Sensing Technology for measuring Particle Number & Mass in Indoor Environments

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Cambridge Particle Meeting – June 28th 2019

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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

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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.

Lancaster University

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

CALL CLEAN AIR LOVERS & LOBBYISTS

vives

OCCUPATIONAL HEALTH AND SAFETY

Evaluation of exposure to nanomaterials

RESEARCH CENTER ITENE BUSINESS, SCIENCE & INNOVATION

AIR QUALITY MAPPING

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

NAQTS Innovate UK Newton Fund

BENCHMARKING VEHICLES "COMFORT"

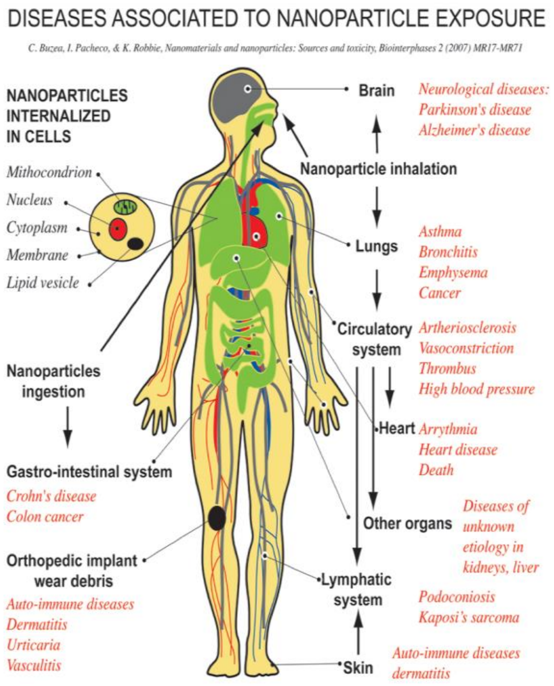
Air Quality, Noise, and Vibration

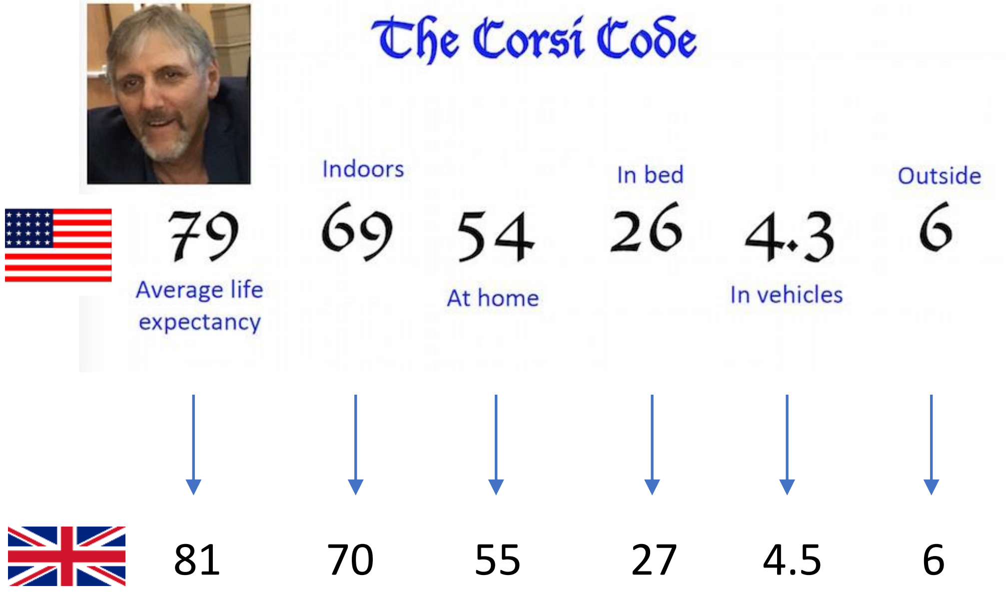
Data on in-cabin comfort from 100s of vehicles per year

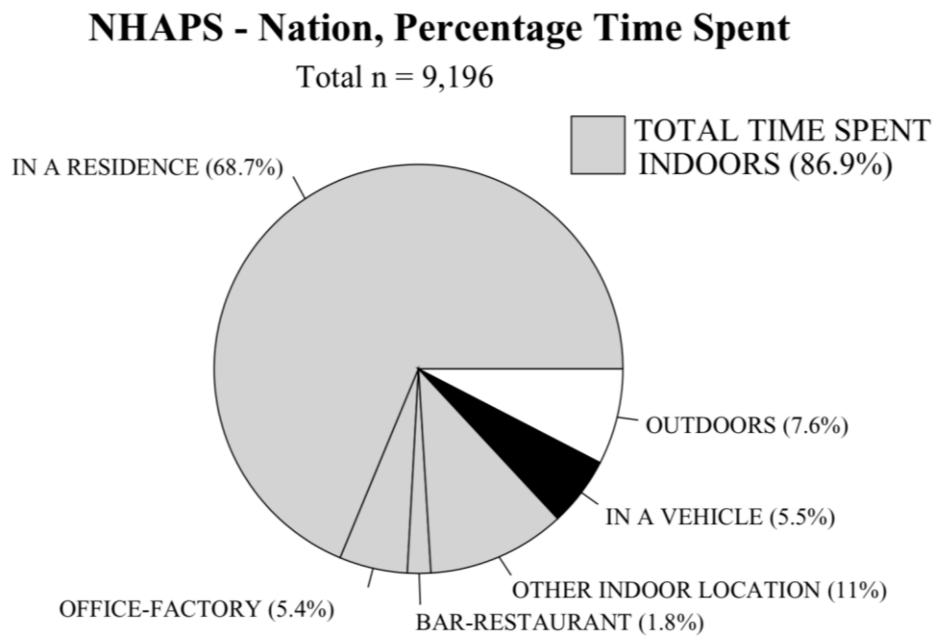
EMISSIONS ANALYTICS

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







NAQTS V2000

- **PN** - CPC with 20:1 pre-dilution (IPA, d_{50} 15nm)
- **PM** – Laser light scattering
- **CO, NO_2, NO** – Electrochemical
- **CO, NO_2, VOCs** – Metal Oxide
- **VOCs** – Real-time and thermal desorption tubes for GC-MS Analysis
- **CO_2** – 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

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Our CPC Technology

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

CERTIFICATE OF CALIBRATION

ISSUED BY Ricardo Energy & Environment
a trading name of Ricardo-AEA Ltd.

DATE OF ISSUE CERTIFICATE NUMBER DRAFT

0401

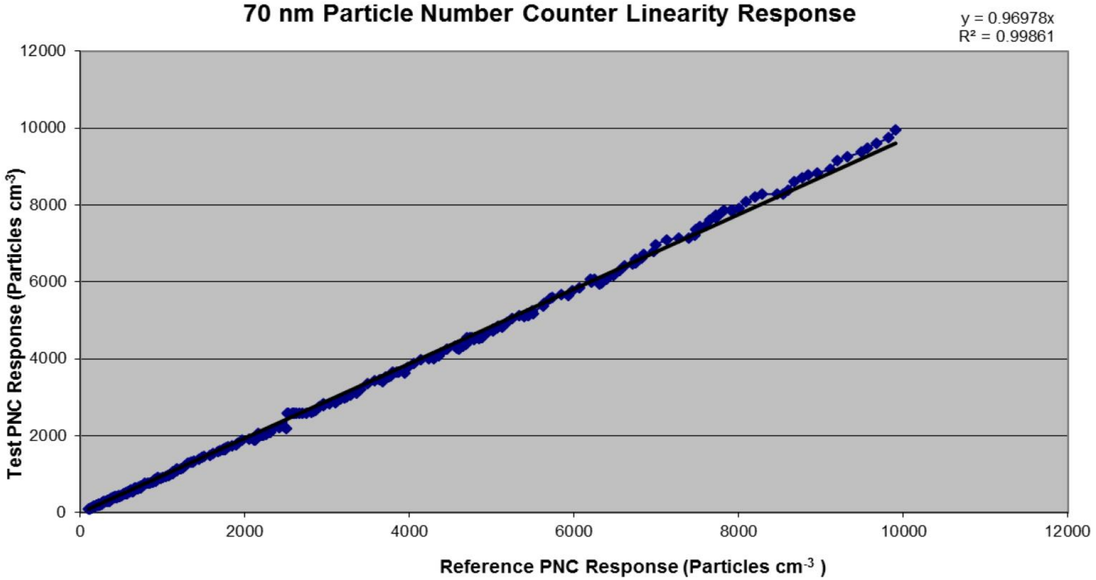
Ricardo Energy & Environment
Particle Measurement Centre
Unit 2 Ludbridge Mill
Reading Road, East Hendred
Wantage, Oxfordshire
OX12 8LN

Page 1 of 5 pages
Approved Signatory
Name
Signature

EXAMPLE ONLY

Particle counting efficiency against d_{50}=10 nm transfer standard

Diameter (nm)	Efficiency	$\lvert x_{min}.(a_1-1)+a_0\rvert$ ≤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



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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
- **<u>BUT low cost sensors ≠ low cost air quality monitor!</u>**
- 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

	School A		School B	
Sensor	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

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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

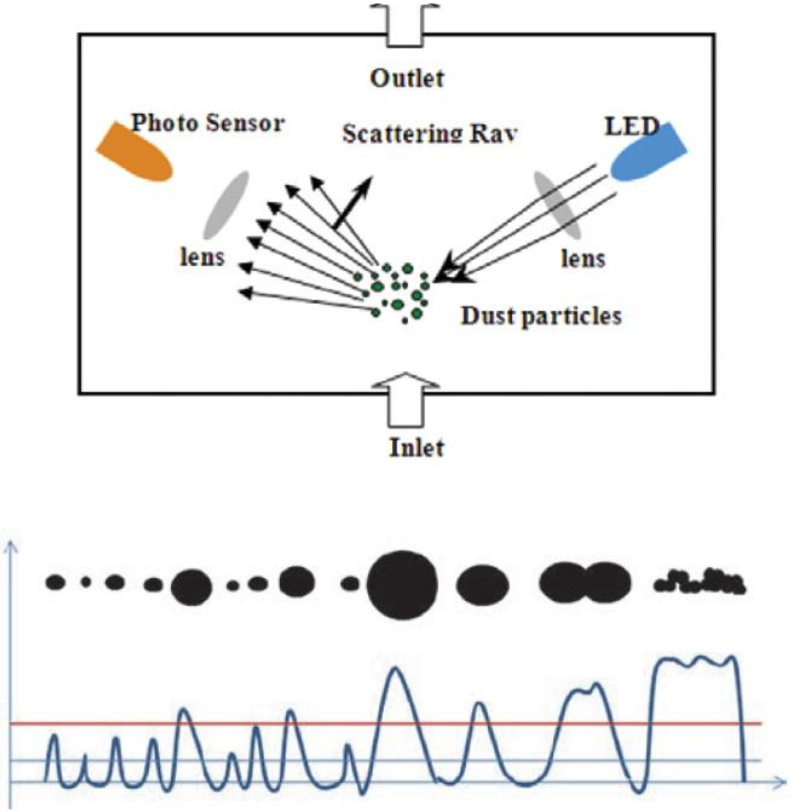

Figure 1 : Detection Principle

Parameter		Symbol	Min.	Typ.	Max.	Unit
Particle Size		D	0.3	2.5	10	um
Detection Range		D_{reg}	1	—	999	μg/m³
Resolution		R	—	1	—	μg /m³
Indication Error (2)	1 ~100 ug/m³	D_{err}	—	—	+/-10	μg /m³
	100~999 ug/m³		—	—	+/-10	%
Warm-Up Time		t_{wup} (2)	—	5	—	s
Response Time		t_{rsp} (2)	—	1	—	s

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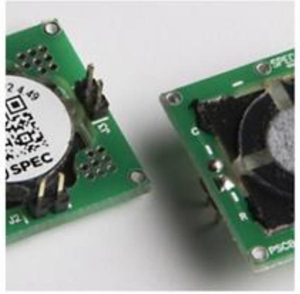
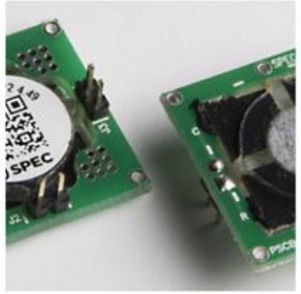
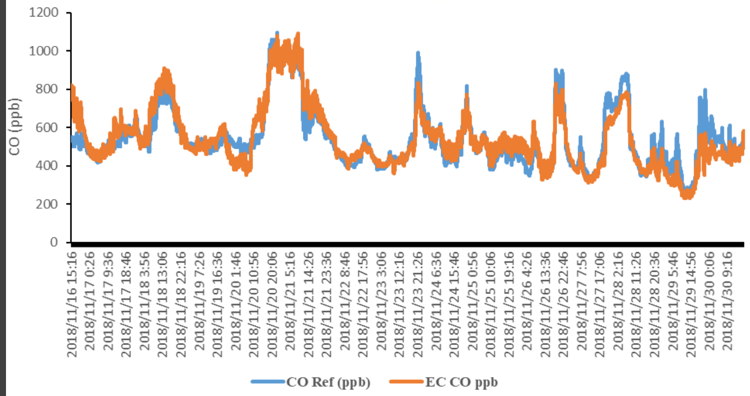
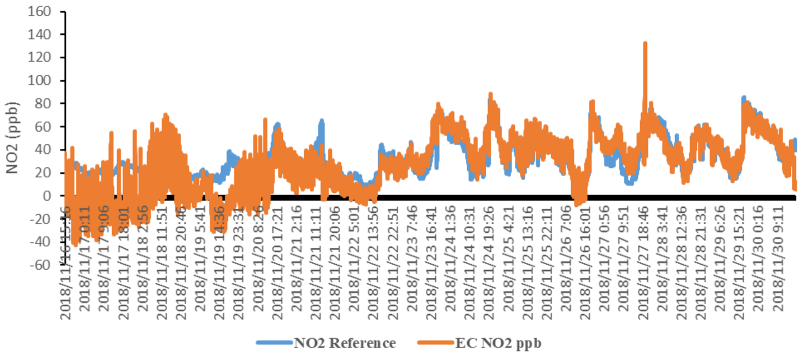
Low Cost PM Technology - Colocation

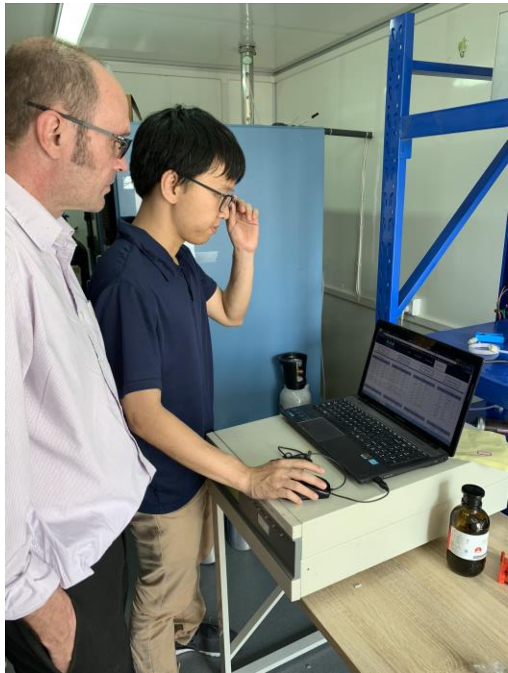
- Extensive colocation activities at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences Supersite to quantify, and improve low-cost sensor accuracy
- We are doing our due diligence on low-cost PM sensors currently





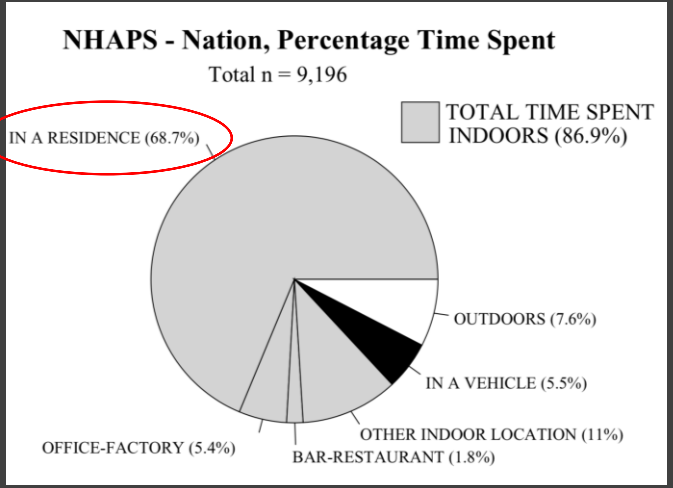


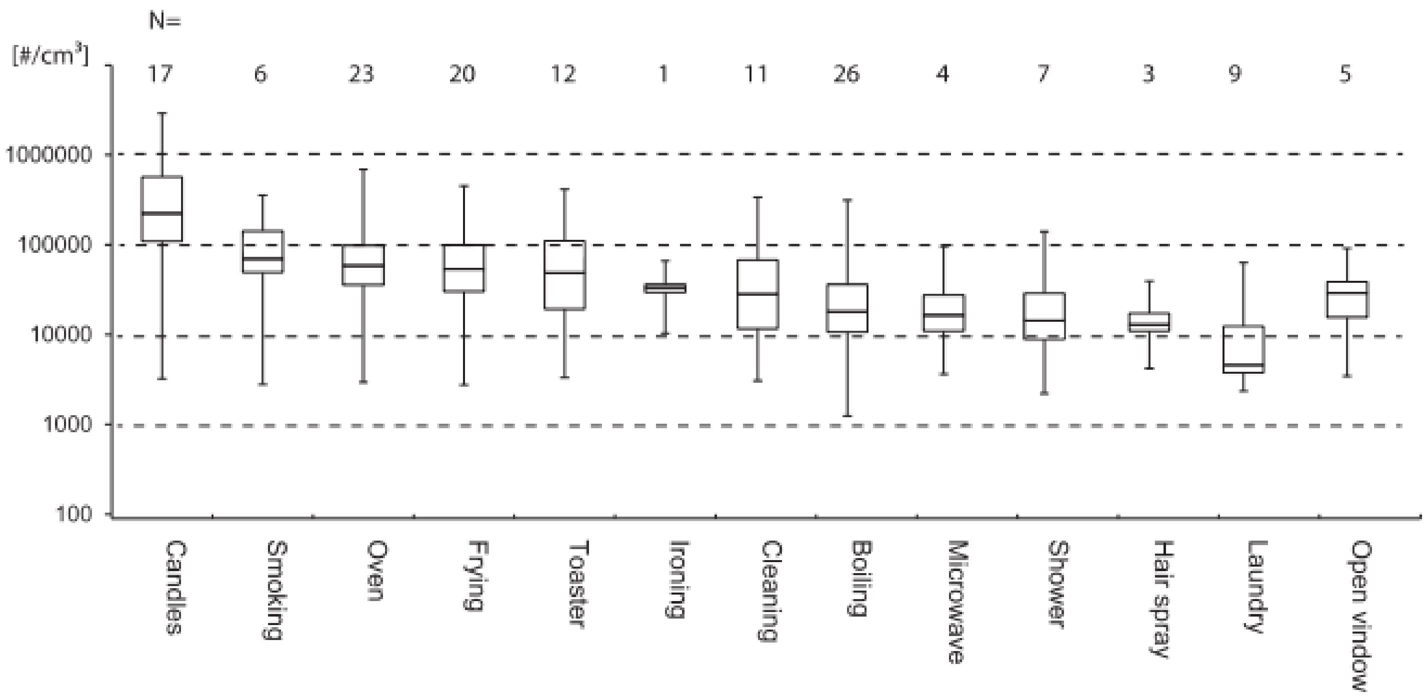




Indoor Air Quality - Homes

- 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)

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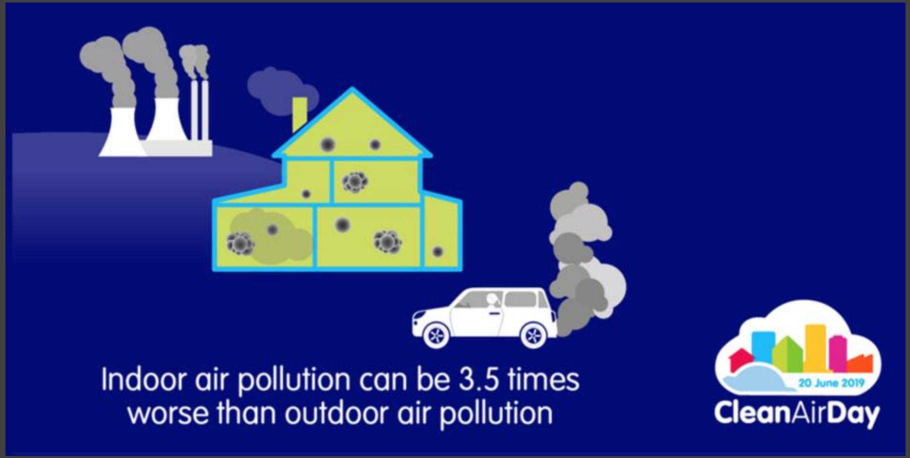
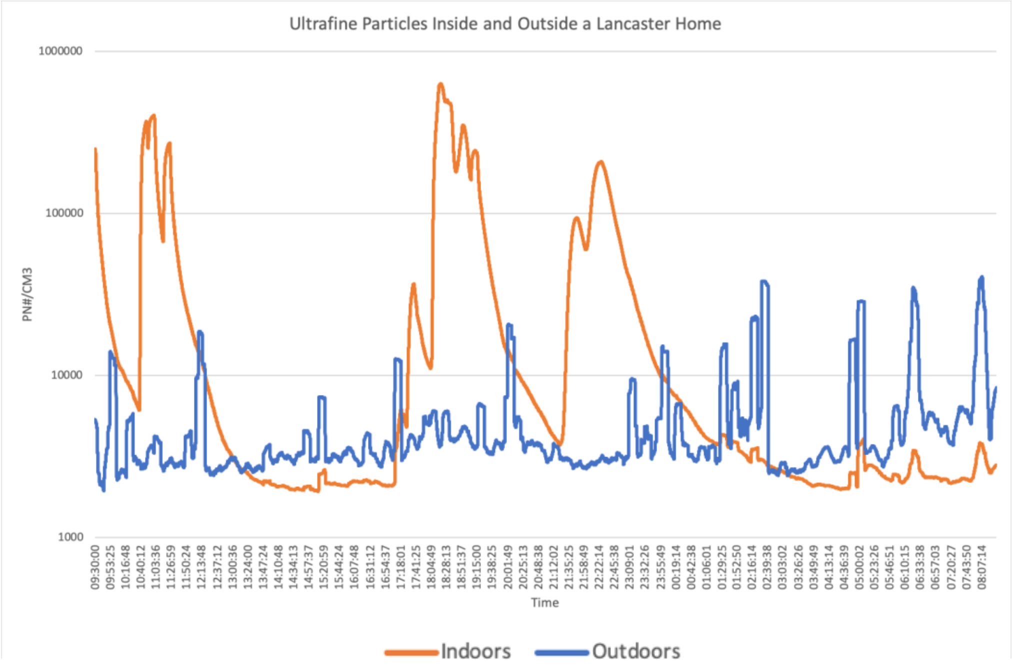
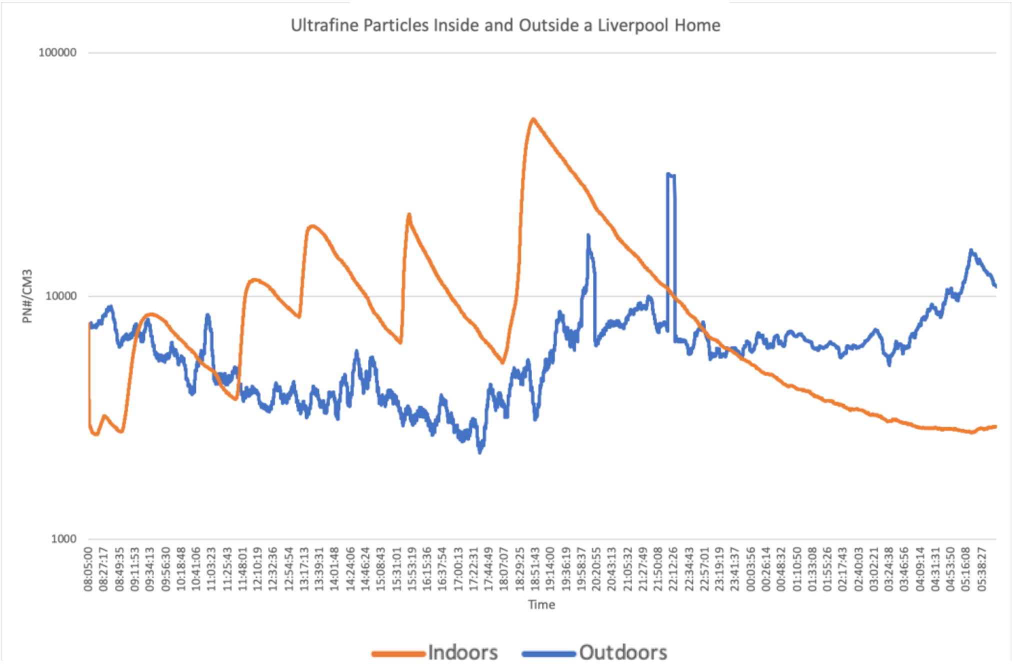
Indoor Air Quality - Homes

- 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

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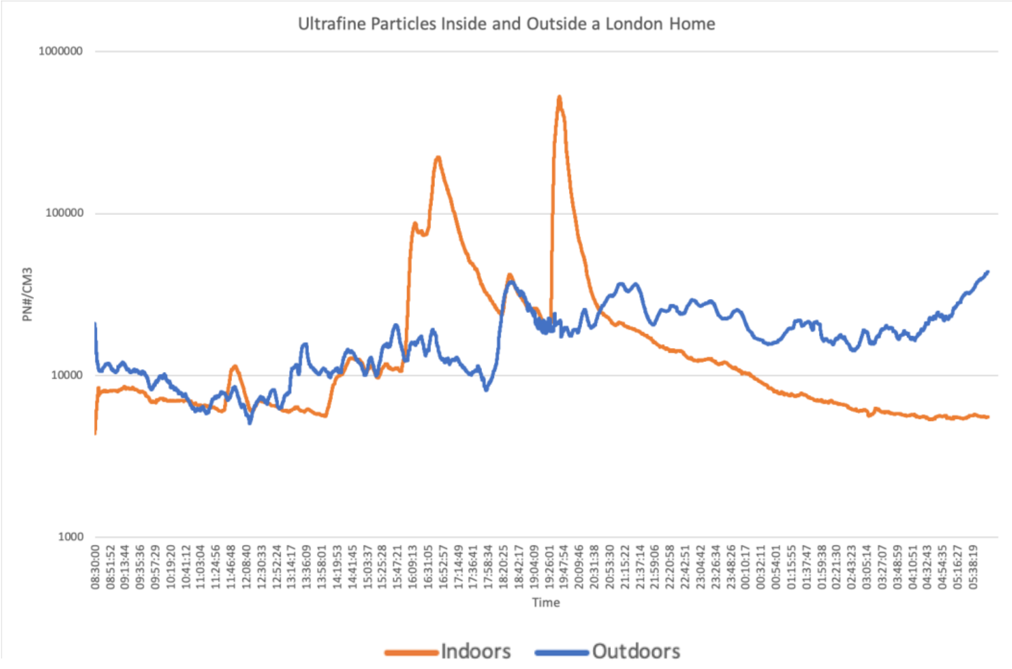
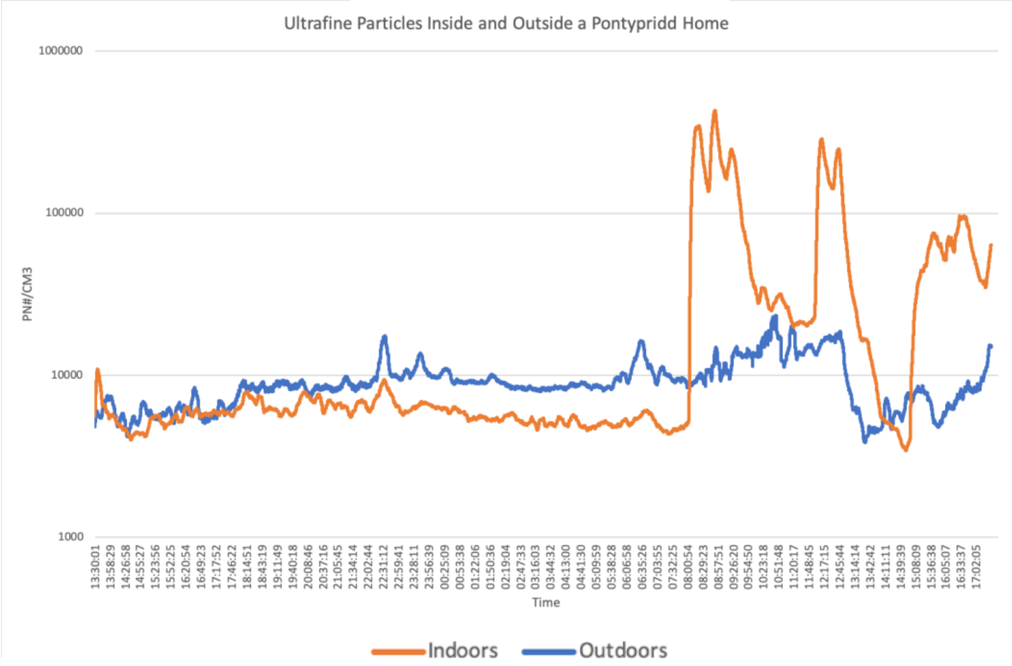
Indoor Air Quality - Homes

- 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
- **<u>We need more measurements in homes to better understand the problem</u>**
- What about energy efficiency?



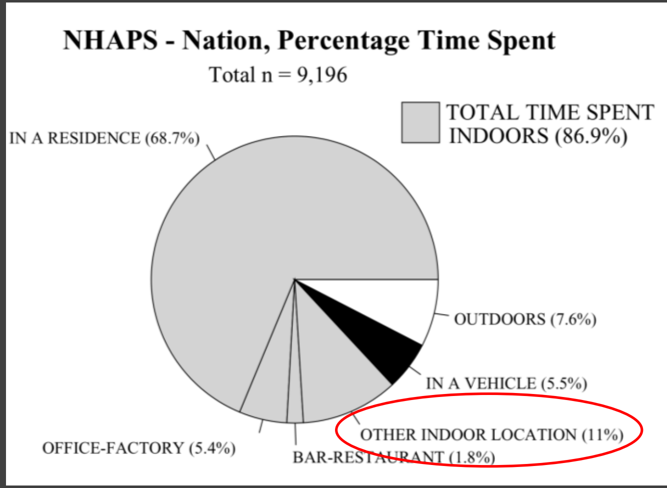
- Indoor 47% more polluted than outdoors
- Largest PNC concentrations from toast and frying steak
- High outdoor background concentrations

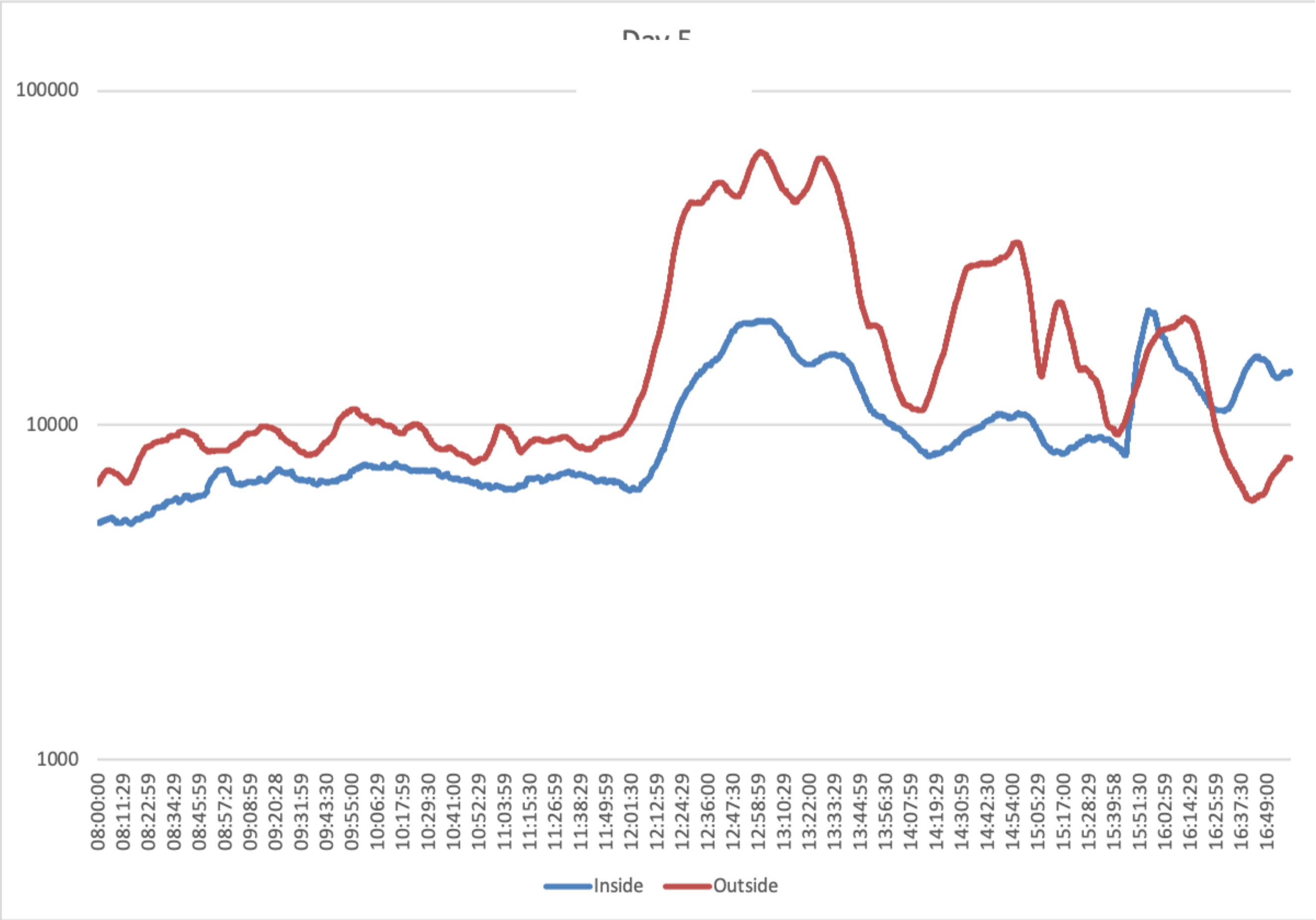


- Indoor 3x more polluted than outdoors
- Largest PNC related to cooking activities
- Some correlation between outdoor and indoor peaks suggesting PN infiltration

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

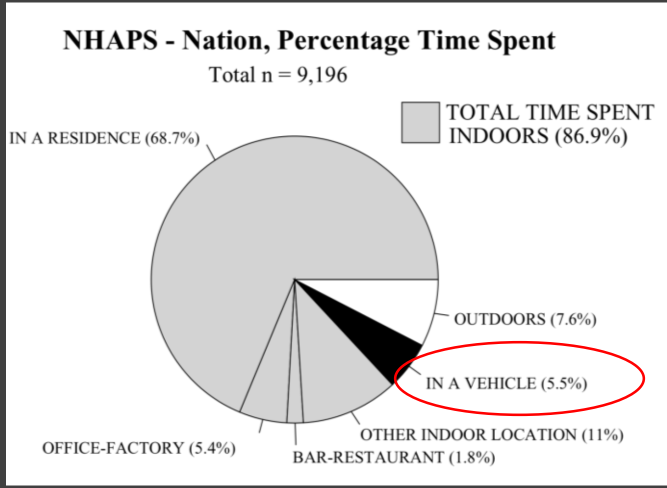
	Max	Min	Median	Mean	SD
08:00 – 17:00	22078	5058	8324	9991	4191
08:00 – 09:00	7428	5058	5751	5858	702
15:00 – 16:00	22078	8120	9045	10903	4154

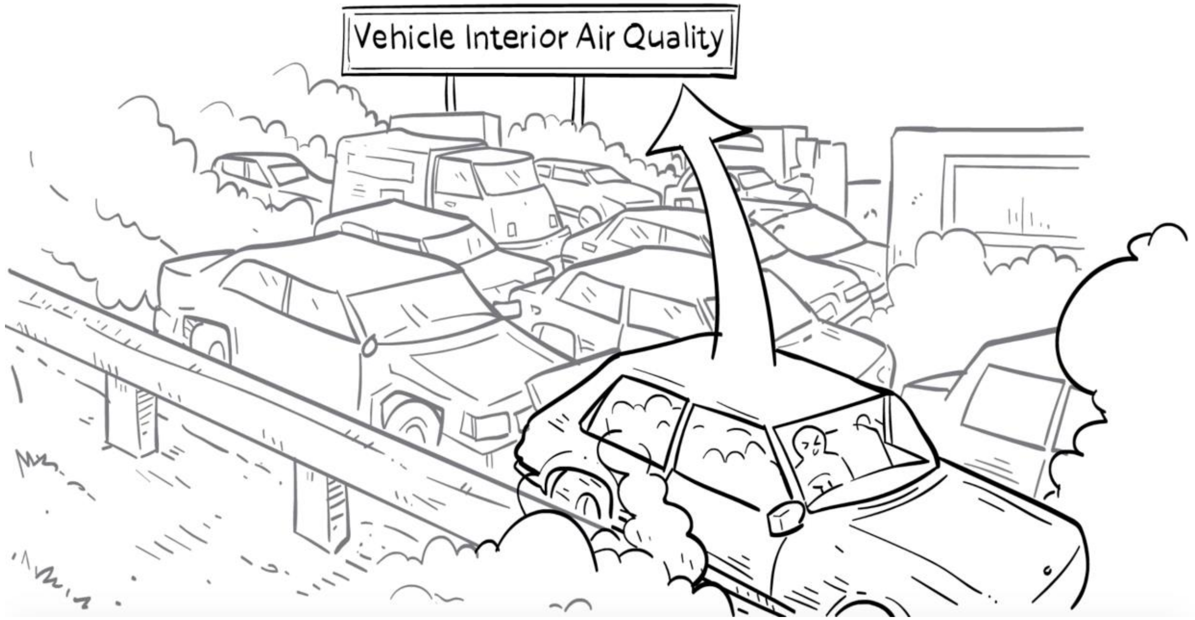
OUTSIDE

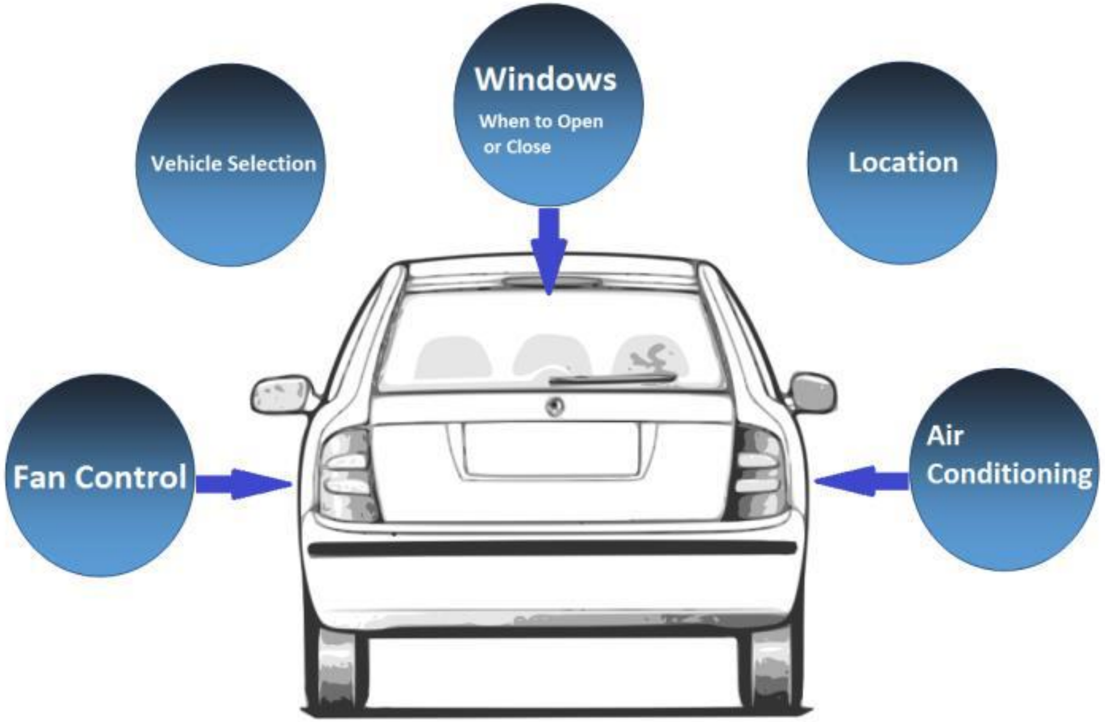
	Max	Min	Median	Mean	SD
08:00 – 17:00	65660	5950	10321	18653	15397
08:00 – 09:00	9592	6656	8424	8299	903
15:00 – 16:00	29710	9399	14798	15768	4560

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

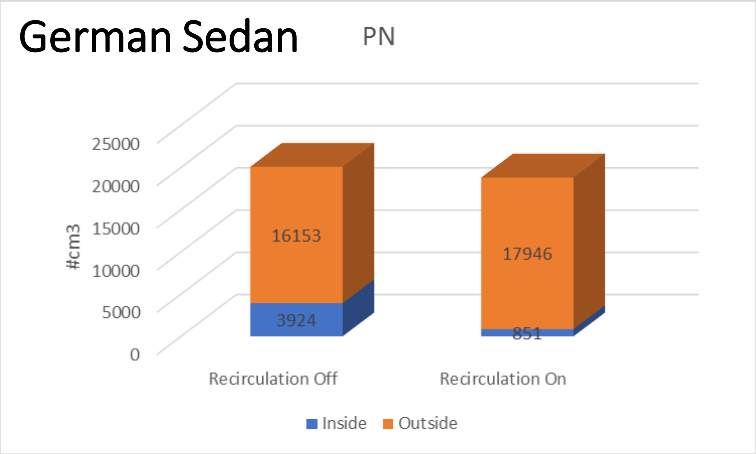


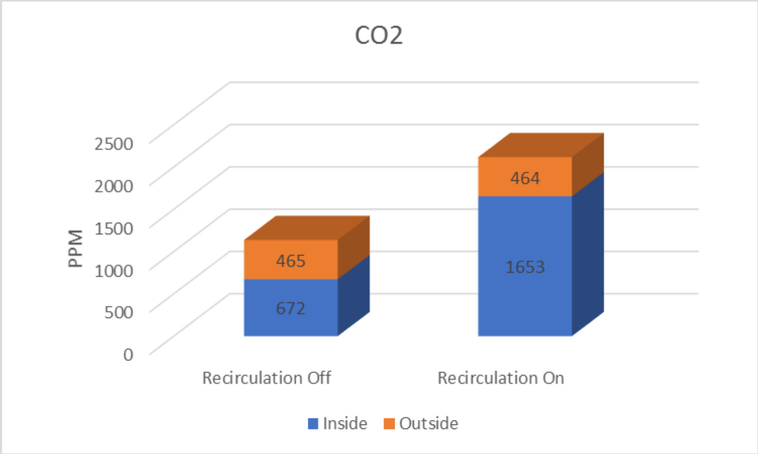




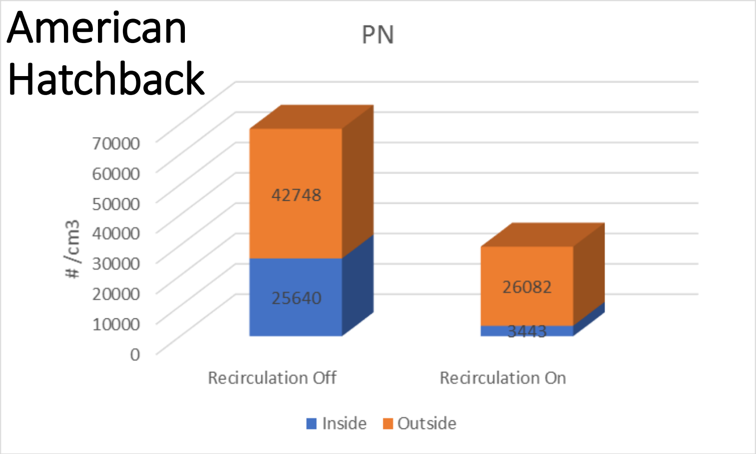
Effect of Occupant Behaviour

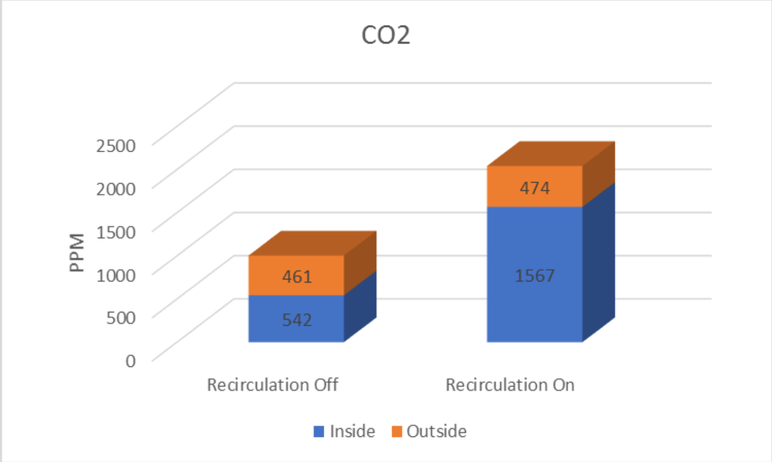
- **Ingress Ratio** – How much outside air pollution is getting into the cabin?
- **Stuffiness Factor** – How well is the vehicle ventilating CO_2?





	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	24%	1.4
Recirculation On	5%	3.6



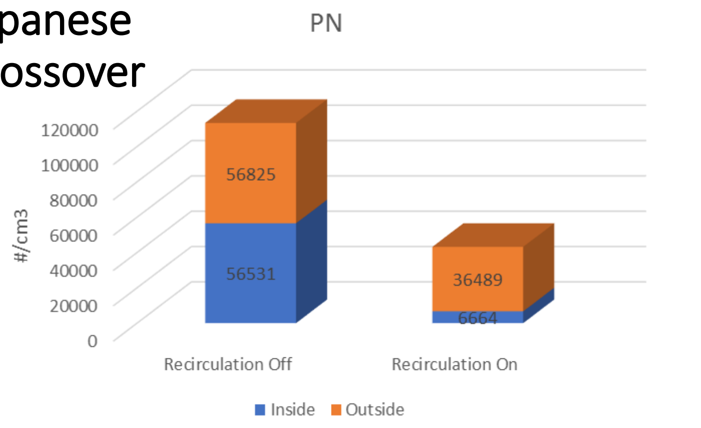


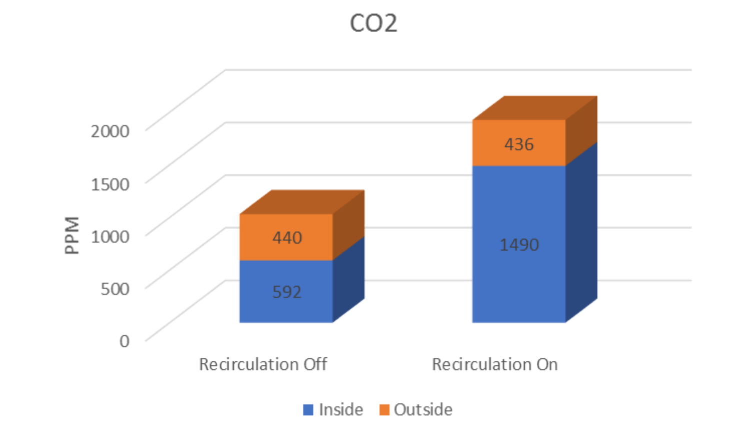
	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	60%	1.2
Recirculation On	13%	3.3

Effect of Occupant Behaviour

- **Ingress Ratio** – How much outside air pollution is getting into the cabin?
- **Stuffiness Factor** – How well is the vehicle ventilating CO_2?

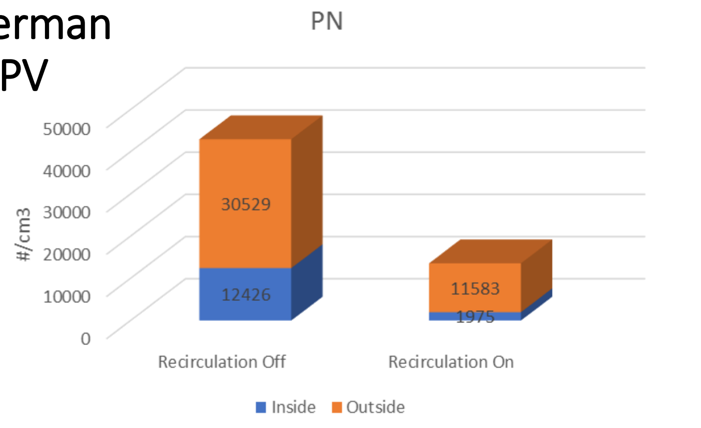
Japanese Crossover

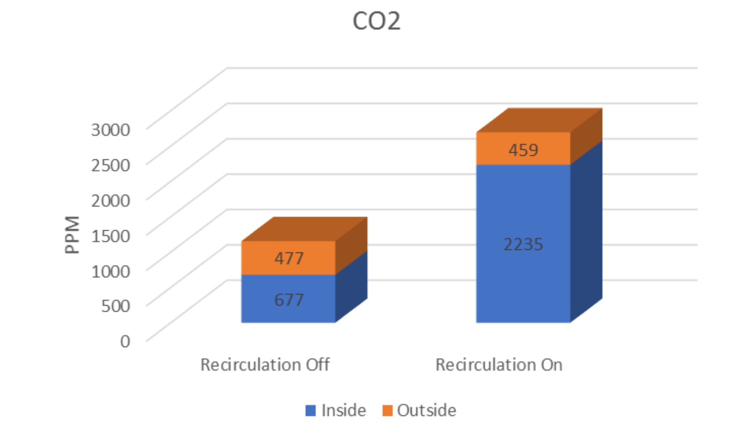




	INGRESS RATIO	STUFFINESS FACTOR
Recirculation Off	99%	1.3
Recirculation On	18%	3.4

German MPV





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

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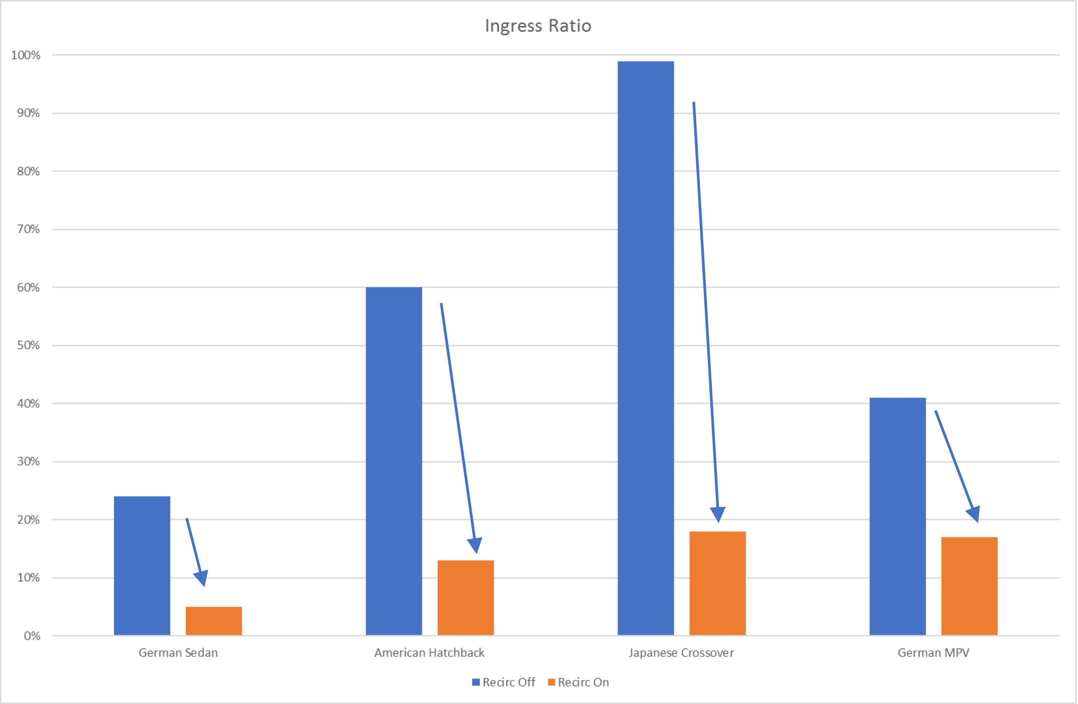
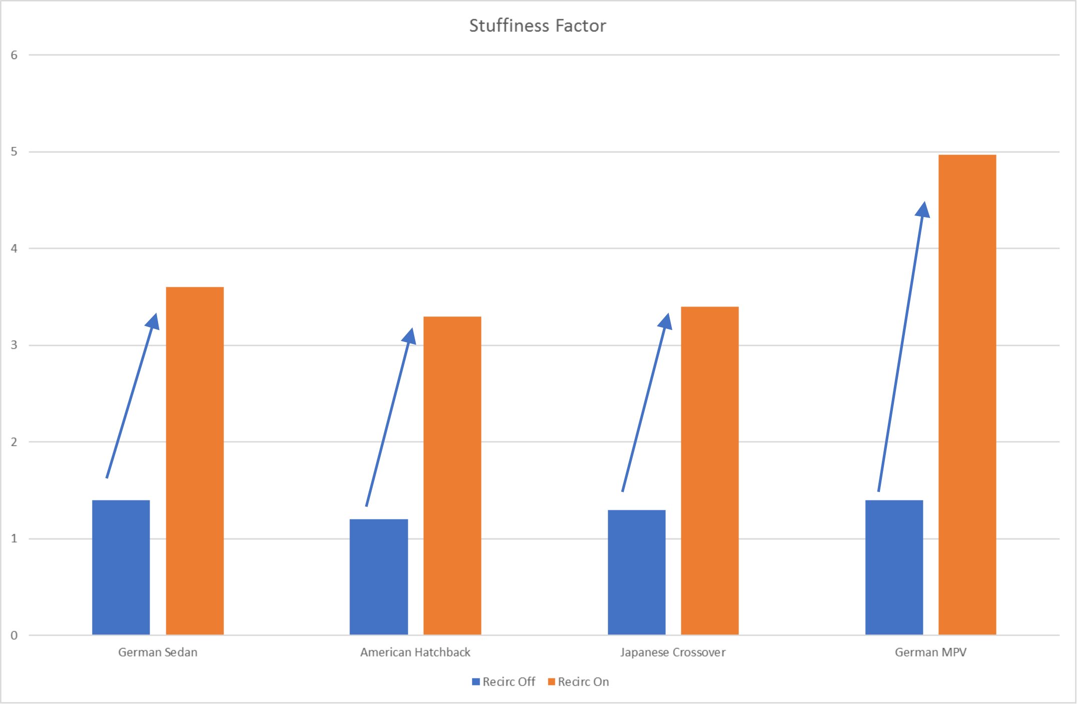
Effect of Occupant Behaviour - Summary

- 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



CO_2



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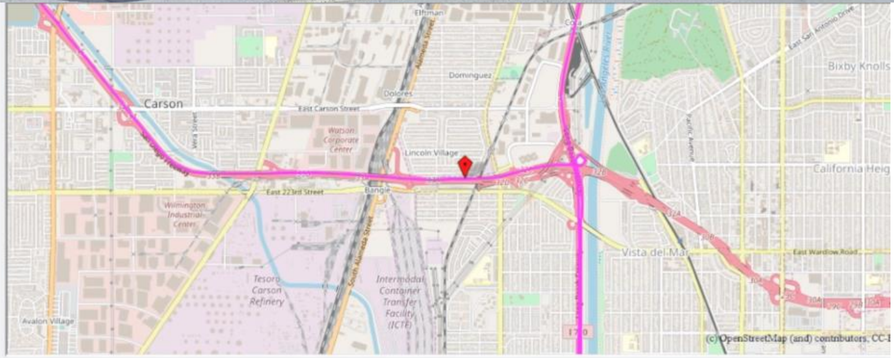
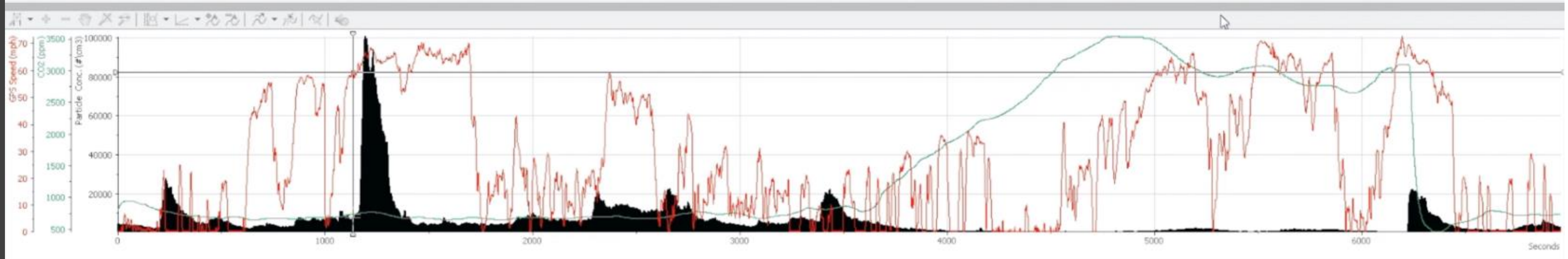
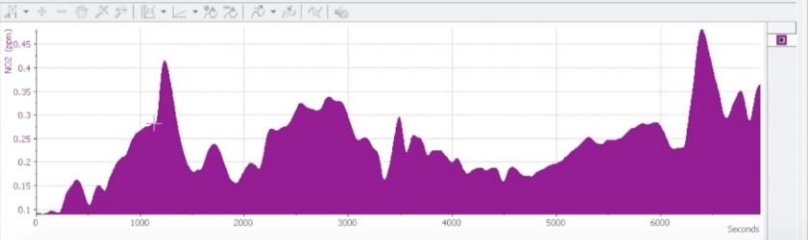
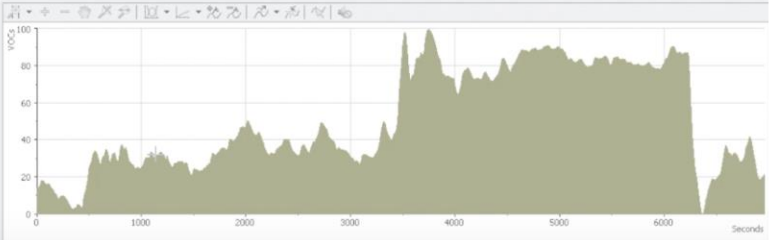
Effect of Occupant Behaviour

- 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









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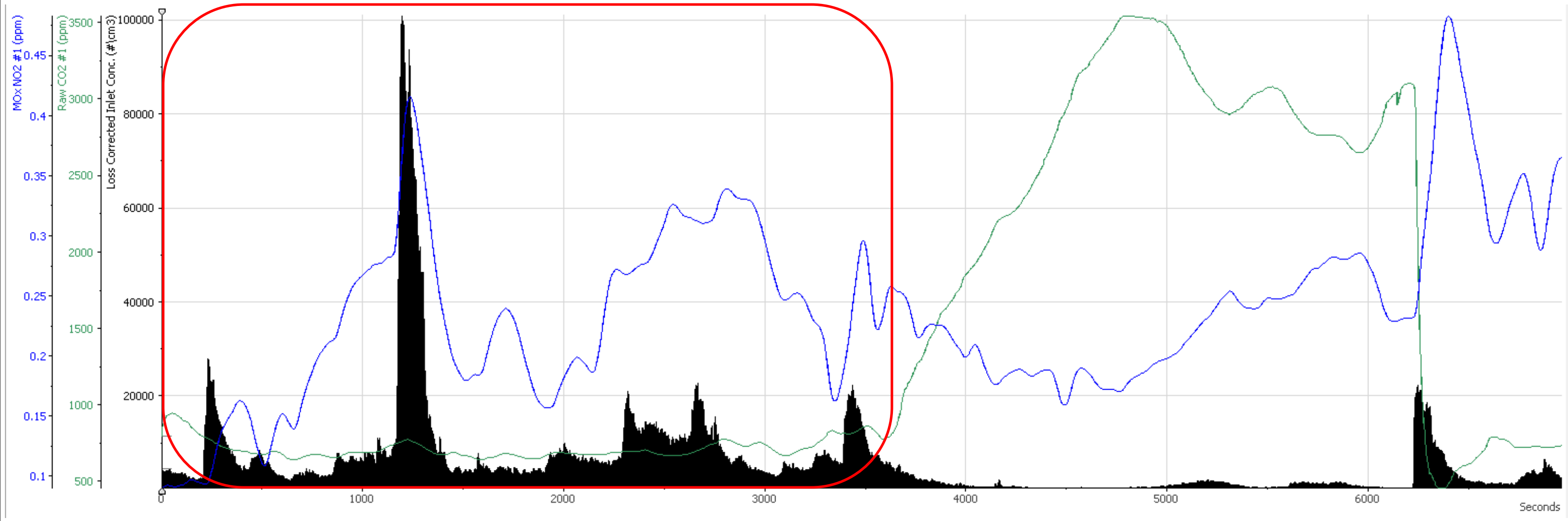
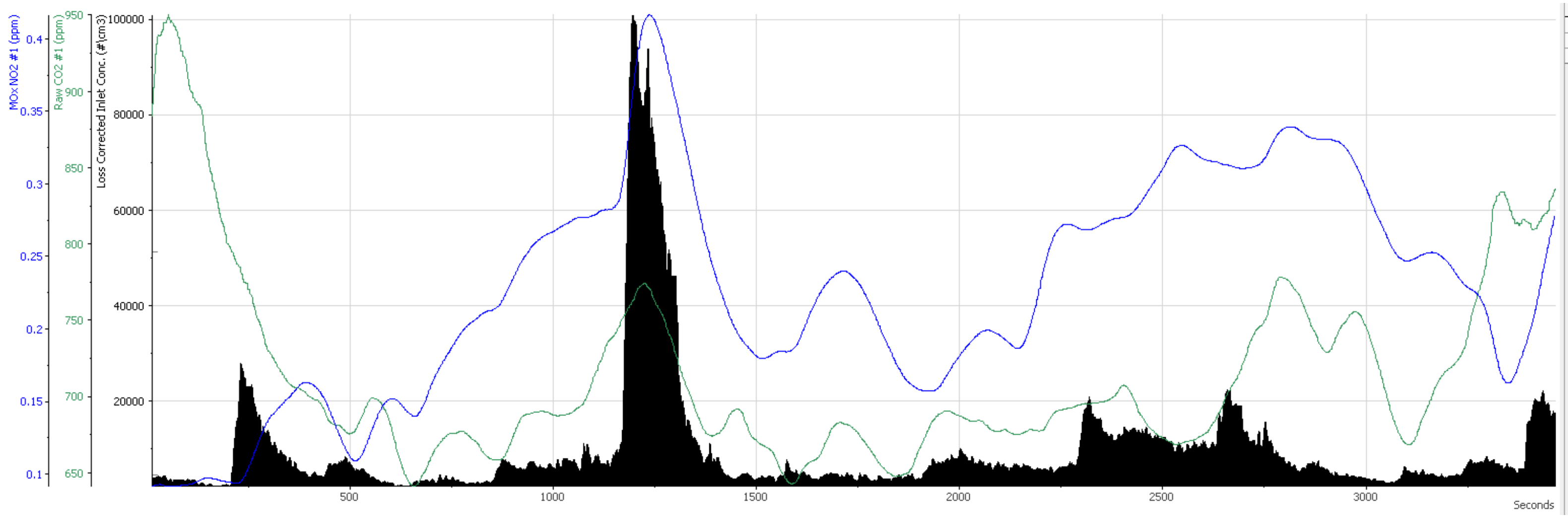
Effect of Occupant Behaviour – "Fresh Air" Mode

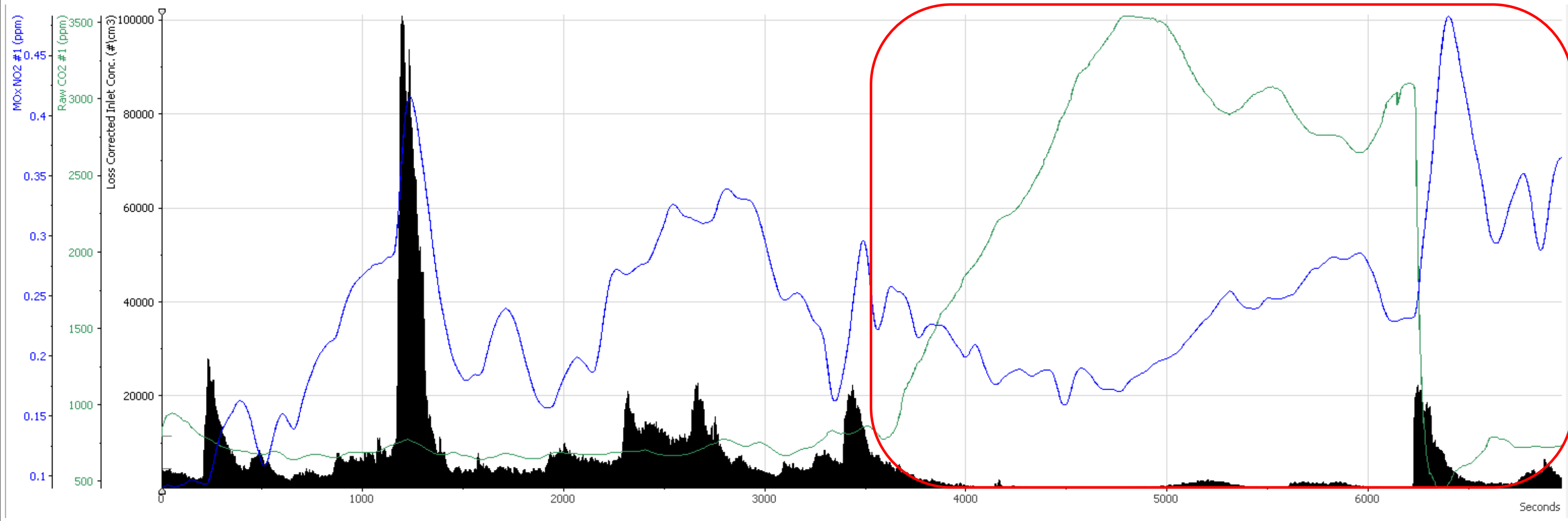
- PN peaks at 100,900 #/cm3
- Vehicle is well ventilated, with CO_2 concentrations <1000ppm
- VIAQ is susceptible to extremely localized air quality: dirty diesels!

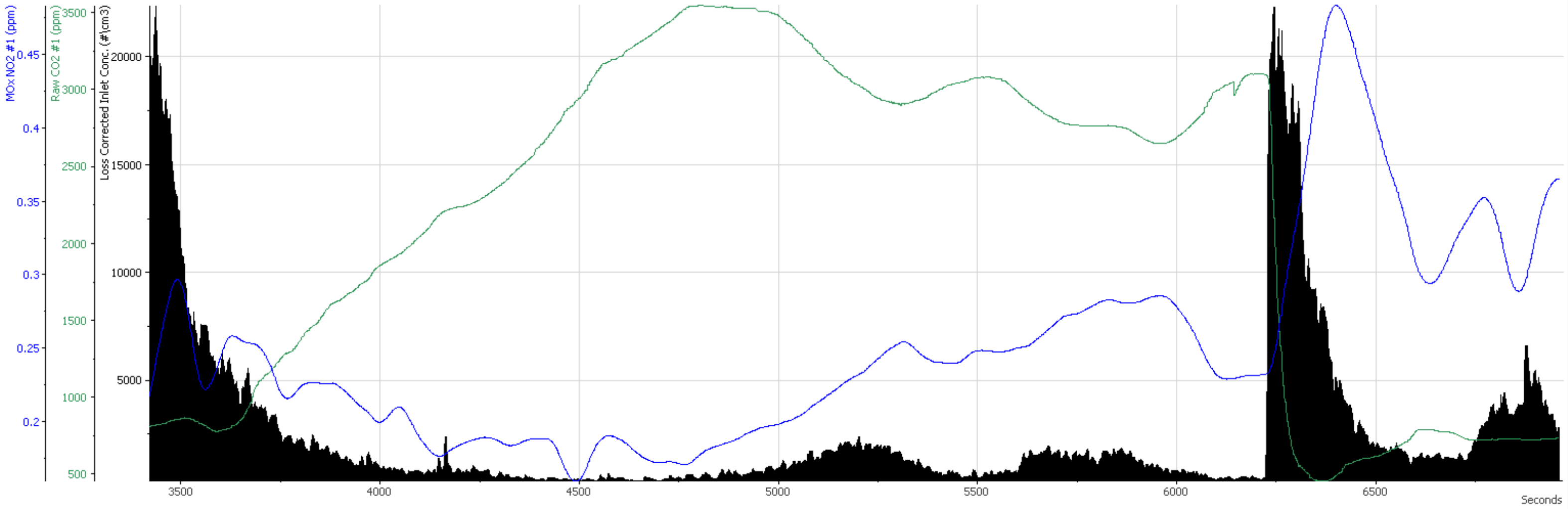




Effect of Occupant Behaviour – Recirculation Mode

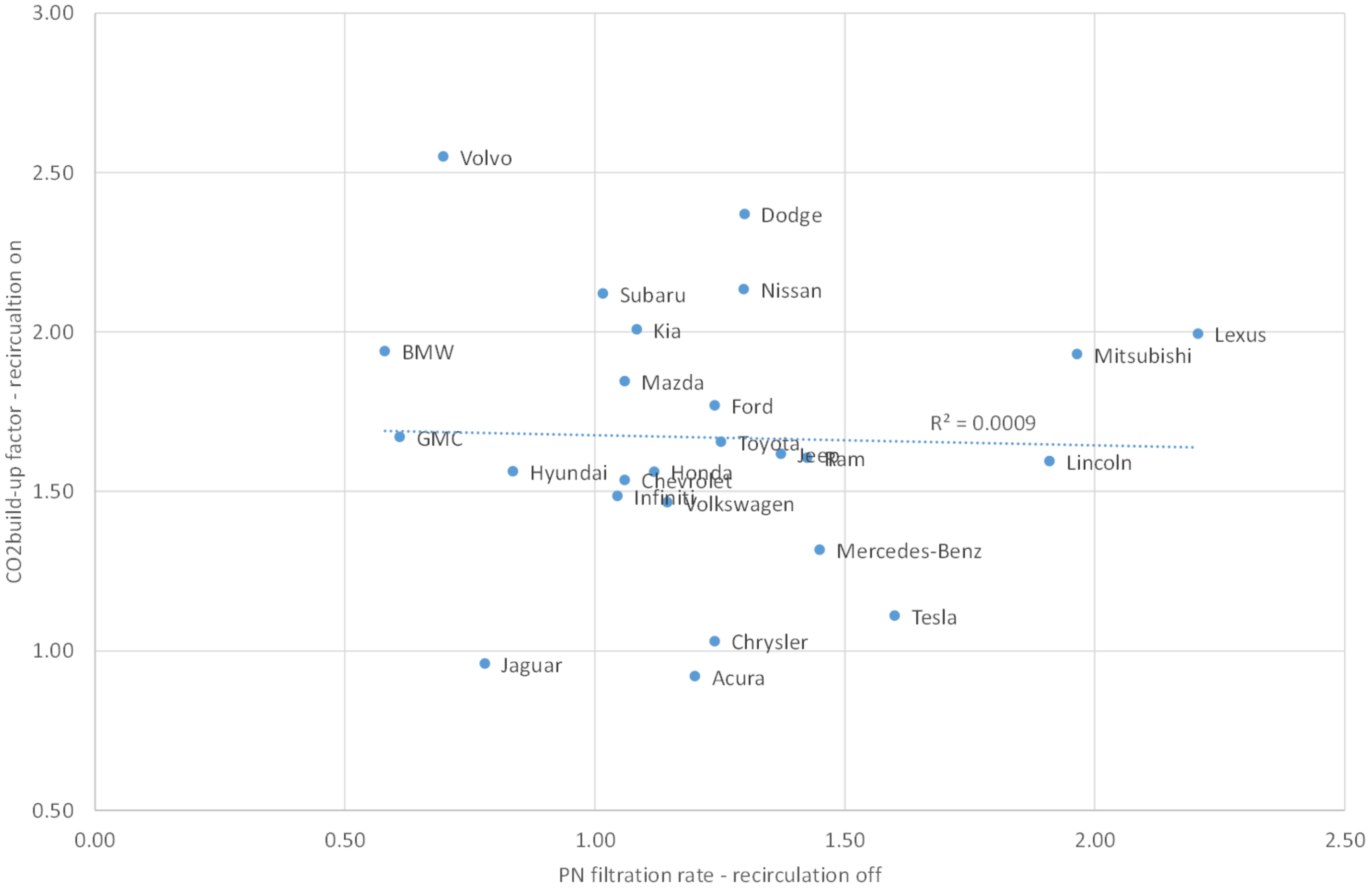
- PN exponential decay to low concentrations
- CO_2 peaks at >3500ppm
- Increased leakage of HVAC associated with higher speeds, results in some CO_2 ventilation, and some PN infiltration
- Obvious dichotomy between PN & CO_2





Effect of Occupant Behaviour – Recirculation Mode

- Independent ratings to quantify and compare to empower consumers
- Driver choice between PN from fresh air mode and CO_2 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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