



Sensing Technology for measuring Particle Number & Mass in Indoor Environments

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Overview

- Who We Are & What We Do
- Why care about indoor air quality?
- Sensing technology for indoor air quality
- NAQTS V2000
 - Particle Number - CPC
 - Particle Mass – Laser light scattering
- Applications
 - Indoor Air Quality (IAQ) - Homes & Schools
 - Vehicle Interior Air Quality (VIAQ)
- Conclusions

Who We Are and What We Do

National Air Quality Testing Services (NAQTS) is a social business that is passionate about improving the quality of life.

We seek to improve awareness of indoor air quality through widespread public and commercial monitoring using our holistic, high-quality, air pollution monitoring technology.

Based in UK (Lancaster University Environment Centre and Cardiff), Ann Arbor, Michigan, USA, and Guangzhou, China.

INDOOR AIR QUALITY & ENERGY EFFICIENCY

Developing models for assisting building design and modification whilst ensuring energy efficiency and good indoor air quality.



CITIZEN SCIENCE - INDOOR:OUTDOOR AIR QUALITY

Air quality toolkits for citizen science measurements. Capturing real-time pollution levels during school drop off/pick up times, as well as levels of student exposure in the classroom



OCCUPATIONAL HEALTH AND SAFETY

Evaluation of exposure to nanomaterials



AIR QUALITY MAPPING

Routine mobile monitoring for measuring time-integrated concentrations at high spatial resolution



BENCHMARKING VEHICLES "COMFORT"

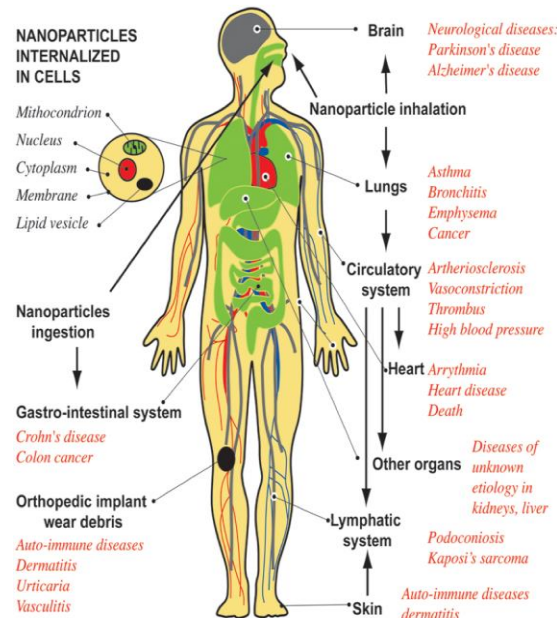
Air Quality, Noise, and Vibration

Data on in-cabin comfort from 100s of vehicles per year

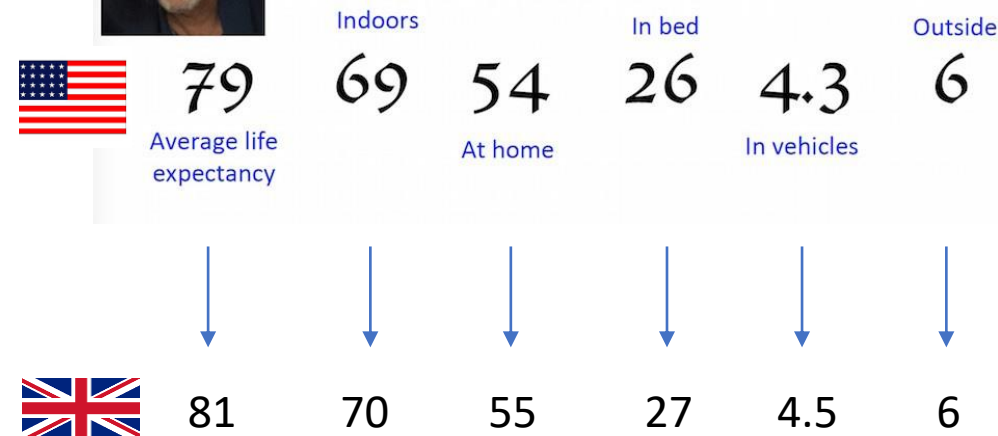


DISEASES ASSOCIATED TO NANOPARTICLE EXPOSURE

C. Buzou, I. Pacheco, & K. Robbie, Nanomaterials and nanoparticles: Sources and toxicity, Biointerphases 2 (2007) MR17-MR71



The Corsi Code



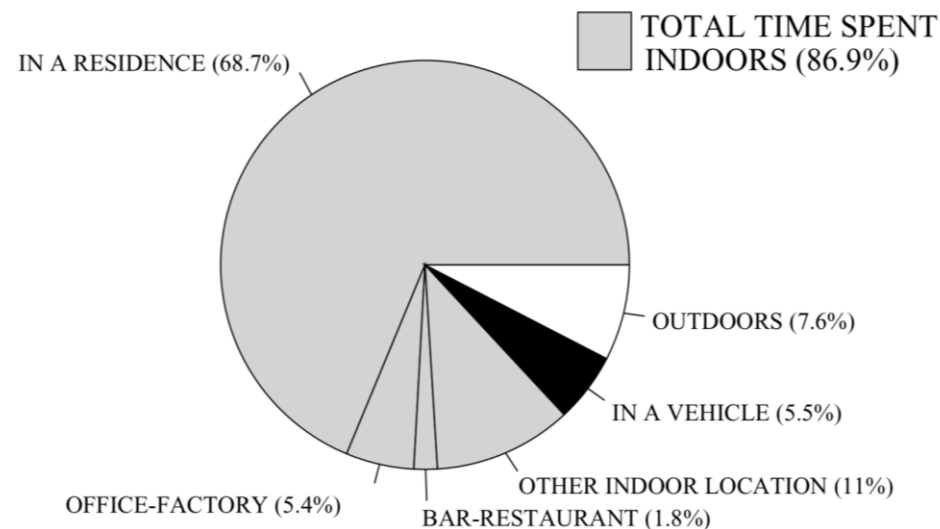
Why care about indoor air quality?

- ~87% of our time indoors
 - In a vehicle (5.5%)
 - In a residence (68.7%)
 - Office/factory (5.4%)
- Significant indoor sources from everyday activities
- Potential for indoor air pollution to get "trapped"
- Lack of public & political awareness



NHAPS - Nation, Percentage Time Spent

Total n = 9,196



NAQTS V2000

- **PN** - CPC with 20:1 pre-dilution (IPA, d_{50} 15nm)
- **PM** – Laser light scattering
- **CO, NO₂, NO** – Electrochemical
- **CO, NO₂, VOCs** – Metal Oxide
- **VOCs** – Real-time and thermal desorption tubes for GC-MS Analysis
- **CO₂** – NDIR
- **T, P, RH** – BME280
- **Vibration** – 3D accelerometer and 3D Gyro
- **Noise** – dBA
- **Vibration** – 3D accelerometer and 3D Gyro
- **Web GUI with SQL Database**
- **GSM**



**Integrated measurement device for a “holistic”
understanding of air quality**

Our CPC Technology

- Regulatory grade PN: ISO 27891
- Full mixing “fast” CPC
- 20:1 pre-dilution (IPA, d_{50} 15nm)



CERTIFICATE OF CALIBRATION

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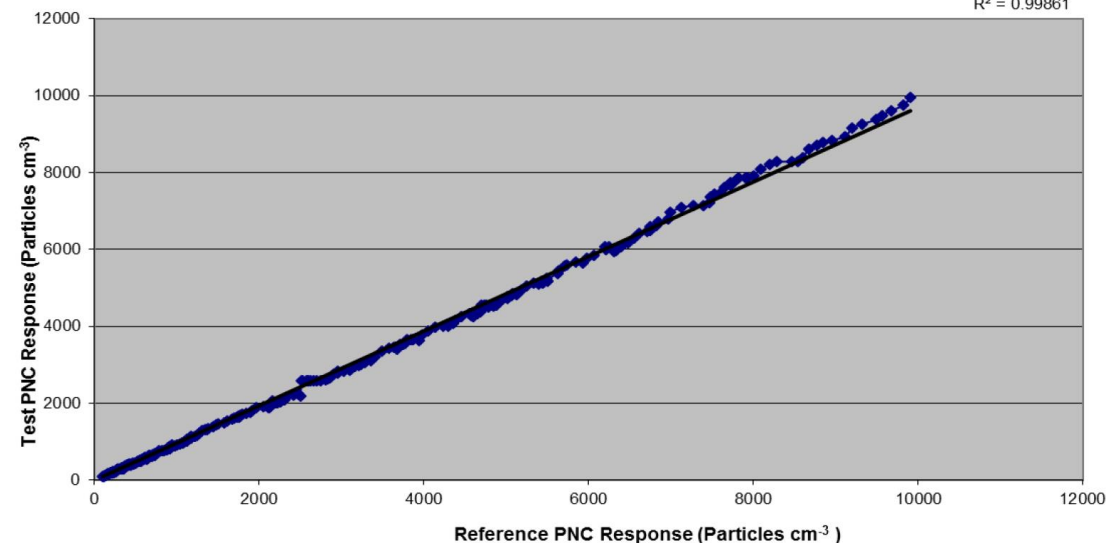
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Page 1 of 5 pages
 Approved Signatory
 Name
 Signature

EXAMPLE ONLY

Particle counting efficiency against $d_{50}=10$ nm transfer standard				
Diameter (nm)	Efficiency	$ x_{min.}(a_1-1)+a_0 $ ≤5% max	Standard Error of Estimate (SEE) ≤10% max	Correlation coefficient
200	107.0%	-	-	0.999
100	104.0%	-	-	0.999
70	97.0%	0.67%	0.90%	0.999
55	104.0%	-	-	0.997
30	98.9%	-	-	0.998
23	104.0%	-	-	0.998

70 nm Particle Number Counter Linearity Response



Low Cost PM Technology

- Low-cost sensors can help us identify pollution sources, better understand personal exposure, and complement existing networks to increase the spatial resolution of measurements
- **BUT low cost sensors ≠ low cost air quality monitor!**
- What is “good enough” data?

IoT deployment for city scale air quality monitoring with Low-Power Wide Area Networks

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Particulate matter sensors Alphasense OPC-N2, Plantower PMS5003, Plantower PMS7003, Honeywell HPMA115S0

Sensor	School A		School B	
	RMSE	R ²	RMSE	R ²
Alphasense OPC-N2	0.052	0.276	0.045	0.259
Plantower PMS5003	0.030	0.694	0.024	0.577
Plantower PMS7003	0.027	0.669	0.024	0.566
Honeywell HPMA115S0	0.044	0	0.038	0

Low Cost PM Technology

- By measuring both ultrafine, fine, and coarse particles, we can get a better understanding of indoor aerosol characteristics and source apportionment
- Combustion particulates dominated by UFP
- Re-entrained particles dominated by coarse mode

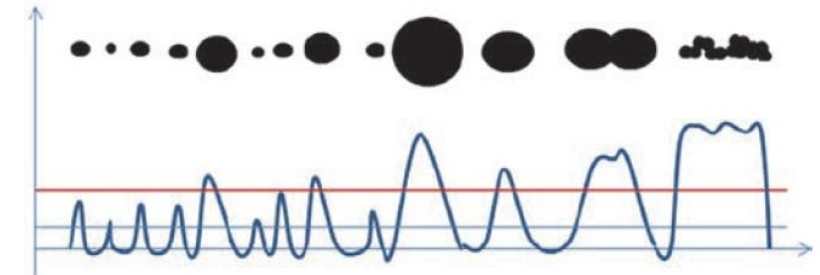
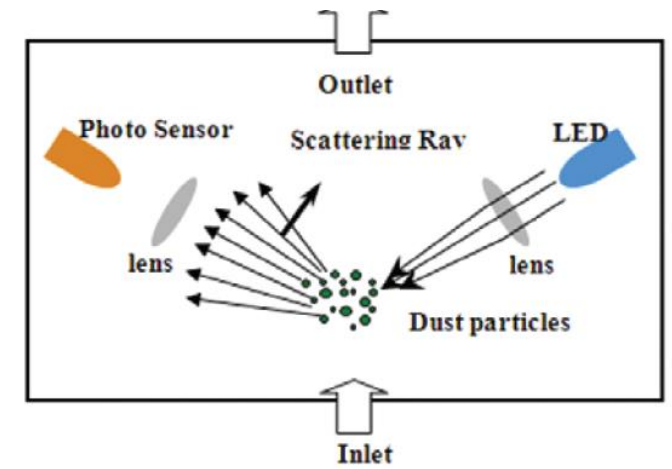
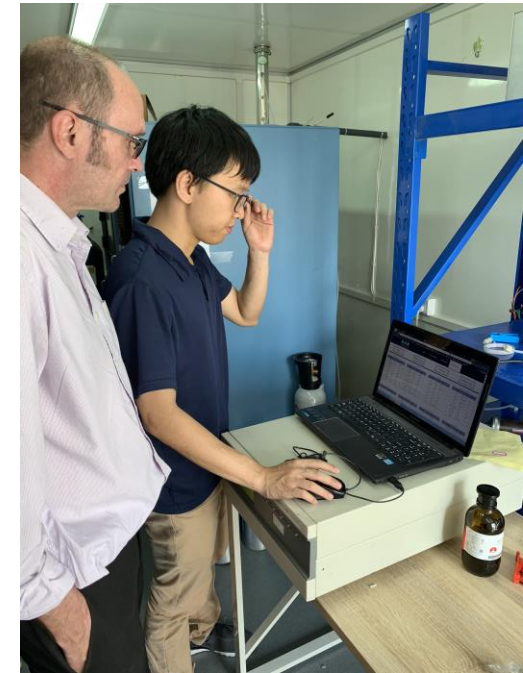
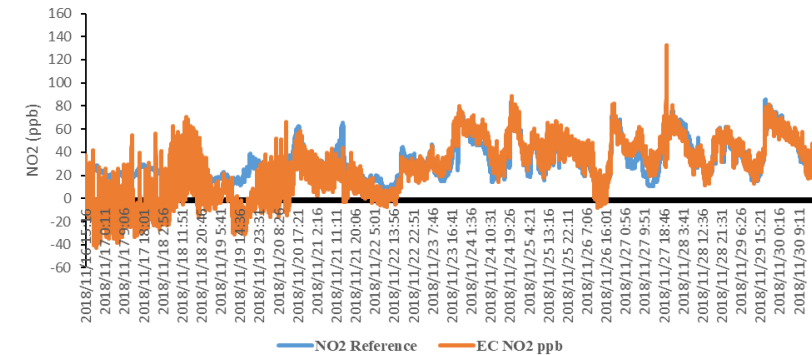
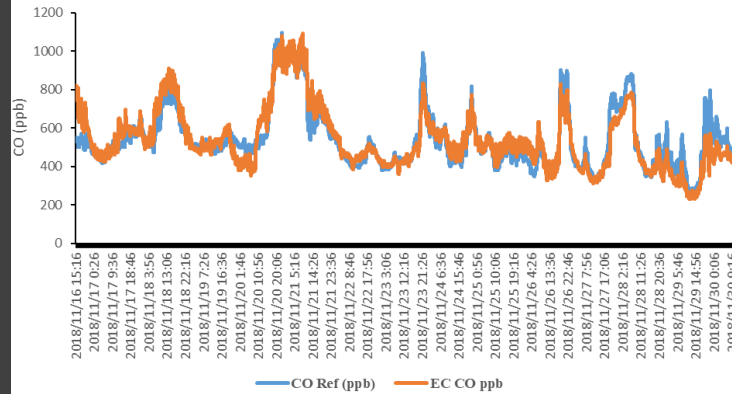
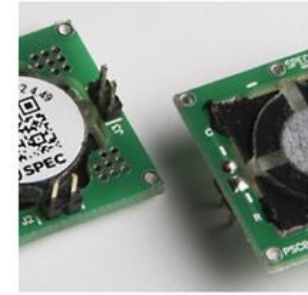
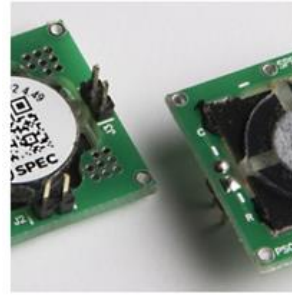


Figure 1 : Detection Principle

Parameter	Symbol	Min.	Typ.	Max.	Unit
Particle Size	D	0.3	2.5	10	um
Detection Range	D_{reg}	1	—	999	$\mu\text{g}/\text{m}^3$
Resolution	R	—	1	—	$\mu\text{g} / \text{m}^3$
Indication Error ⁽²⁾	D_{err}	1 ~100 $\mu\text{g}/\text{m}^3$	—	—	+/-10 $\mu\text{g} / \text{m}^3$
		100~999 $\mu\text{g}/\text{m}^3$	—	—	+/-10 %
Warm-Up Time	$t_{wup}^{(2)}$	—	5	—	s
Response Time	$t_{rsp}^{(2)}$	—	1	—	s

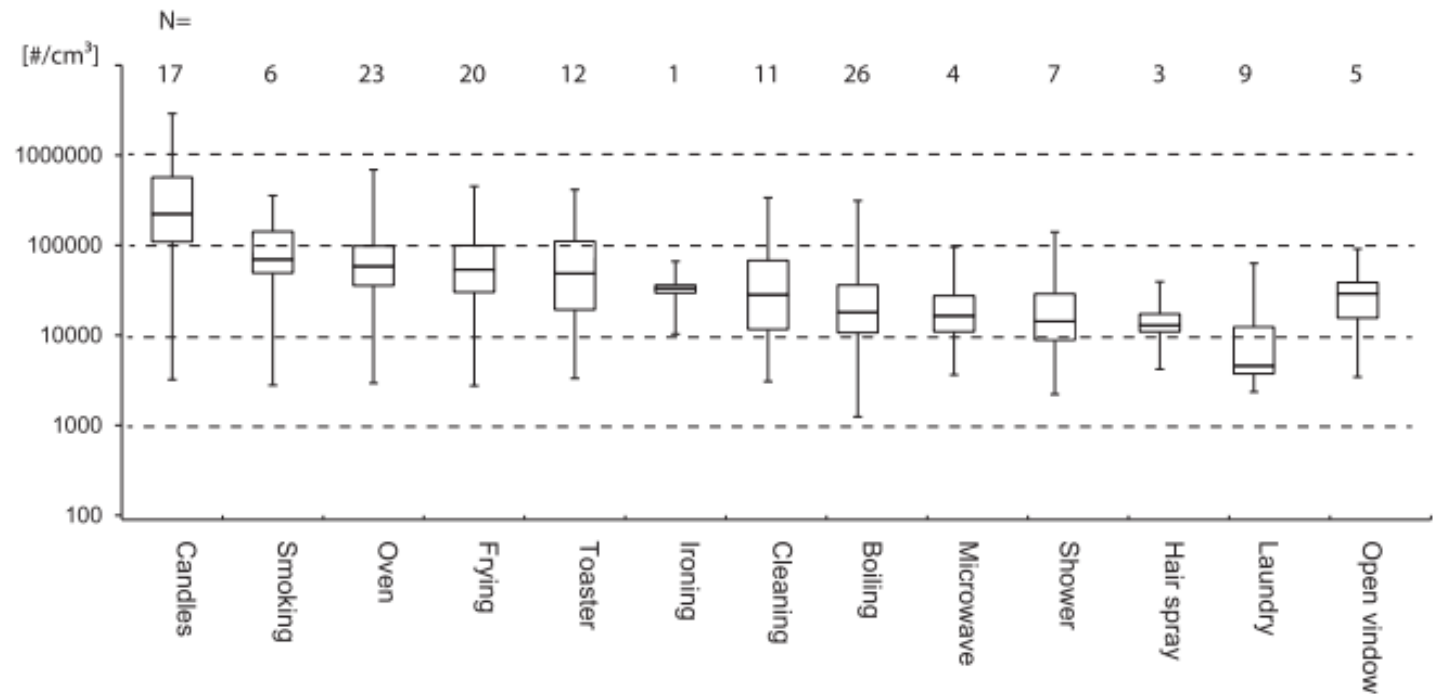
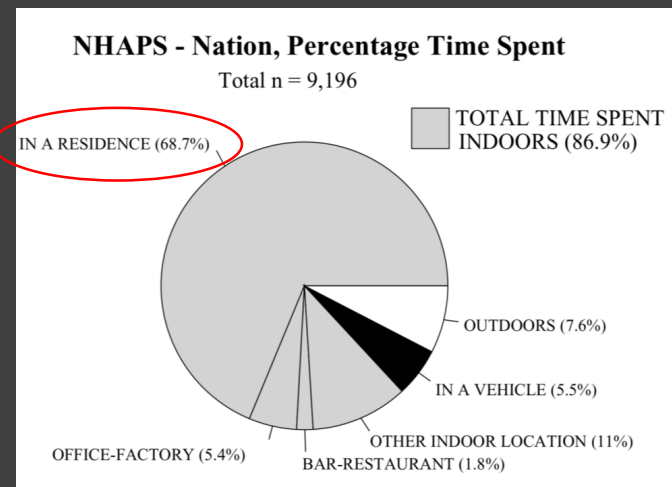
Low Cost PM Technology - Colocation

- Extensive colocation activities at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences Supersite to quantify, and improve low-cost sensor accuracy
- We are doing our due diligence on low-cost PM sensors currently



Indoor Air Quality - Homes

- 68.7% of our time in a residence
- Significant indoor sources from everyday activities
- More time spent here by vulnerable populations

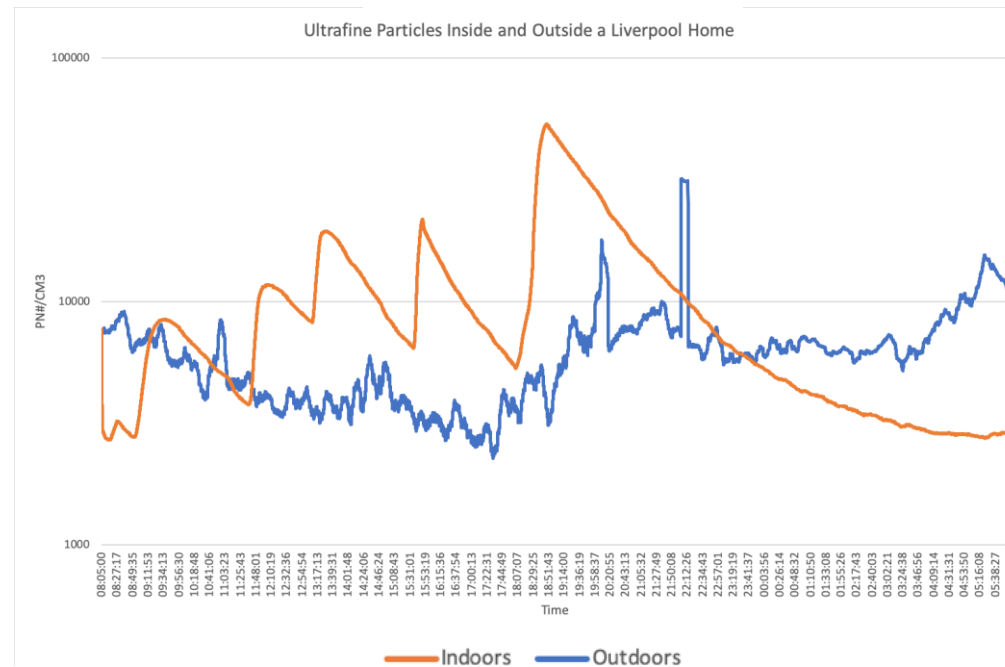
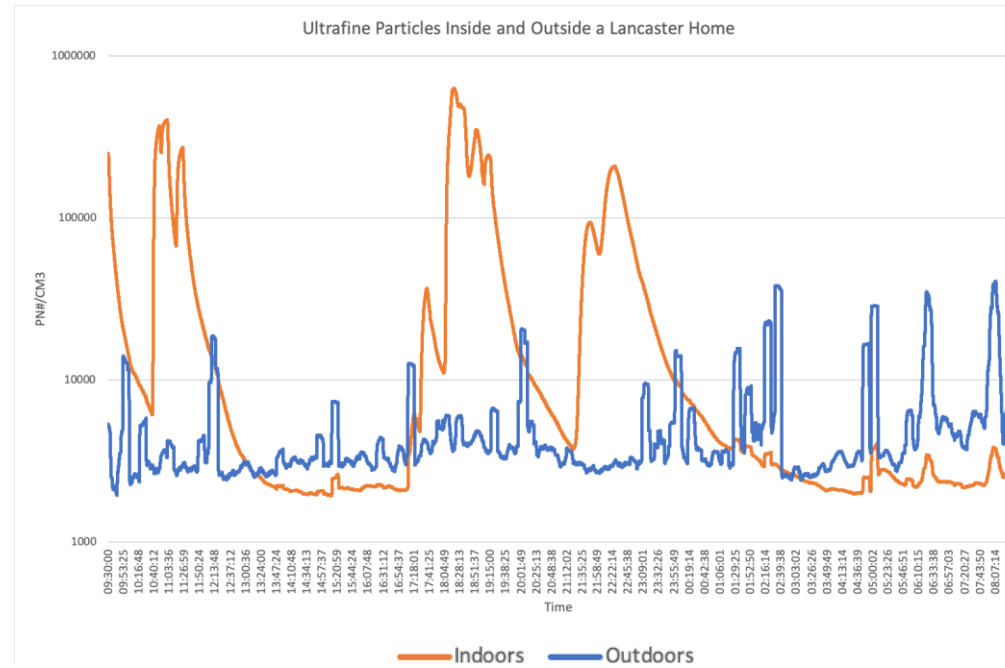


Summary of PNC from various activity influenced periods (Isaxon et al., 2015)



Indoor Air Quality - Homes

- Measurements in four homes across the UK for Clean Air Day 2019, using the V2000
- Investigating role of location and activity on indoor PN concentrations
- 10 min rolling averages (1s data)



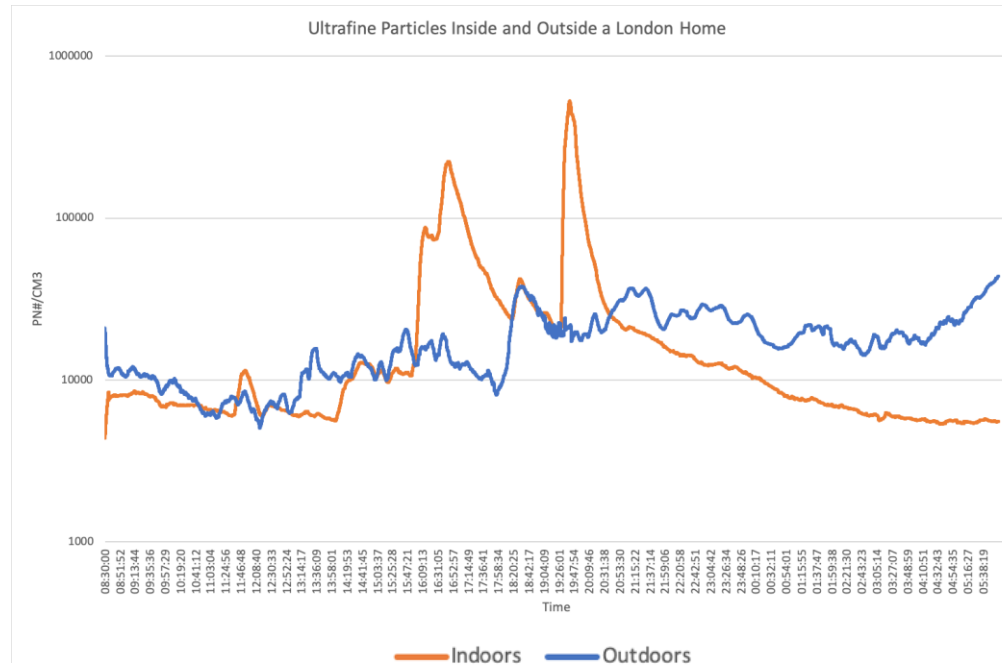
- Indoor 7x more polluted than outdoors
- Largest PNC from toast, gas stove, and wood burner
- Penetration of outdoor particles correlate with train timetable
- Long decay rates



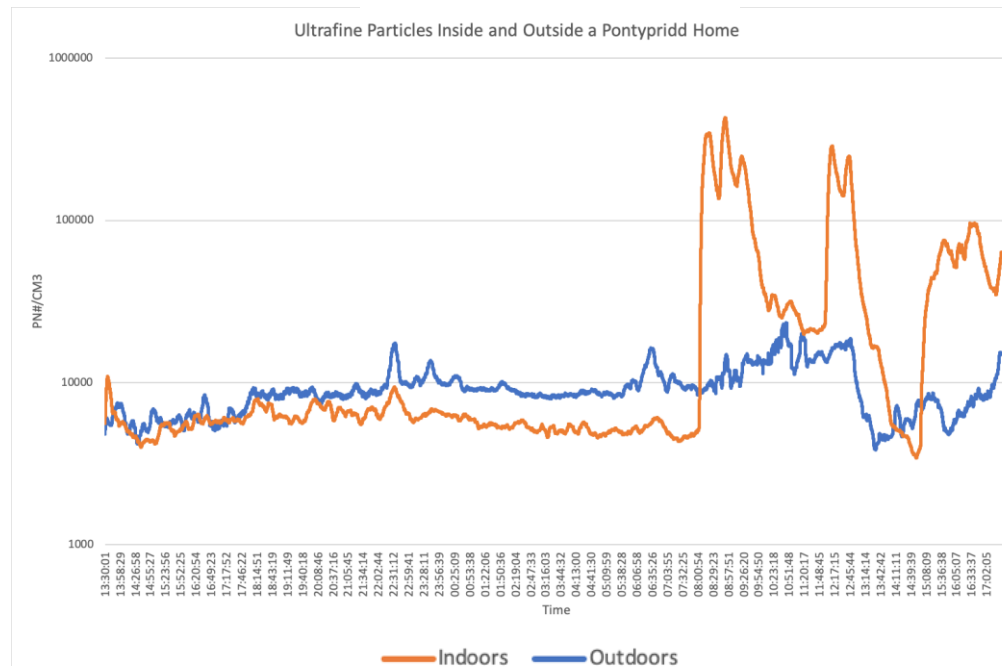
- Indoor 60% more polluted than outdoors
- Largest PNC related to cooking activities
- Long decay rates

Indoor Air Quality - Homes

- Location less important in determining indoor concentrations, however, evidence of ingress
- Role of individual activities important
- Simple actions can be taken to minimise exposure
- Illegal concentrations outside, legal concentrations inside
- We need more measurements in homes to better understand the problem
- What about energy efficiency?



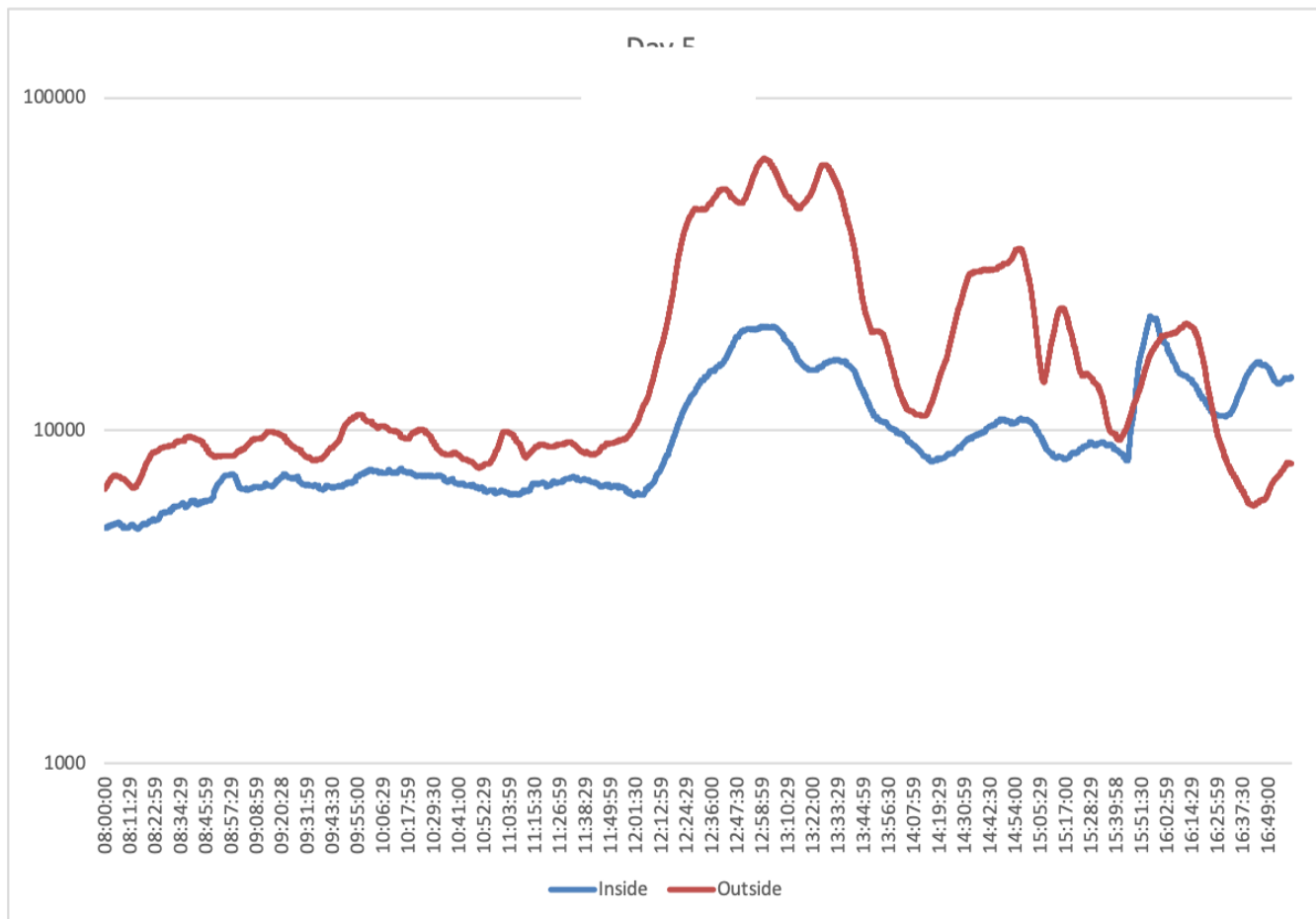
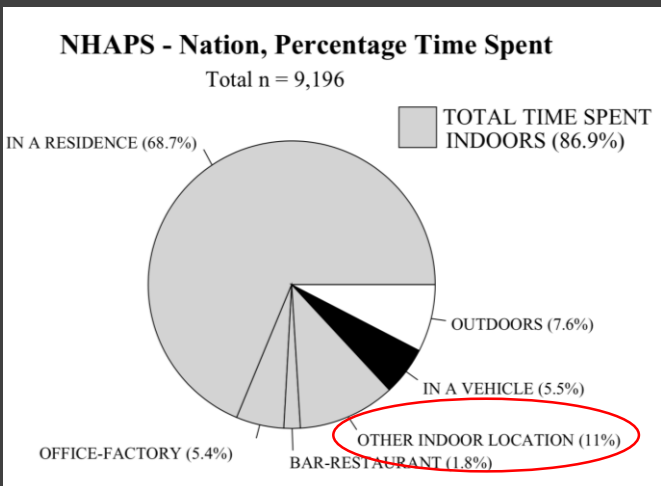
- Indoor 47% more polluted than outdoors
- Largest PNC concentrations from toast and frying steak
- High outdoor background concentrations



- Indoor 3x more polluted than outdoors
- Largest PNC related to cooking activities
- Some correlation between outdoor and indoor peaks suggesting PN infiltration

Indoor Air Quality - Schools

- Children are especially susceptible to air pollution (Pope & Dockery, 2006)
- Poor IAQ associated with poor academic performance (Mohai et al., 2011).
- Children spend a significant amount of time at school: ~190 days per year, and ~30 hours per week.



INSIDE

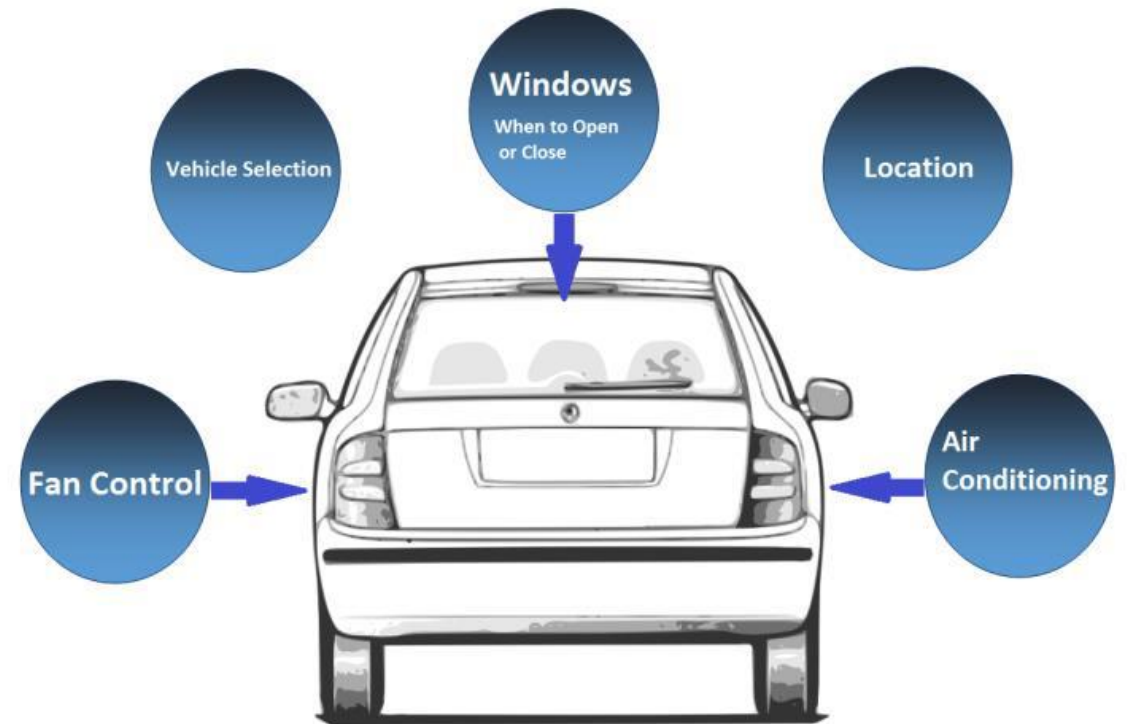
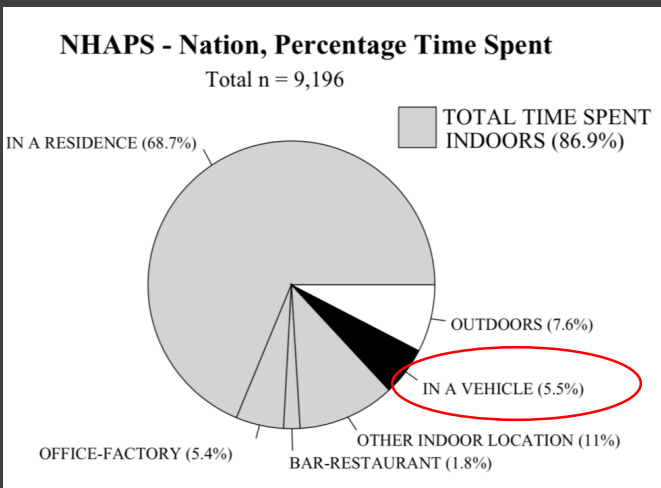
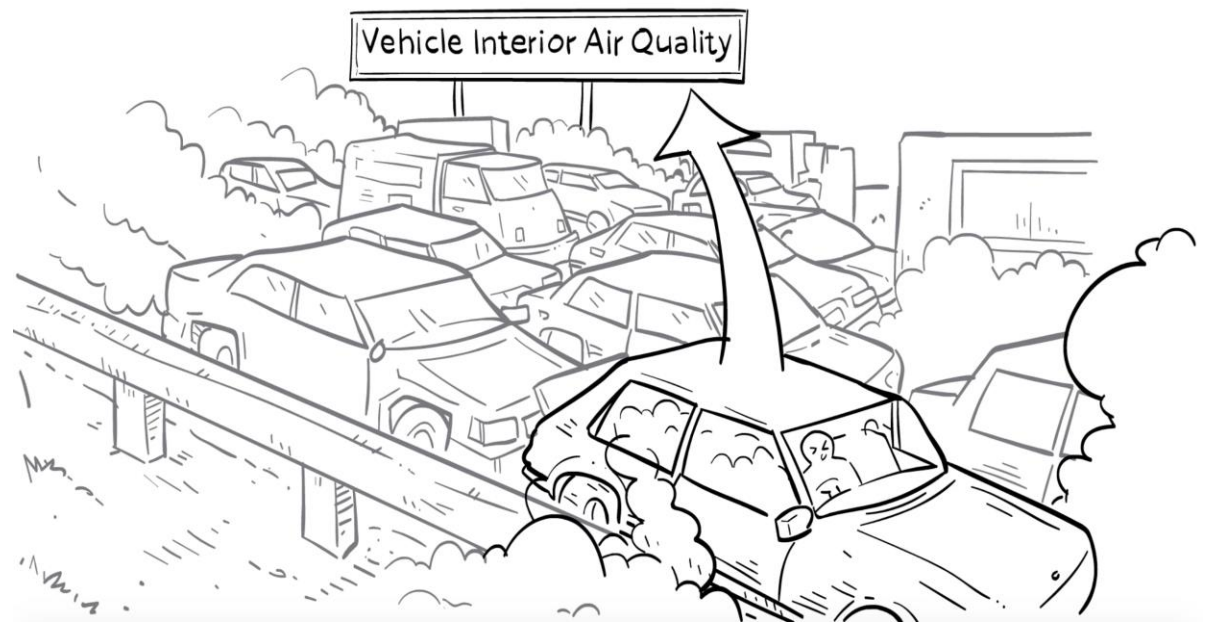
	Max	Min	Median	Mean	SD
08:00 – 17:00	22078	5058	8324	9991	4191
08:00 – 09:00	7428	5058	5751	5858	702
15:00 – 16:00	22078	8120	9045	10903	4154

OUTSIDE

	Max	Min	Median	Mean	SD
08:00 – 17:00	65660	5950	10321	18653	15397
08:00 – 09:00	9592	6656	8424	8299	903
15:00 – 16:00	29710	9399	14798	15768	4560

Vehicle Interior Air Quality (VIAQ)

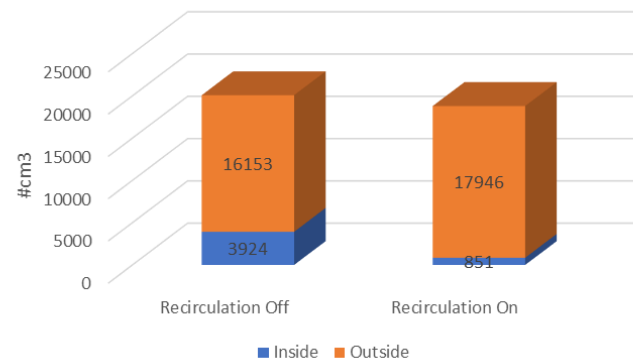
- 5.5% of our time in a vehicle
- Immediate proximity to significant pollutant sources (other vehicles), plus in urban areas, high outdoor concentrations



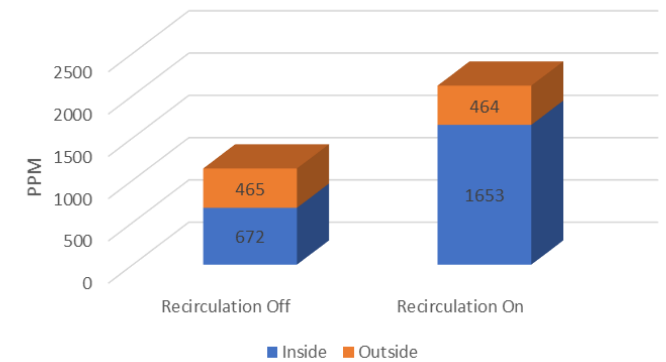
Effect of Occupant Behaviour

- Ingress Ratio – How much outside air pollution is getting into the cabin?
- Stiffness Factor – How well is the vehicle ventilating CO₂?

German Sedan PN



CO2



INGRESS RATIO

STIFFNESS FACTOR

Recirculation Off

24%

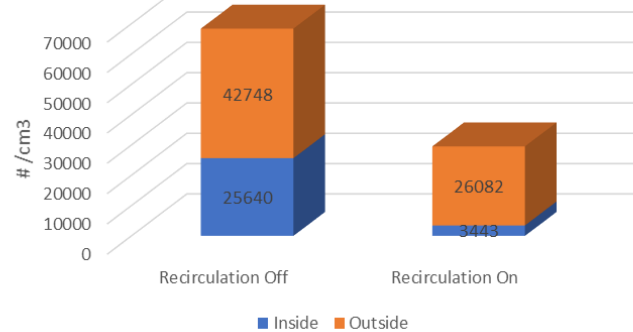
1.4

Recirculation On

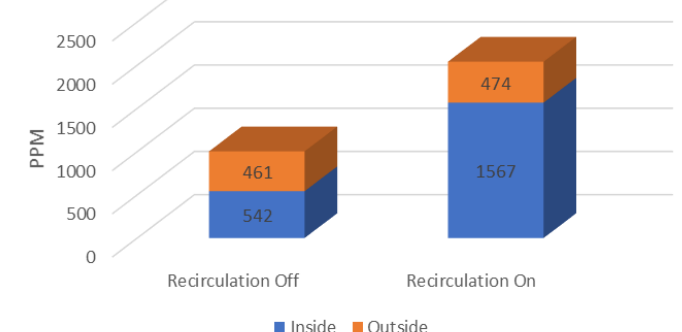
5%

3.6

American Hatchback PN



CO2



INGRESS RATIO

STIFFNESS FACTOR

Recirculation Off

60%

1.2

Recirculation On

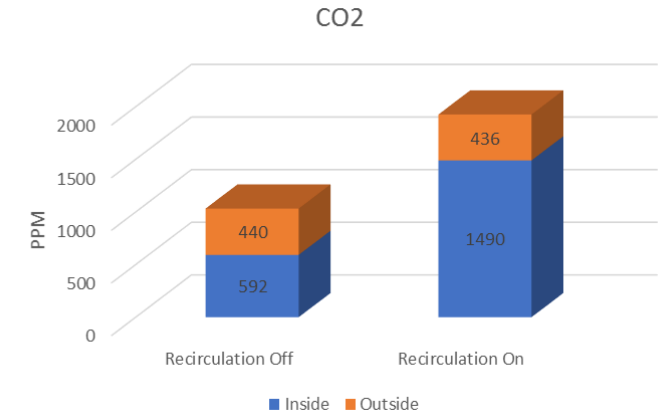
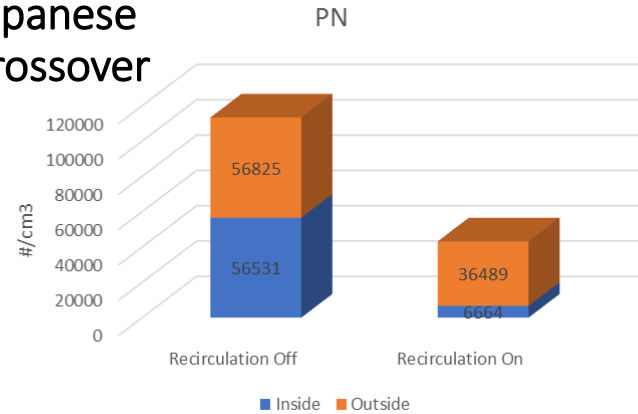
13%

3.3

Effect of Occupant Behaviour

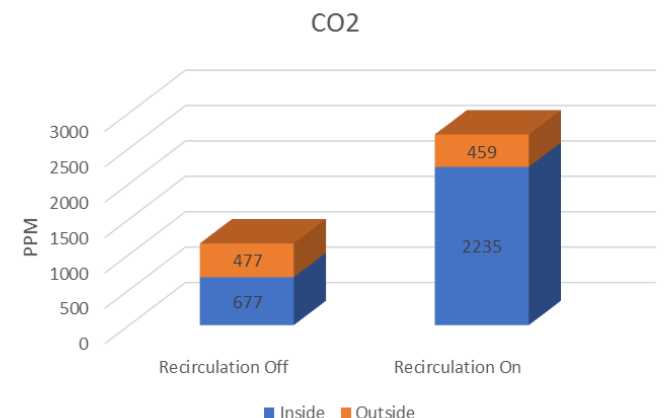
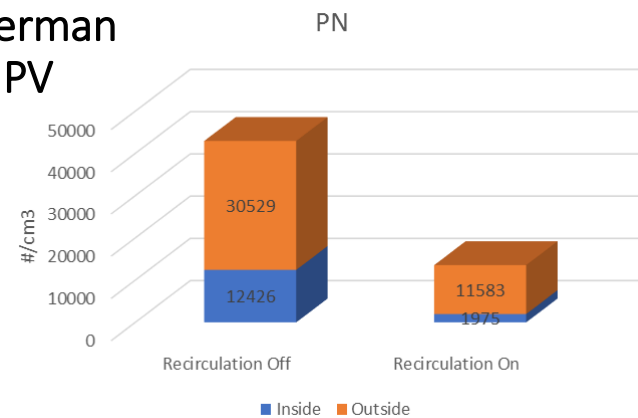
- Ingress Ratio – How much outside air pollution is getting into the cabin?
- Stiffness Factor – How well is the vehicle ventilating CO₂?

Japanese Crossover



	INGRESS RATIO	STIFFNESS FACTOR
Recirculation Off	99%	1.3
Recirculation On	18%	3.4

German MPV

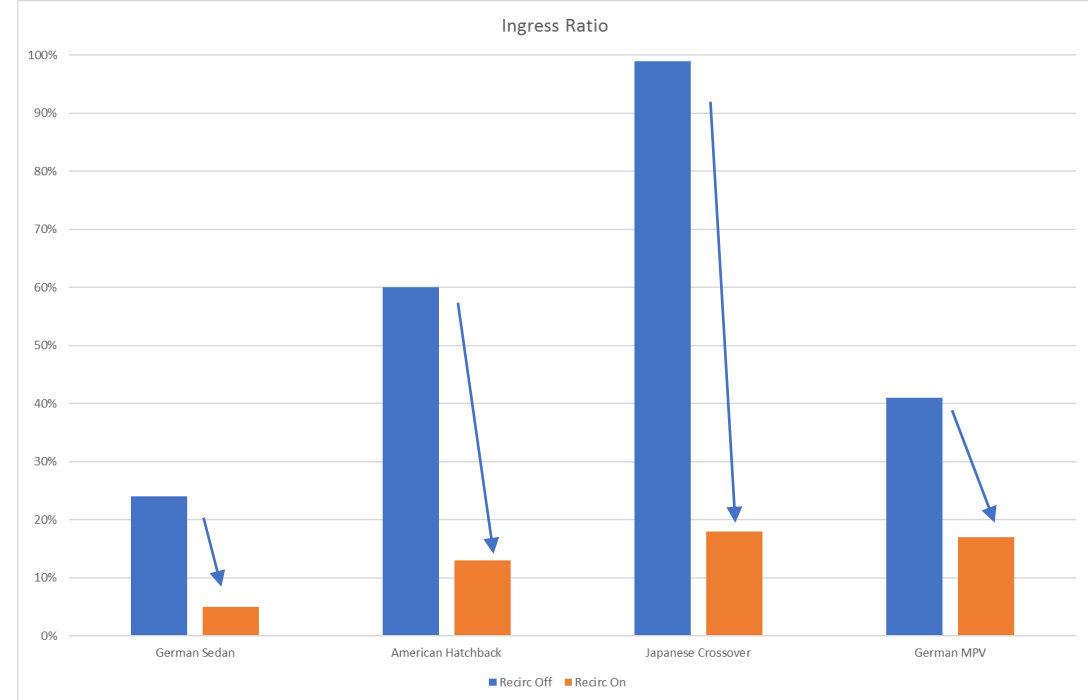


	INGRESS RATIO	STIFFNESS FACTOR
Recirculation Off	41%	1.4
Recirculation On	17%	4.97

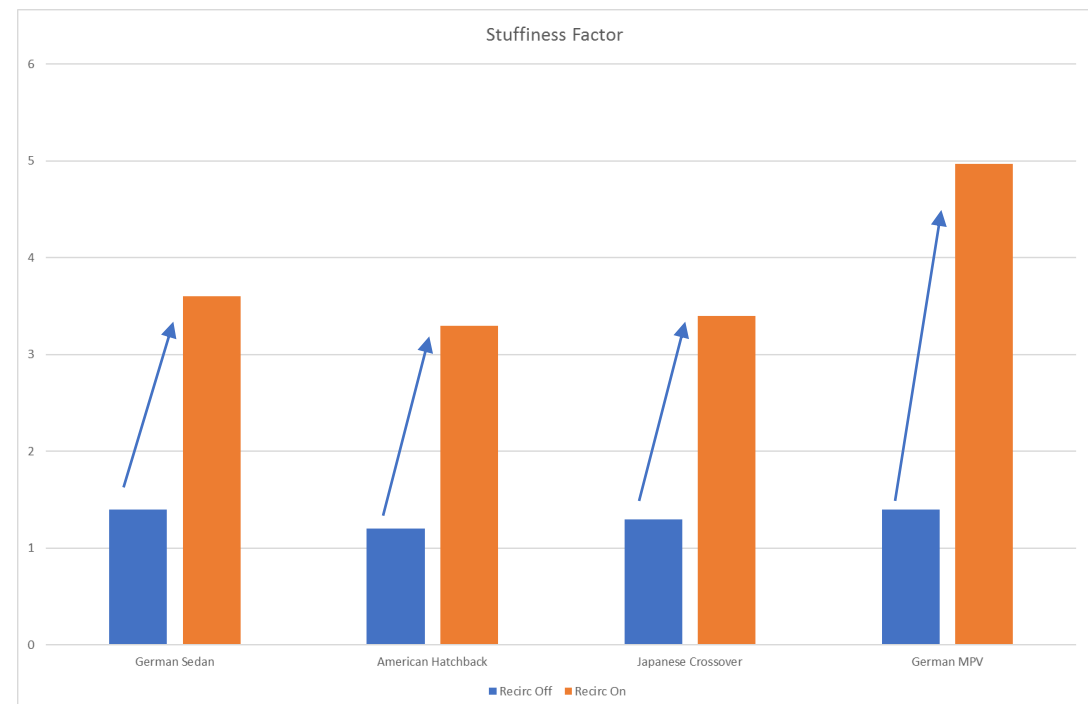
Effect of Occupant Behaviour - Summary

- These data show the **heterogeneity of Ingress Ratios**
- 24-99% with recirculation mode off, 5-17% with recirculation mode on
- An **inherent tradeoff** between protecting passengers from ambient ingress, and adequate ventilation
- **Huge influence of passenger habit on dose.** By driver education, and automation of HVAC controls, exposure can be reduced significantly

PN

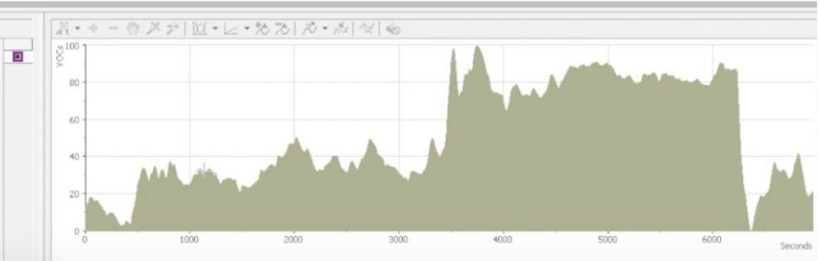
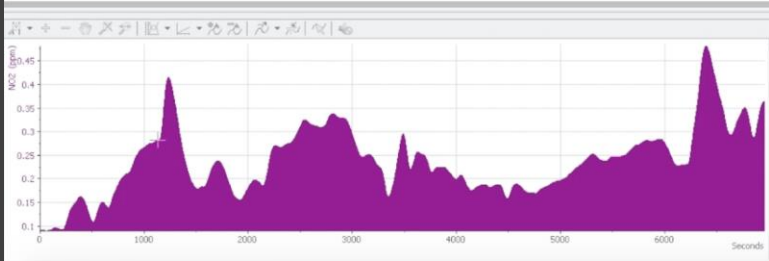
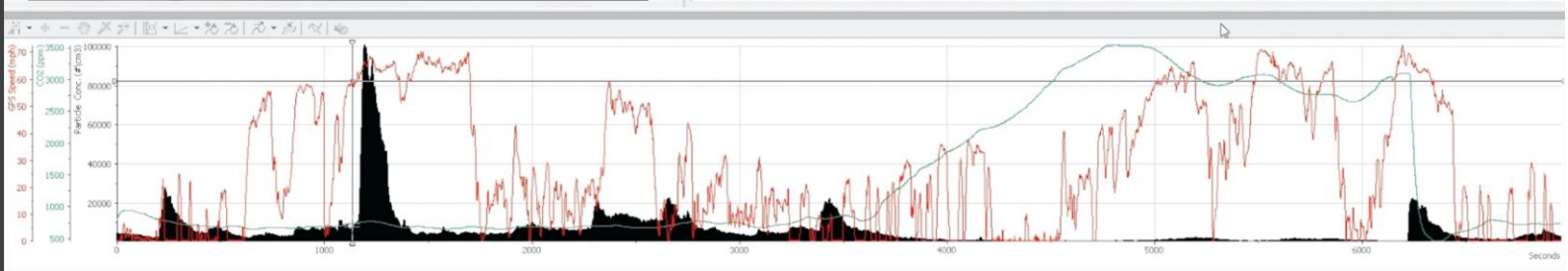
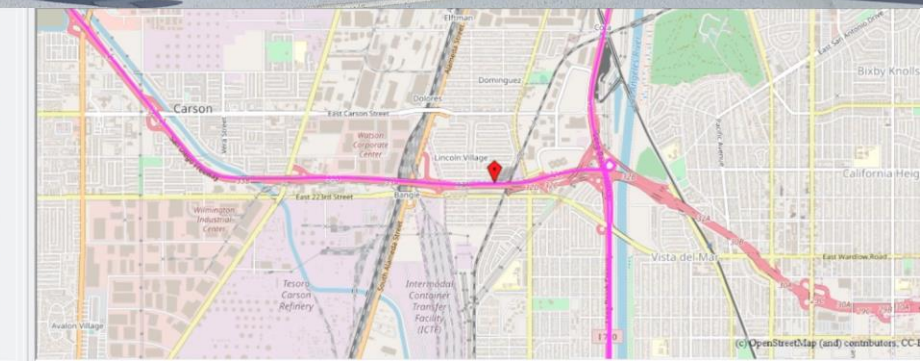


CO2



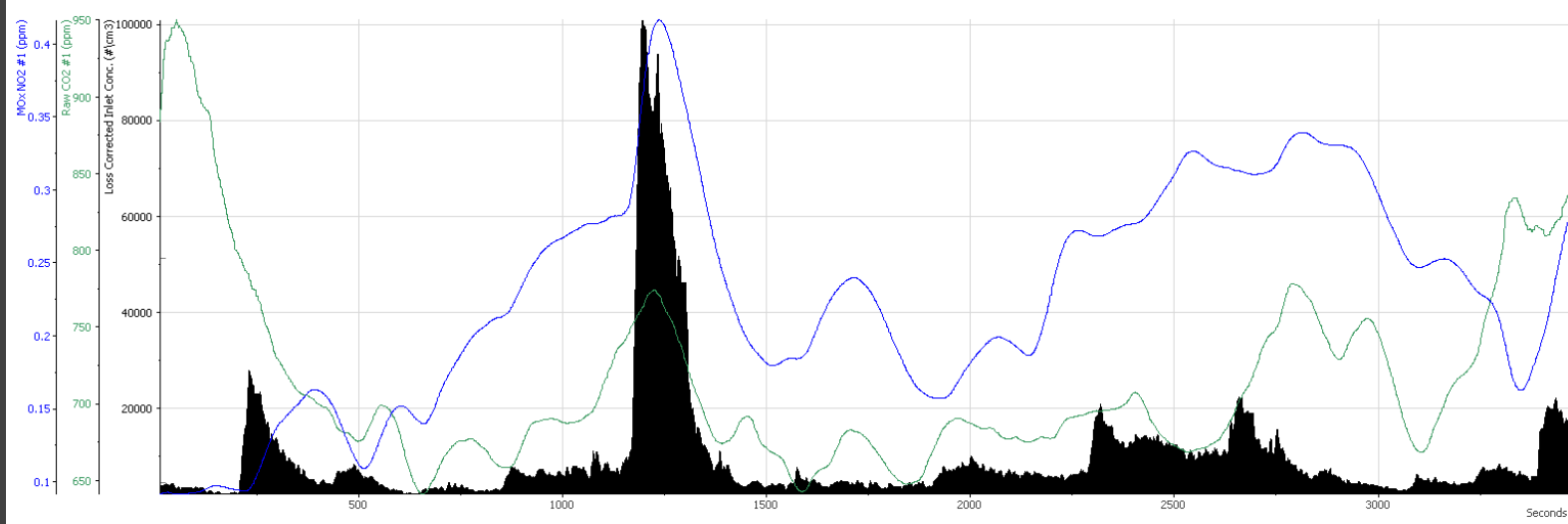
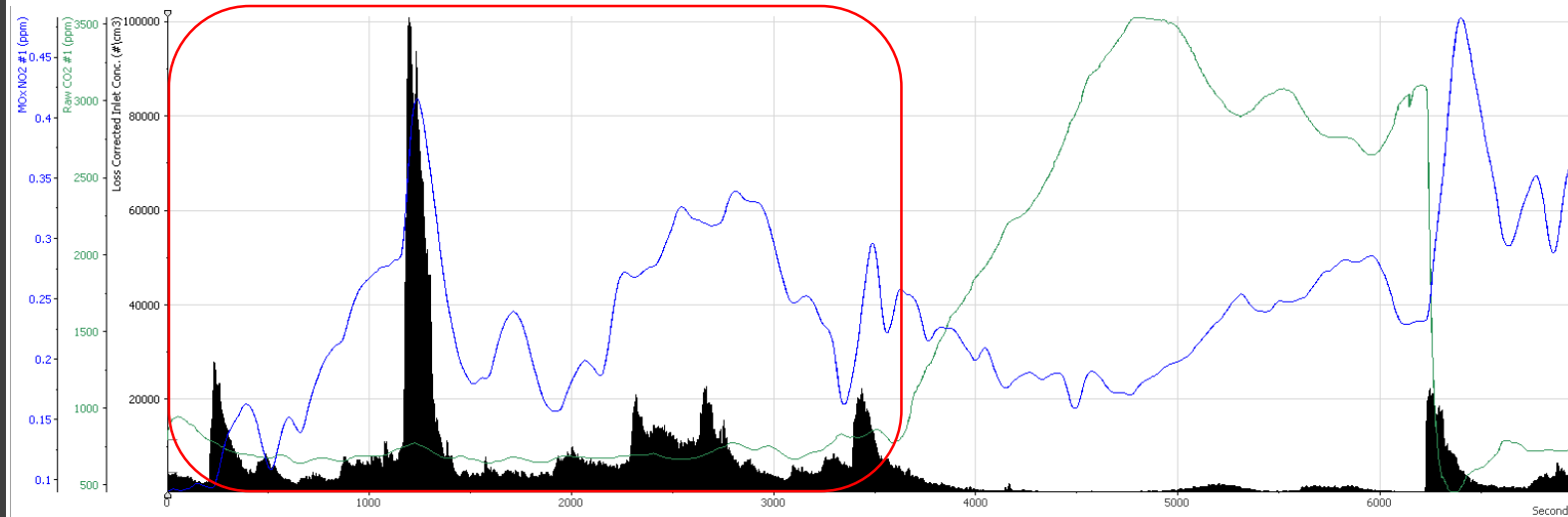
Effect of Occupant Behaviour

- Drive from Long Beach to Downtown LA
- ~ 2 hours in length
- A variety of HVAC settings
 - “Fresh Air” mode
 - Recirculation mode
- A variety of speeds
 - High
 - Low
 - Stop/start
- A variety of locations
 - Urban
 - Highway



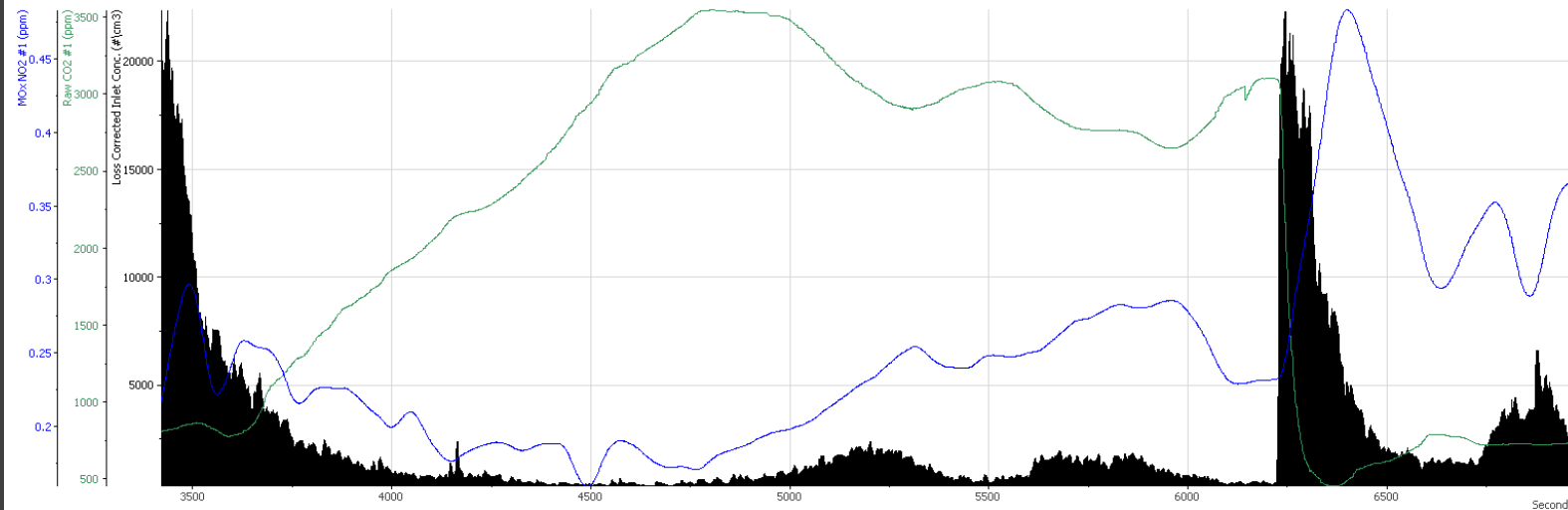
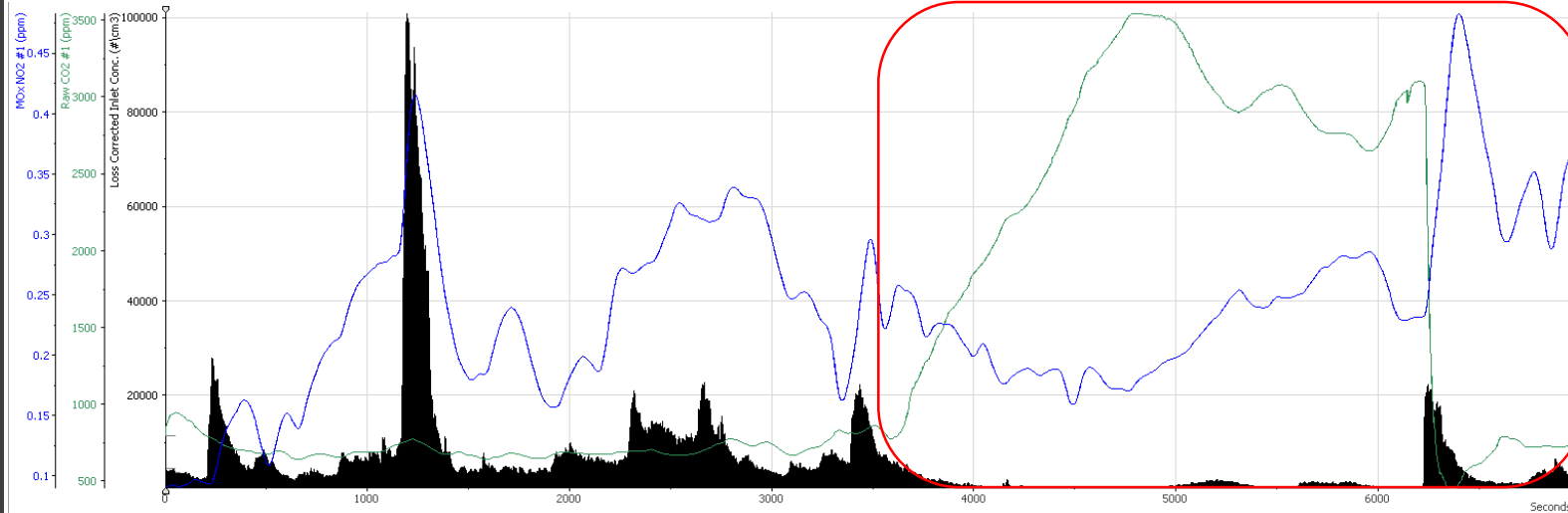
Effect of Occupant Behaviour – "Fresh Air" Mode

- PN peaks at 100,900 #/cm³
- Vehicle is well ventilated, with CO₂ concentrations <1000ppm
- VIAQ is susceptible to extremely localized air quality: dirty diesels!



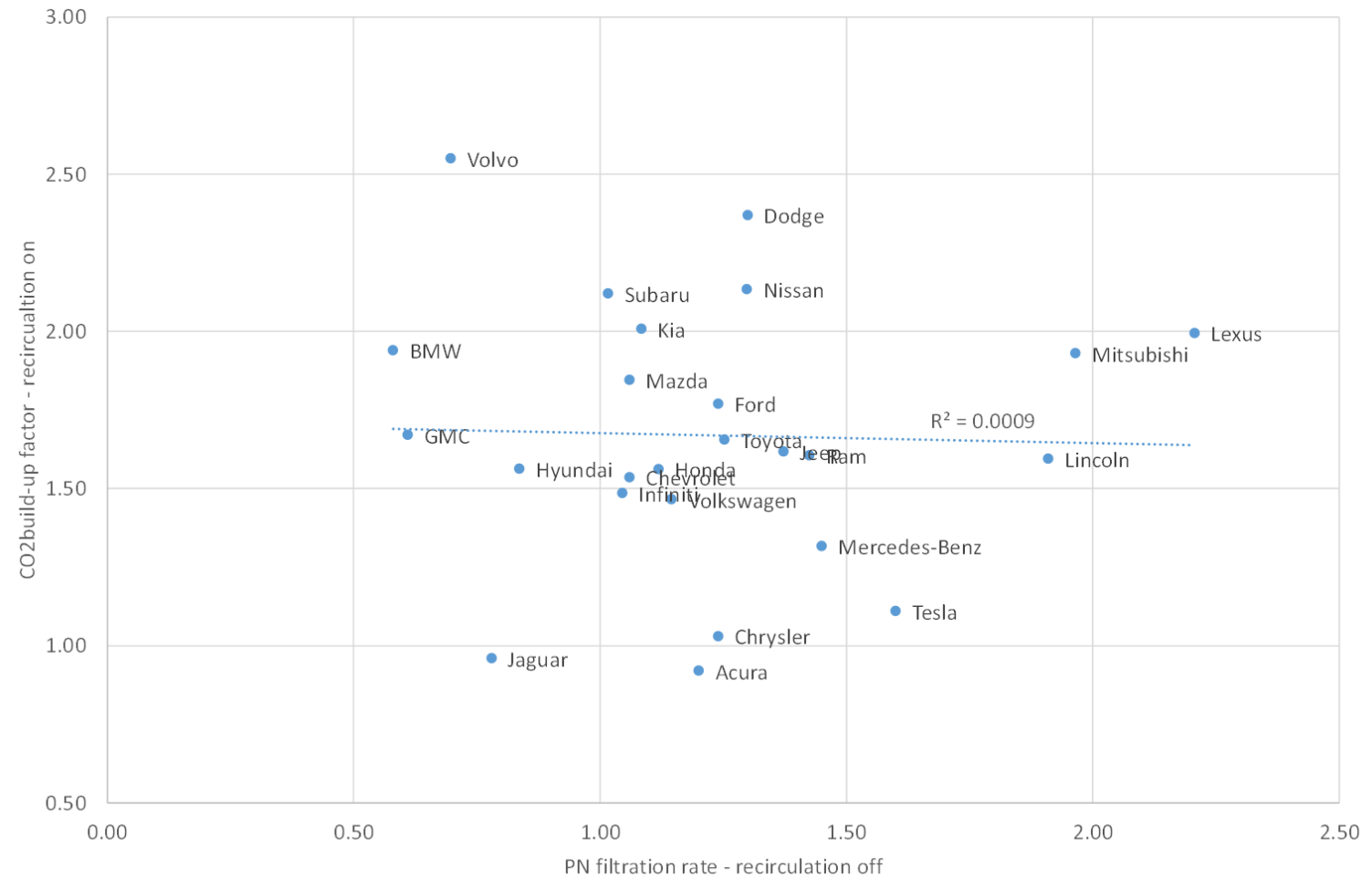
Effect of Occupant Behaviour – Recirculation Mode

- PN exponential decay to low concentrations
- CO₂ peaks at >3500ppm
- Increased leakage of HVAC associated with higher speeds, results in some CO₂ ventilation, and some PN infiltration
- Obvious dichotomy between PN & CO₂



Effect of Occupant Behaviour – Recirculation Mode

- Independent ratings to quantify and compare to empower consumers
- Driver choice between PN from fresh air mode and CO₂ build-up from recirculation mode
- No correlation suggests no trade-off – independent design decisions
- Trade-off is more likely on design cost



Conclusions

- Increasing importance of measuring indoors
- Measurements must be holistic and include UFP and larger size fractions
- Role of individual action in the indoor environment important
- More measurements needed to quantify the problem
- Need to be clear in defining what data is “good enough?”



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