: sub-component of a monitor that detects particles

sensirion.ch

- **Low vs. high cost**:
  - High-cost, lab-grade: typical range 3’000-50’000 USD
  - Low-cost monitor: typical range 100-500 USD (median ~200 USD)
  - Low-cost PM sensor: typical range 1-100 USD

Framework for the utilization of low-cost indoor PM sensors

SENSORS & MONITORS → **DEPLOYMENT** → **DATA** → **OUTCOMES**

Selection; Assessment
- ✓ Lab-based
- ✓ Field

Individual; Network
- ✓ Stationary
- ✓ Mobile
- ✓ Wearable

Exploration; Storage/security; Analysis; Communication

New knowledge; Feedback to user; Automated control

Assessment of low-cost PM sensors and monitors

- About 10% of studies made reference to published protocols
  - Researchers typically adopt their own protocol for assessment of sensors and monitors
  - Variable judgement criteria for “good enough”

Morawska et al. 2018 Environ Int 118: 286-299

- Methods differ in:
  - Duration of testing (short >> long)
  - Measurement environments (lab >> field)
  - Number of replicate technologies
  - Reference method utilized

Studies	Foobot/Reference
Moreno-R. et al. 2018, *JSSS*	1.23 -1.43
Demanega et al. 2021, *BAE*	0.57
Singer and Delp, 2018, *Indoor Air*	0.53 - 0.63

Typical performance indicators:

- Comparison with reference measurements
- Repeatability & reproducibility
- Limit of detection (LOD)
- Dependence on particle size and composition
- Dependence on indoor climate

Comparison with reference measurements

- Generally high degree of correlation with reference measurements: $R^2 > 0.5$
- In the lab, low-cost PM sensors typically perform much better ($R^2 > 0.8$)
  - **Lab:** sensors report time-averaged concentration within 50-200% from the reference (for $PM_{2.5}$)
  - **Field:** sensors suffer significant response factor changes

Demanega et al. 2021, BAE 107415

Lab vs field:

- Lab: Difficult to maintain a low PM concentration during long time
- Lab: Composition and concentration of the test aerosol may not be representative of aerosols in the study area
- Field: Changing particle composition, size and environmental factors

fitnews.com

Repeatability and reproducibility

- For majority of sensor manufacturers, generally high intra-model consistency
  - R^2 typically above 0.8
  - But… typically tested in the lab

Mukherjee et al. 2017 Sensors, 17: 1805
Zou et al. 2020 STBE, 26: 237-249

- Could be influenced by the PM concentration range, source type, “drift”, etc:
  - E.g. reproducibility for cigarette smoke is higher compared to Arizona Test Dust
  - E.g. risk of accumulation of larger particles in the sensing zone (sensor drift)
  - E.g. PM organic > PM inorganic, at identical concentrations

Limit of detection (LOD)

- Sensor performance could be compromised at low concentrations
  - Problematic below 10 μg/m³

Holstius et al., 2014 AMS, 7: 1121-1131
Jovašević-Stojanović et al., 2015, Environ Pollut 206: 696-704
Kumar et al., 2015 Environ Int, 75: 199-205

Coefficient of Determination (R^2): Low-cost $PM_{2.5}$ vs. Reference

$PM_{2.5}$ mass	< 20 μg/m³	>20 μg/m³
Sharp	0.13	0.99
Shinyei	0.35	0.86
Plantower	1.00	1.00
Innociple	0.96	0.97
Nova SDS011	0.95	0.99
Nova SDL607	0.99	1.00

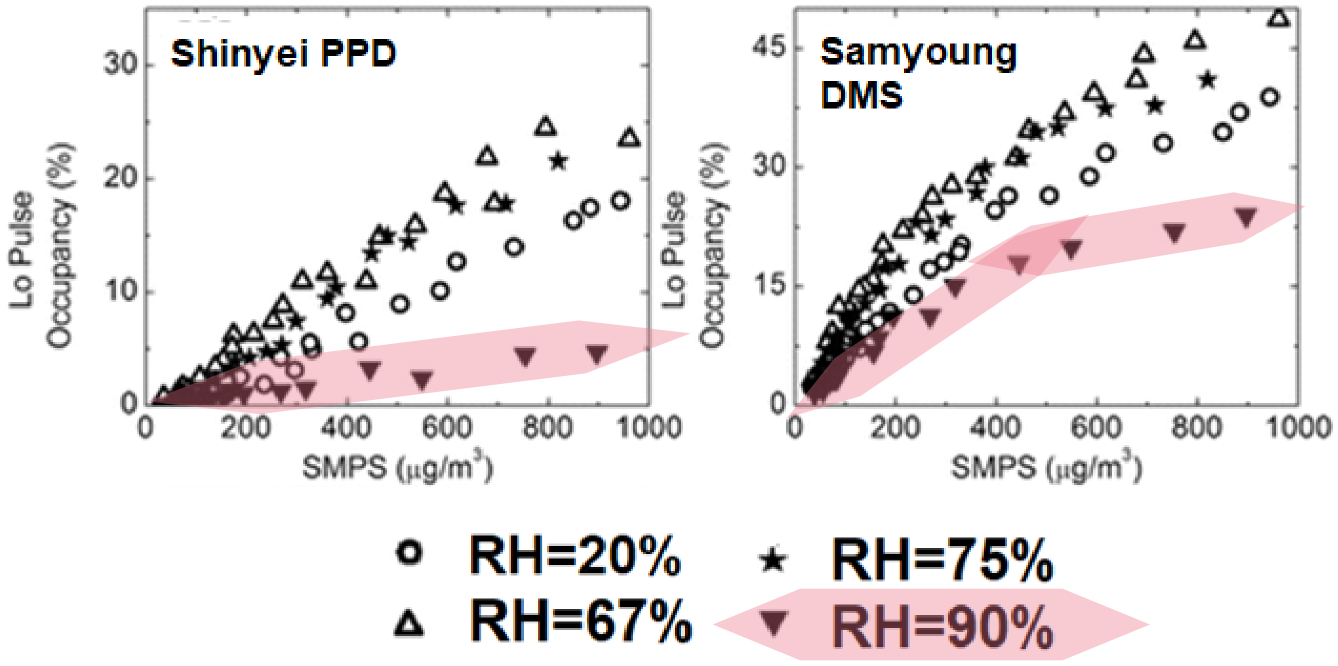
Adapted from Jayaratne et al. 2020 AAQR, 20: 520-532

Need for calibrating sensors individually for each environment of their intended use

Influence of indoor climate

- Low-cost PM sensors do not dry particles
  - This can lead to compromised accuracy as a function of particle hygroscopicity

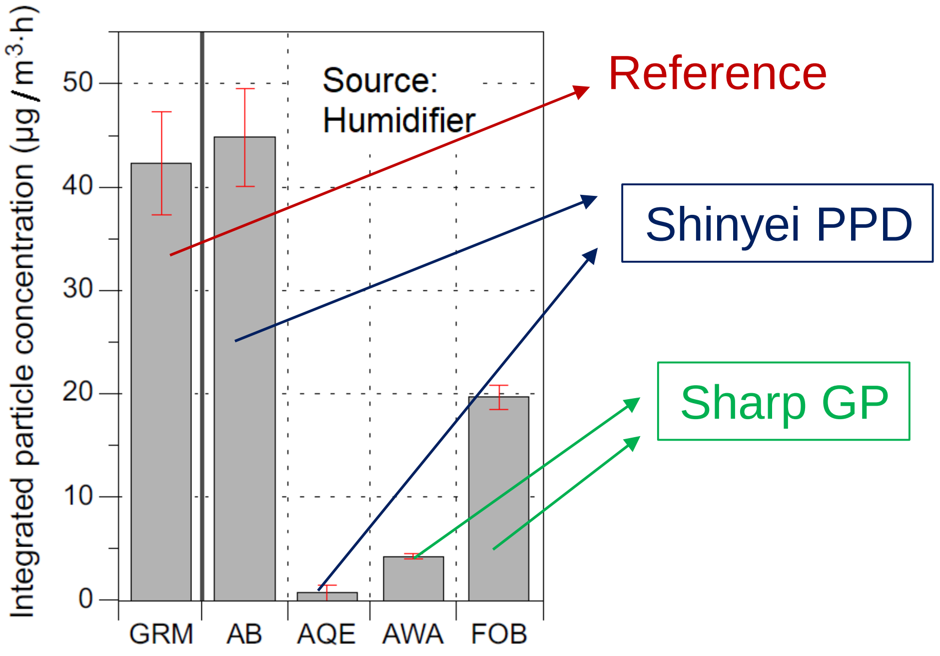
- Humidity seems to matter more compared to air temperature
  - Threshold ~85%
  - Aerosol composition matters



Adapted from Wang et al. 2015 Aerosol Sci Tech, 49: 1063-1077

Recommendations for stakeholders

- **For standard / guideline developers:** Formulate standard guidelines for assessing the short and long term performance of sensors that can be used by all
- **For researchers**: Standardize performance testing to assess the performance and allow inter-comparison between studies. Pre-test / calibrate sensors under the conditions in which the sensors/monitors will be used
- **For sellers / manufacturers (personal view)**: Offer selection of sensors / monitors that are pre-calibrated for various types of indoor and outdoor environments
  - & offer more transparency for calibrations algorithms
- **For non-expert users?**



Adapted from Singer and Delp 2018, INA, 28: 624-639

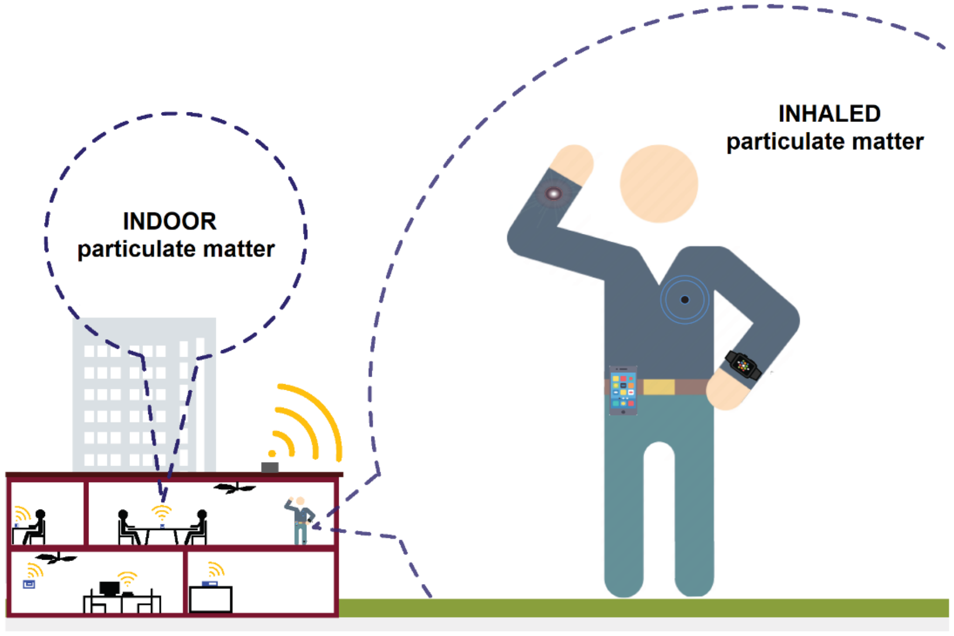
Deployment challenges and needs

- At present, only voluntary actions exist for continuous PM monitoring
- Early experimentations with continuous PM sensing indoors
  - WELL v2 A08: Air quality monitoring and awareness (optional):
    - Continuous monitoring every of $PM_{2.5}$ or PM_{10} (accuracy 25% at 50 μg/m³)
    - min once recording every 10 min
    - one sensor every 325 m^2 (3'500 ft^2)

Research questions to improve deployment guidelines:

- How to ensure long-term performance in field environments?
- What is the optimal time resolution for low-cost PM sensors?
- What is the optimal sensor placement and density to capture human exposures?

Deployment challenges and needs



Building scale   Human scale

Indoor aerosols: Episodic emissions and frequent spatial concentration gradients

• • •

Often associated with humans

Personal $PM_{2.5}$ and PM_{10} clouds

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They cannot be effectively captured with stationary PM measurements

Need for portable, robust, inexpensive, and quiet real-time PM sensors (growing field)

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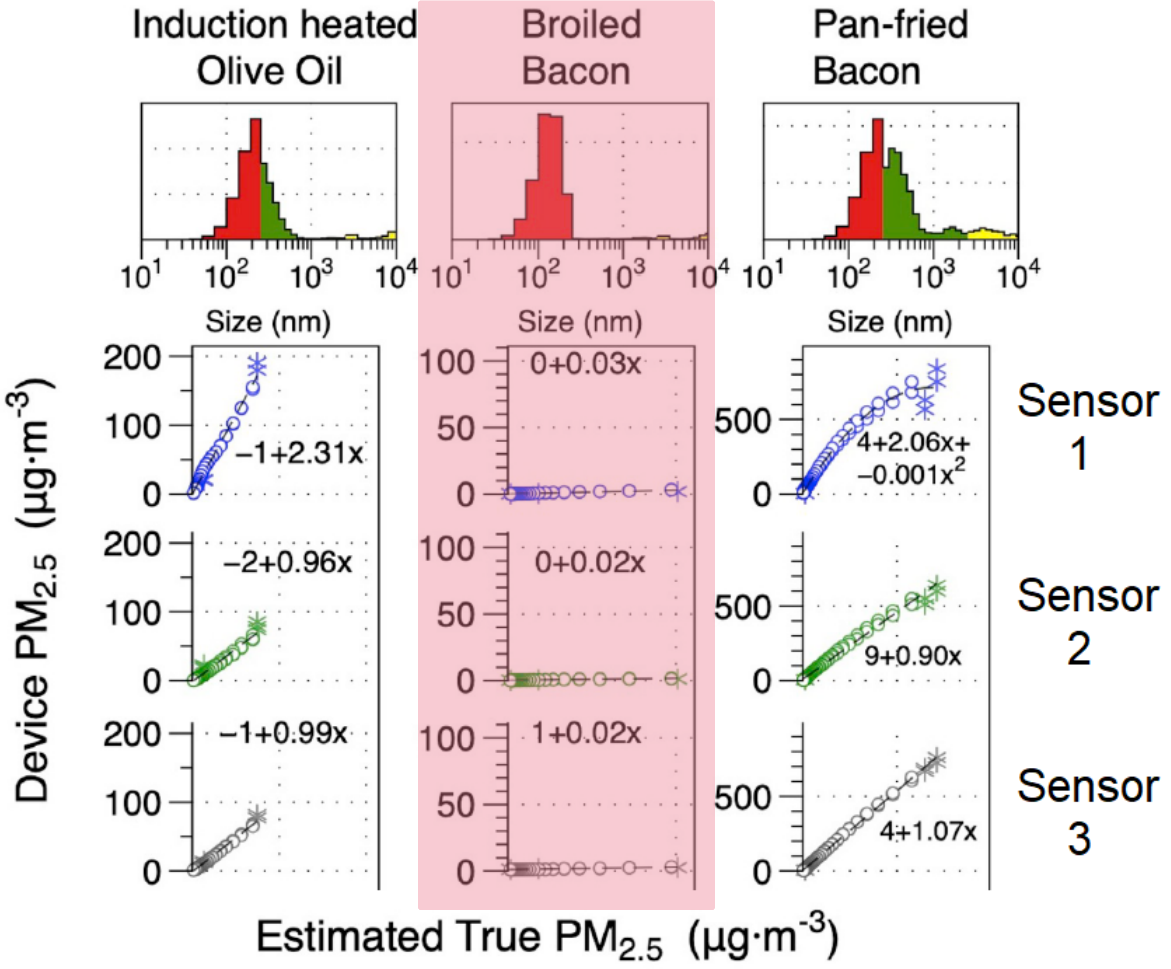
Important for improving nexus between indoor spaces and exposures to PM

Other needs: Ultrafine particles (UFP)



Adapted from Wang et al. 2020 Build Environ, 106654

- At present, there are no low-cost sensors available for UFP monitoring
  - This is especially important for spaces where strong sources of UFP can be identified (combustion, electrical appliances, etc.)
- Word of caution: Many UFP sources also emit particles above 0.3 µm!

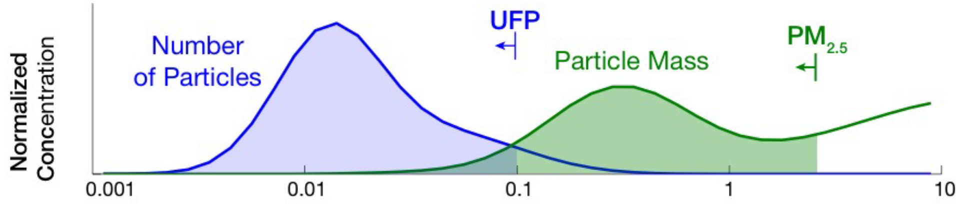


Image by Prof. Joshua S. Apte, UC Berkeley

- Need: New measurement approaches for detecting the UFP range at low cost

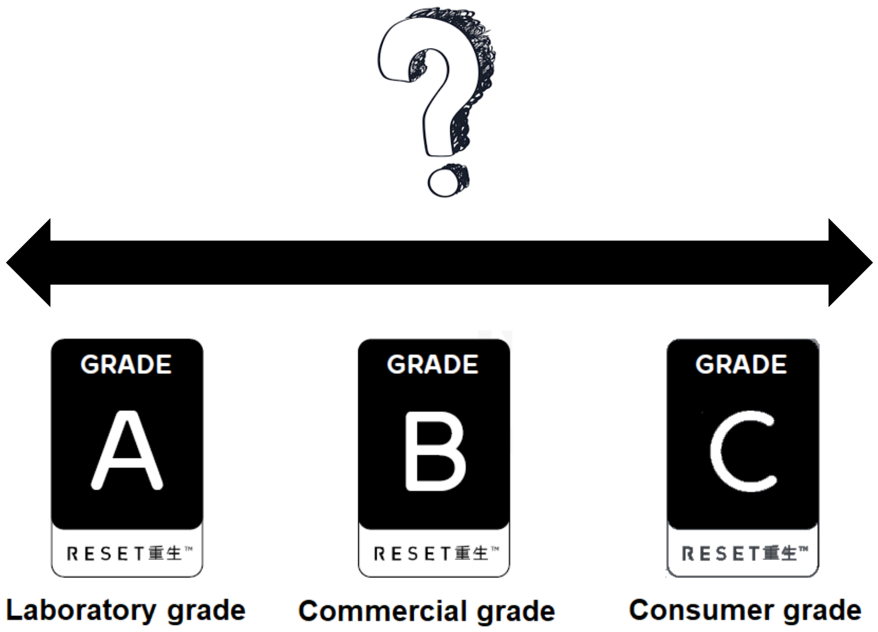
Not to forget about optimal trade-offs

- Do we need low-cost sensors to be as good as high-grade equipment?
- Can sensor data serve as a new class, rather than a proxy for traditional measurements?

Lab-grade

(e.g. TSI 3321, Grimm 11a)

- Measure almost every particle in a volume which requires complex & expensive design
- The scattering process repeatable, leads to less measurement noise



Adapted from RESET™ 2018

Consumer-grade

- Designed for optimized cost, size and performance
- Measures only a small fraction of particles (small air flow, very focused and small laser detection area)
- Simpler optical design that leads to higher measurement noise

Summary

- Exciting new opportunities and needs
- At present:
  - No sensor is ideal for all applications – need to find optimal trade-off
  - $PM_{2.5}$ sensors – probably good enough for PM management (sometimes for UFP)
  - Not fully ready to replace more established methods in which precise and absolute determination is needed (e.g. regulatory compliance, epidemiological studies, etc.)
- Research needs – Many!
  - More (long term) field validations & developments are needed to assess evolving sensors and monitors with application to health studies
- Advancing knowledge in low-cost measurement techniques for indoor PM increases the likelihood that future control interventions can be used both to prevent undesired health consequences and to promote beneficial health outcomes