Flow of Nanoparticles In And Around Road Vehicles

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CEHE – Centre For Environmental And Health Engineering

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OUTLINE

- **BACKGROUND**
  - Nanoparticles; Origin; Importance?
  - Why are they distinct from other pollutants?

- **EMISSION AND DISPERSION OF ATMOSPHERIC NANOPARTICLES**

  Various spatial scales

  - ✓ Behind your car
  - ✓ Inside your car
  - *Roadside/street canyons*
  - *Within cities*

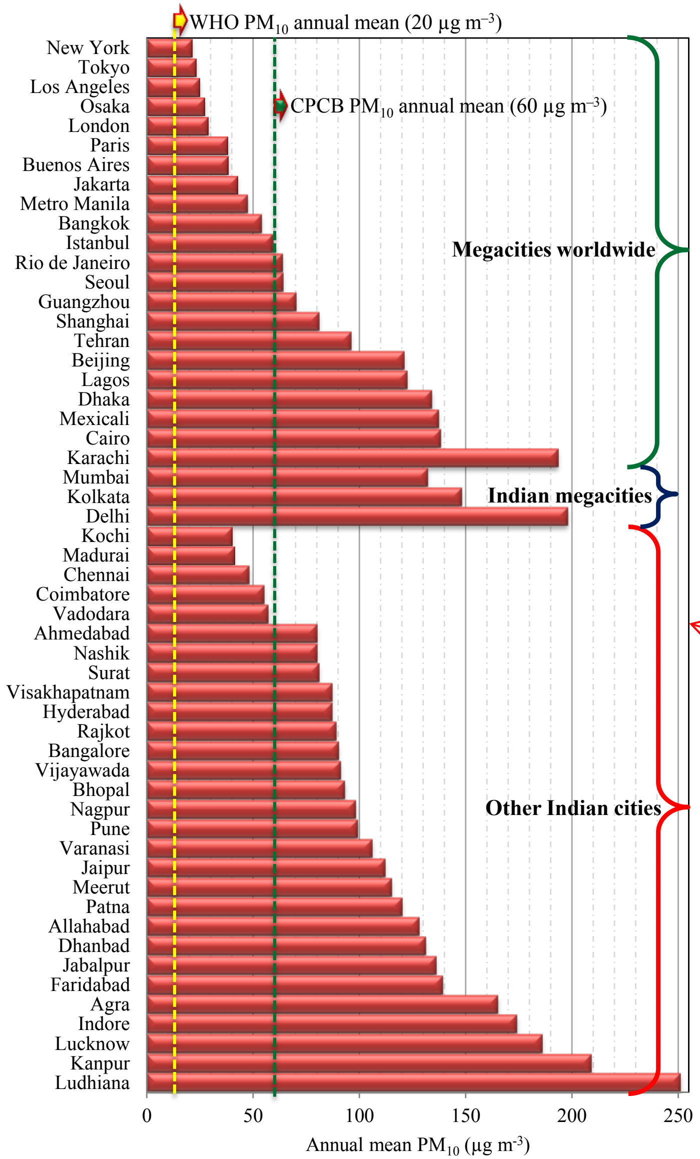
Cities $\sim 10^{3}$ - 10^{4} cm^{-3}

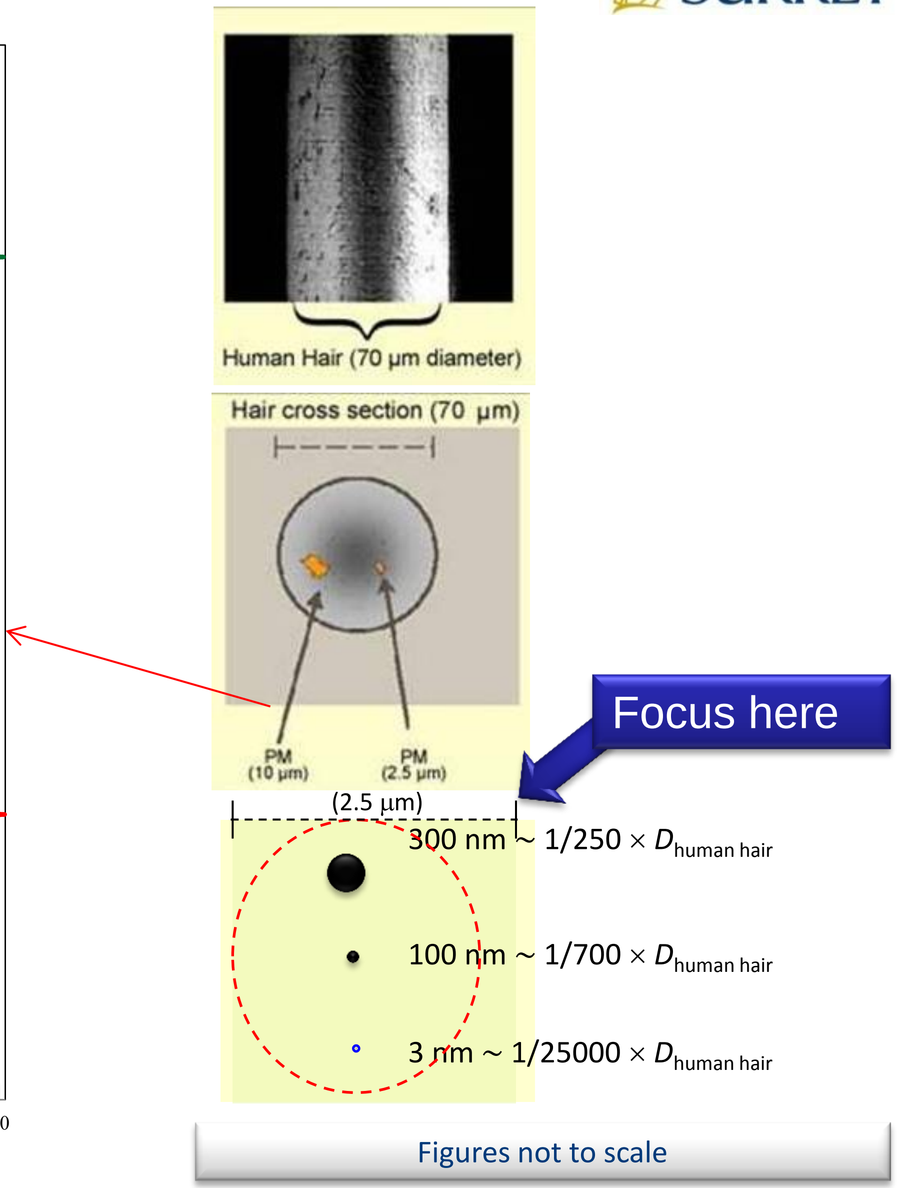
Roadside/Street canyons $\sim 10^{4}$-10^{5} cm^{-3}

On-road (within vehicles) lower end of $\sim 10^{5}$ cm^{-3}

Tailpipe $\sim 10^{6}$-10^{7} cm^{-3}

- **SUMMARY AND CONCLUSIONS**





Taken from: **Kumar, P.,** Jain, S., Gurjar, B.R., Sharma, P., Khare, M., Morawska, L., Britter, R., 2013. Can a "Blue Sky" Return to Indian Megacities? *Atmospheric Environment* 71, 1-4.

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- **Definition of nanoparticles?**
  - Any particle in nanosize range, <10 nm, <50 nm, <100 nm?
  - BIS and EU definition for nanoparticles – any dimension of size between 1 and 100 nm; but this is for MNPs!
  - By analogy of PNCs in urban environments, over 99% of total PNCs <300 nm

- **How do they originate?**
  - Combustion of fossil fuels (road vehicles dominant source)
  - Other sources (e.g. power plants, ship emissions, aircrafts, non-exhaust sources)
  - Formation through gas-to-particle conversion, direct emissions, secondary formation, and mechanical attrition

- **Why Important?**
  - Adverse health effects, role in visibility impairment and global climate change
  - Number based Euro-5& 6 emission standards – ambient air quality standards?
  - Need to understand their dispersion behaviour in various settings for developing modelling tools
  - Road sides, urban street canyons are pollution 'hot spots' because of limited dispersion due to surrounding built–up environment

Taken from: **Kumar, P.,** Robins, A., Vardoulakis, S., Britter, R., 2010. A review of the characteristics of atmospheric urban nanoparticles and the prospects of developing regulatory control. *Atmospheric Environment* 44, 5035-5052 . [*Most downloaded article*]

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WHY ARE THEY DISTINCT FROM OTHER POLLUTANTS?

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- Appropriate treatment of particle dynamics in dispersion model at various urban scales is key for accurate prediction

Symbols +, – and 0 denotes gain, loss and no effect of the transformation processes on particle number concentrations, respectively. Acronyms I, V and n stand for important, very important and no important (can be ignored), respectively.

Transformation processes	Effects on concentrations		Vehicle wake		Street canyons	Neighb–ourhood	City	Tunnel
	number	volume	near	far				
Emissions	+	+	V	V	V	V	V	V
Nucleation	+	+	V	I	I*	I*	I	I
Dilution	+/–	+/–	V	V	V	V	V	V
Coagulation	–	0	n	n	n$	n$	I	V
Condensation	0	+	V	I	n$	n$	I	I
Evaporation	0/–	–	I	V	I	I	n	I
Dry deposition	–	–	V	V	I	I	I	V
Wet deposition	–	–	n	n	n	n	I	n

*Important near the source (i.e. vehicle tail pipe); probably not important later though will depend on the background concentrations, dilution and other meteorological parameters (i.e. wind speed, direction, temperature, solar radiation).
$Depending on the background concentrations, fresh emissions and meteorological parameters.

Taken from: **Kumar, P.,** Ketzel, M., Vardoulakis, S., Britter, R., 2011. Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environments. *Journal of Aerosol Science* 42, 580-603. [*Most cited and downloaded paper*]

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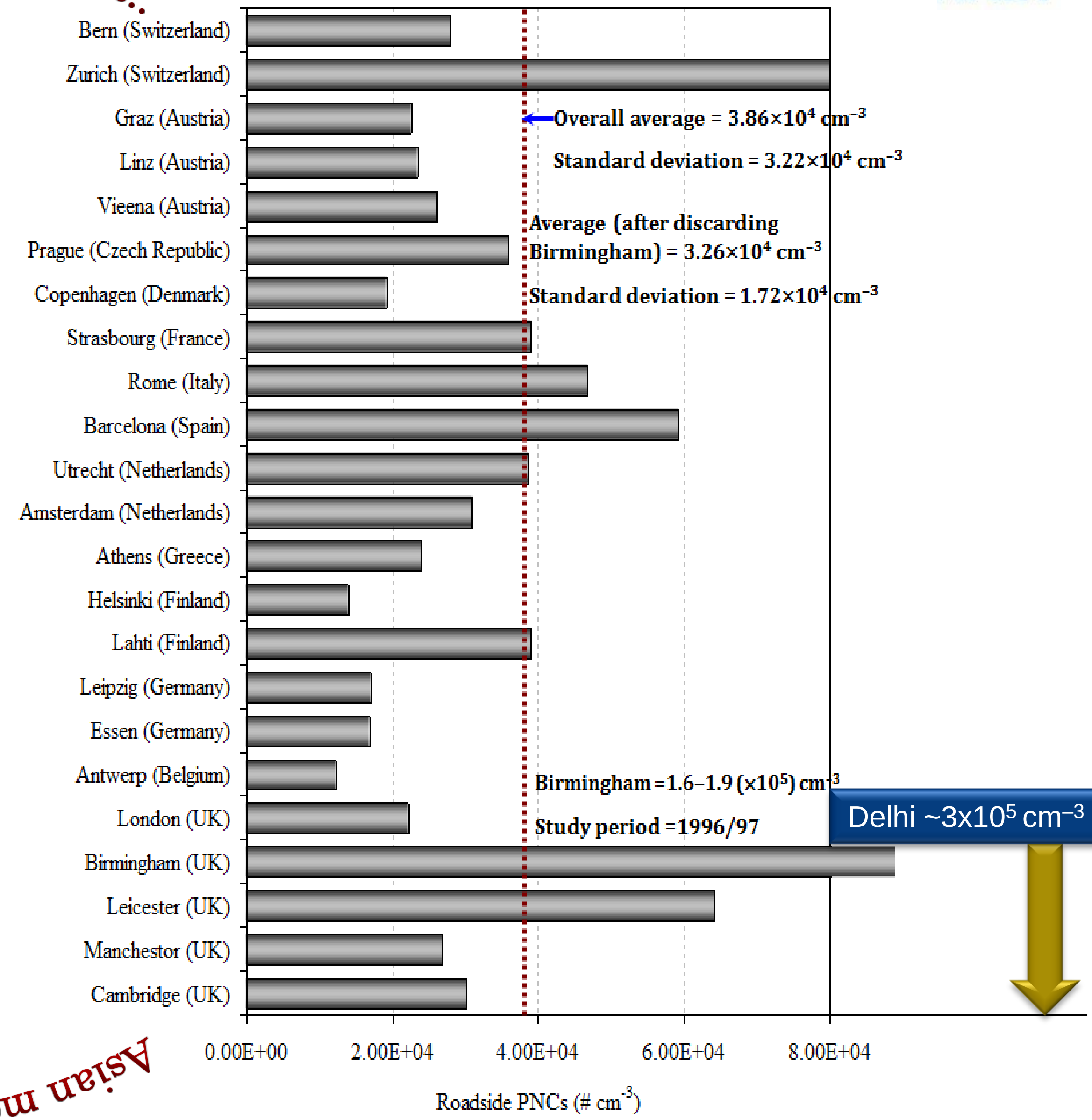
Asian megacities show more than 10's of time higher nanoparticle concentrations compared with European megacities..



Source: **Kumar**, Harrison, Morawska (2012). Handbook of Air Quality in Europe.

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What happens to nanoparticles behind your car?

*Carpentieri, M., **Kumar, P.,** 2011. Ground–fixed and on–board measurements of nanoparticles in the wake of a moving vehicle. *Atmospheric Environment* 45, 5837-5852.

VEHICLE WAKE (FIELD & WIND TUNNEL EXPERIMENTS)

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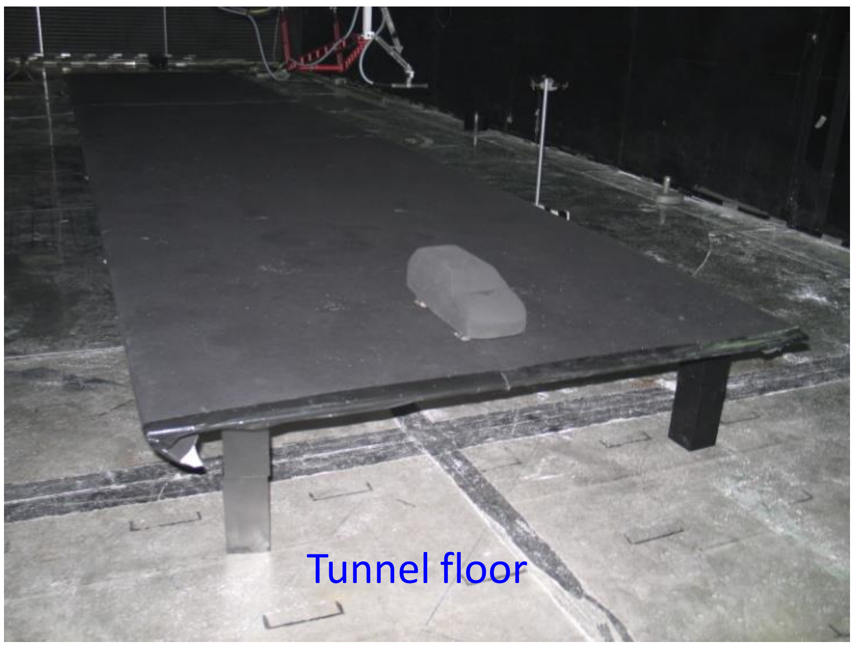
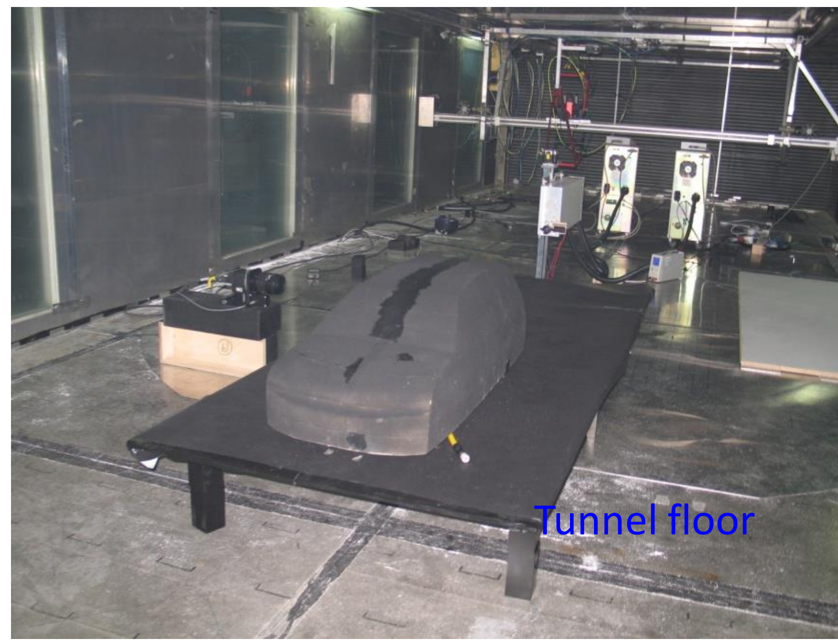
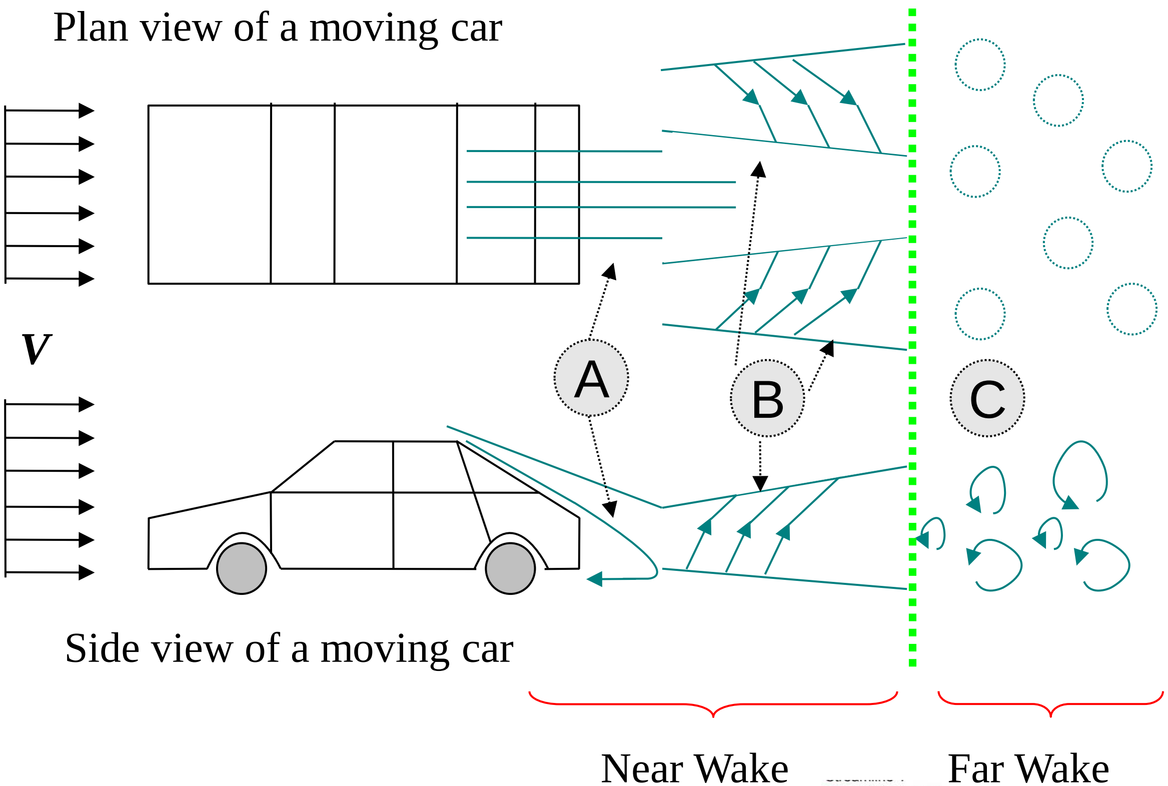
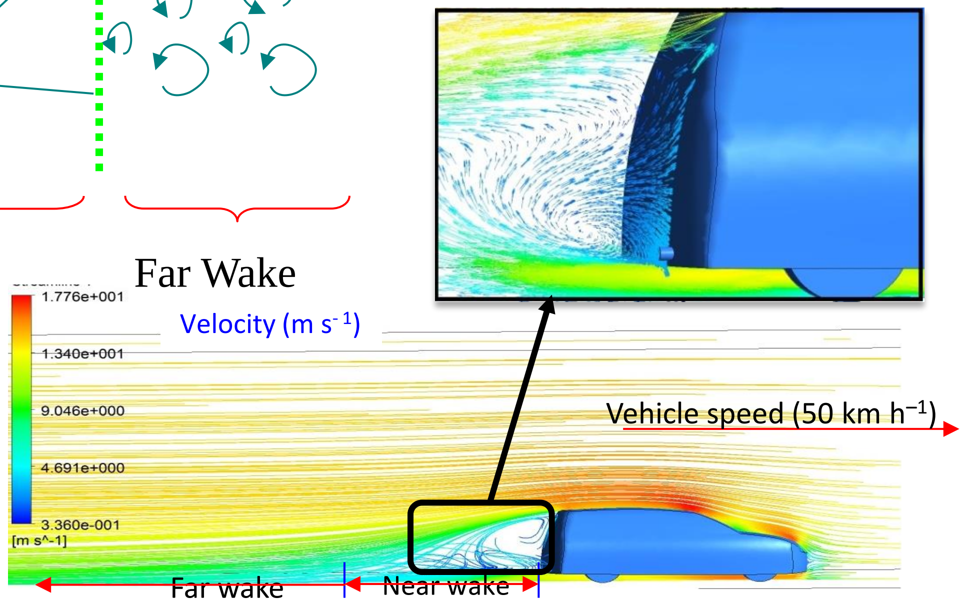




Work from the EPSRC first grant: Carpentieri, M., **Kumar, P.,** Robins, A., 2012. Wind tunnel measurements for dispersion modelling in vehicle wakes. Atmospheric Environment 62, 9-25.

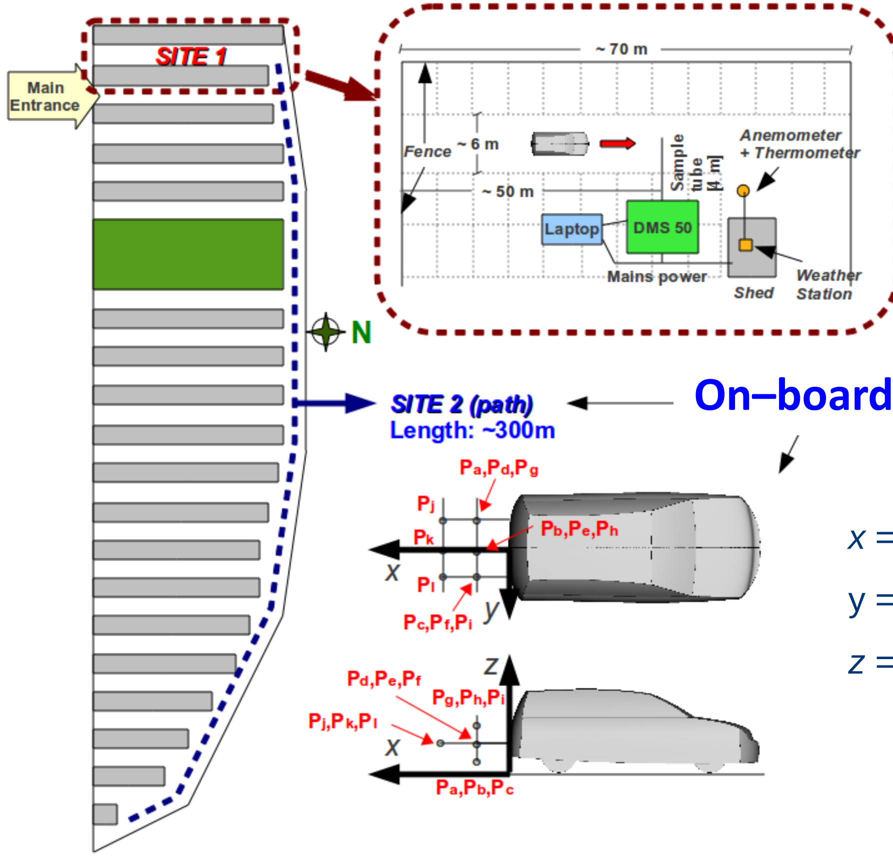
VEHICLE WAKE





Taken from: Carpentieri, M., **Kumar, P.,** Robins, A., 2010. An overview of experimental results and dispersion modelling of nanoparticles in the wake of a moving vehicle. *Environmental Pollution* 159, 685-693.

VEHICLE WAKE (ground–fixed and on–board measurements)*



← Ground–fixed

x = 0.45 and 0.80 m

y = 0.45, 00 and –0.45 m

z = 0.10, 0.55 and 0.90 m

- Ground-fixed point (16 Oct 2010), on-board (13 November 2010 and 29 January 2011)
- 2 different ground–fixed heights: 10 cm and 25 cm from the ground
- Car passes at different speed: approximately 20, 30, 40 and 50 km h^{-1}
- Each test repeated several times for the purpose of data reliability

Taken from*: Carpentieri, M., **Kumar, P., 2011. Ground–fixed and on–board measurements of nanoparticles in the wake of a moving vehicle. *Atmospheric Environment* 45, 5837-5852.

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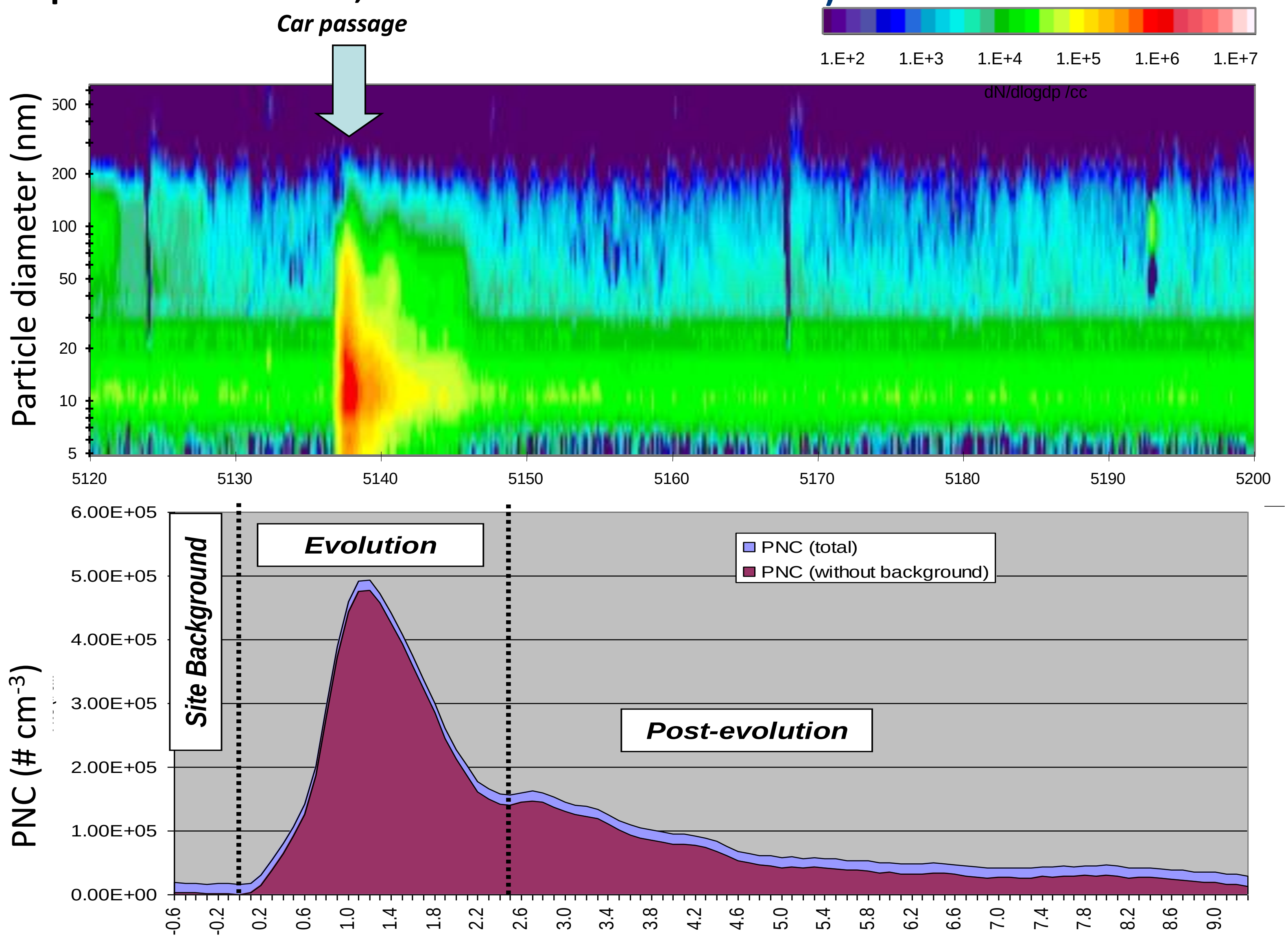
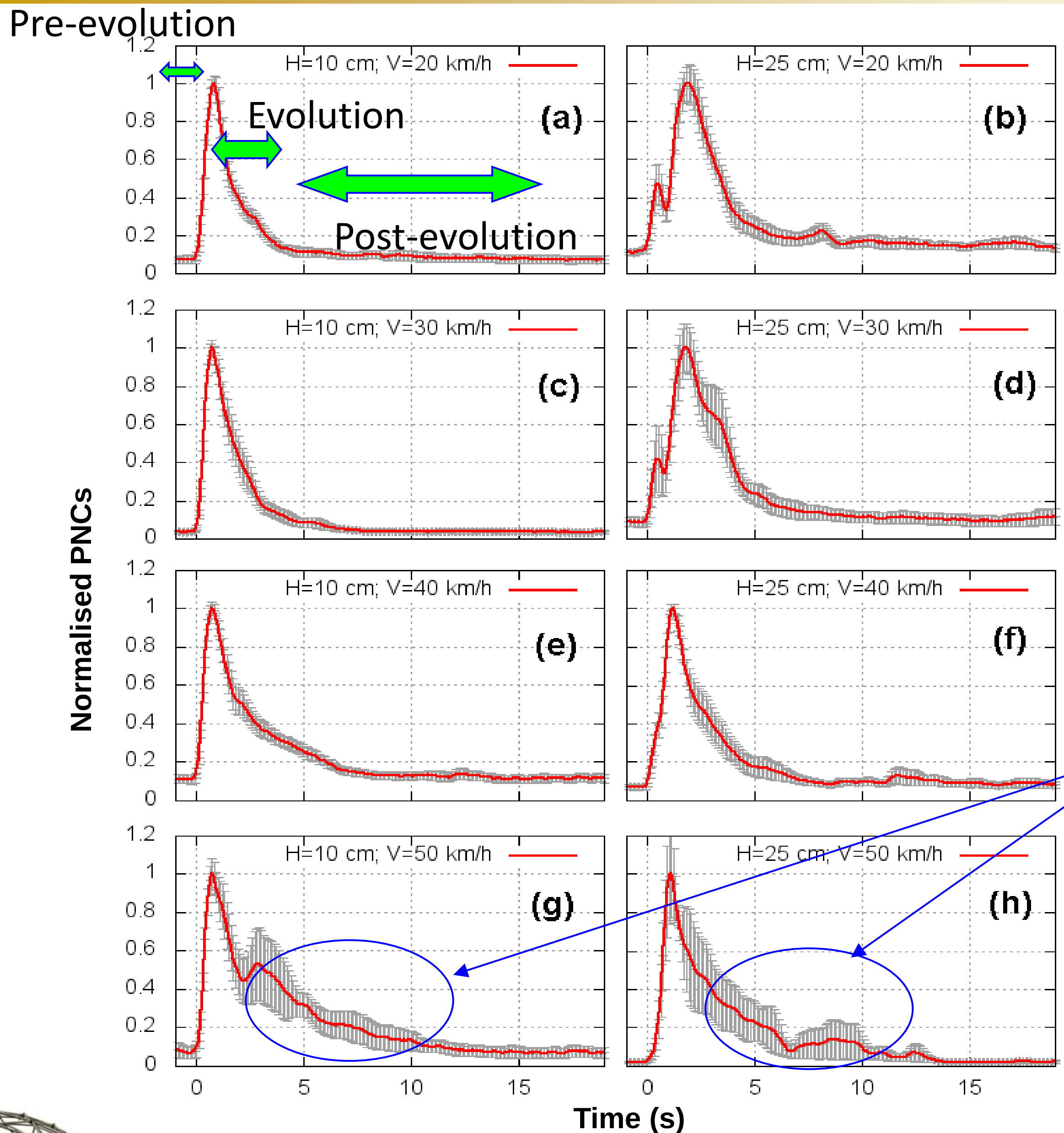
Example case: 20 km h^{-1}; PNC contours and evolution)



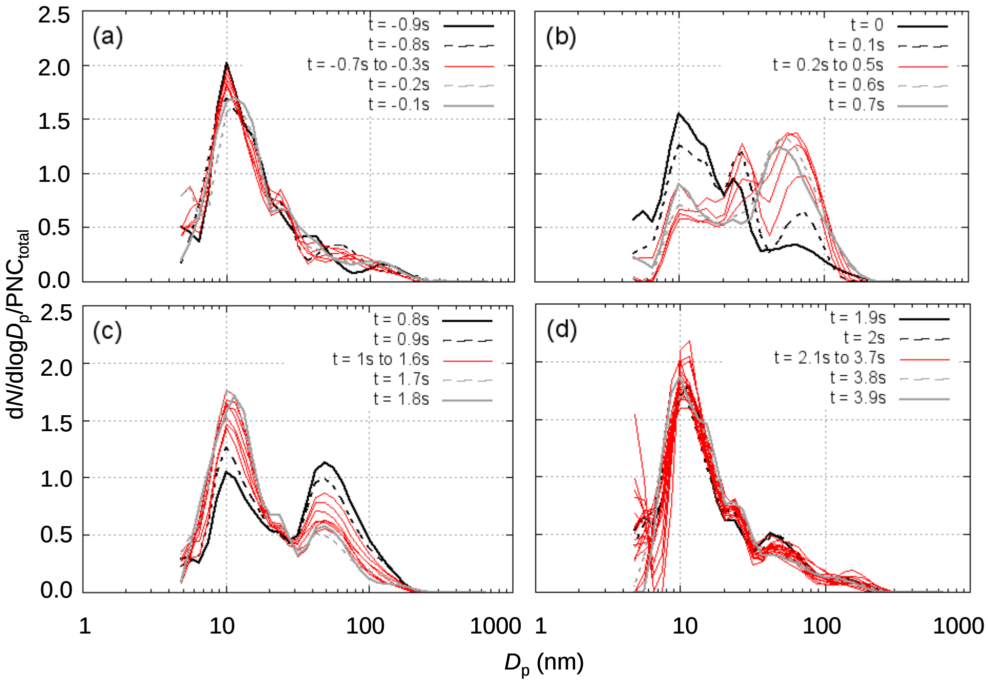
*Taken from: Carpentieri, M., **Kumar, P.,** 2011. Ground–fixed and on–board measurements of nanoparticles in the wake of a moving vehicle. Atmospheric Environment 45, 5837-5852.

VEHICLE WAKE (ground–fixed)



- *t*=0 s; when PNCs start to increase significantly over the background – first sign of PNC detection
- Rapid building of PNCs within 1 s
- Followed by a slower decay towards background
- Decay period increased with vehicle speed, mainly due to higher emissions at higher speeds
- All the effect of emissions measured lasted within 5–15 s.

FIELD COMPAIGN (ground–fixed)



Example case: Normalised size distributions during (a) pre–evolution, (b) evolution 1, (c) evolution 2, and (d) post–evolution for the experimental case: **H = 0.10 m, V = 20 km h^{-1},** Run 01.

(a) Pre-evolution stage: site background; dominated by nucleation mode; peak 10-12 nm

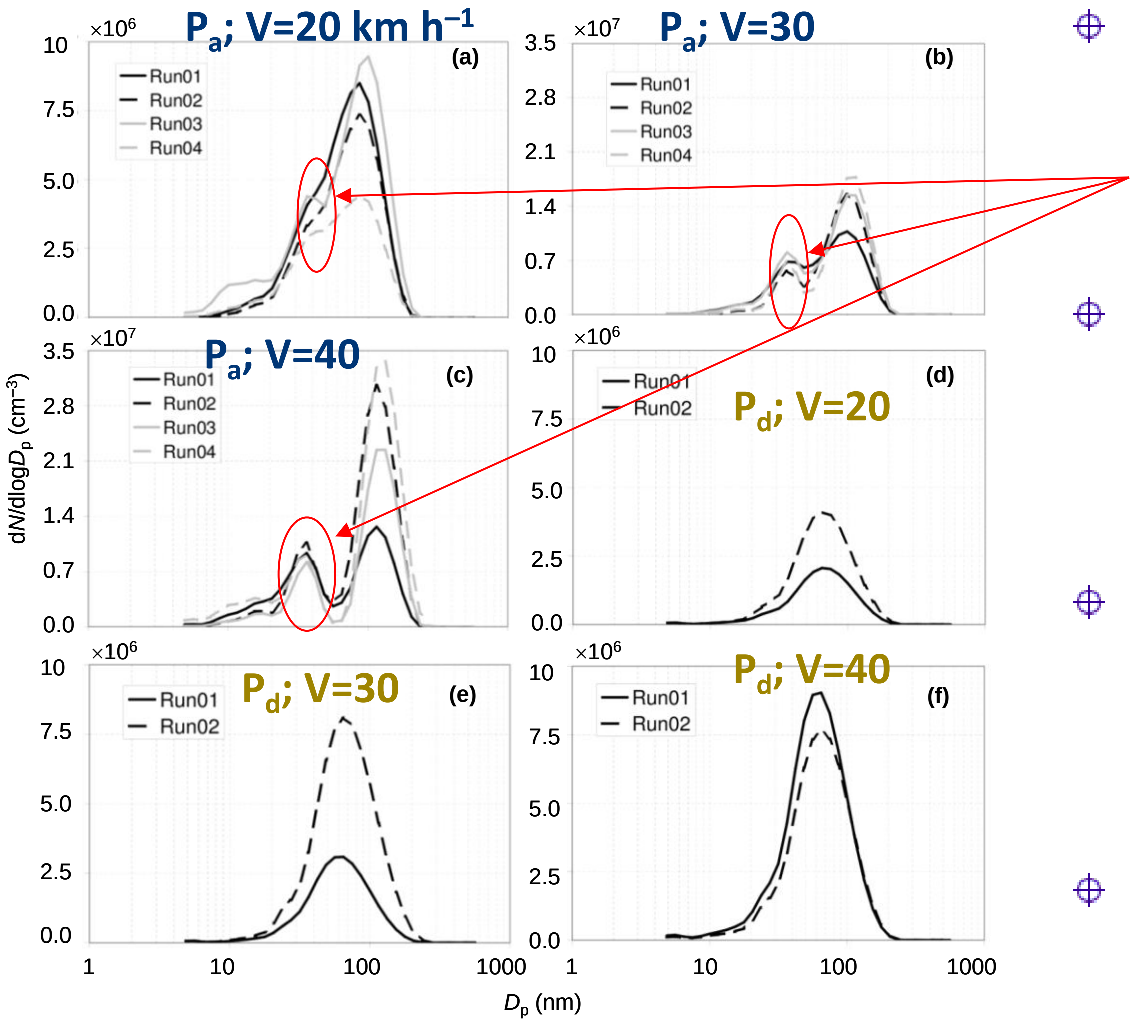
(b) Evolution (1): Most transformation occurred; rapid change in PNDs showing integrated influence of nucleation and dilution

(c) Evolution (2): seems dilution – only effects; PNDs moving up and down like (a) and (d); both evolution sub-stages shows distinct transformation behaviour

(d) Post-evolution: Returned back similar to (a)

VEHICLE WAKE (ground–fixed)

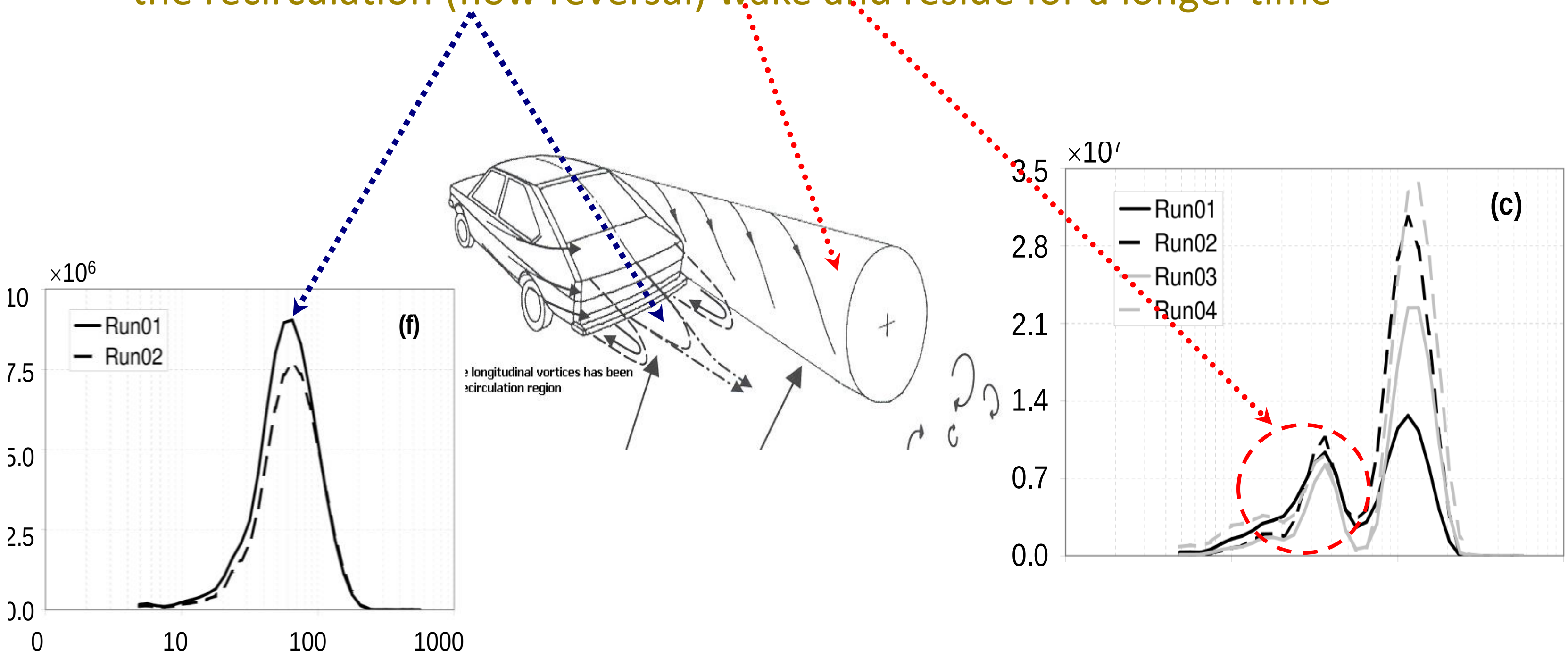
Data points ***in the line of tailpipe*** at different 0.10 and 0.50 m above the road level



Example case: PNDs for on–board measurements at $\mathbf{P_a}$ and $\mathbf{P_d}$.

- P_a (x =0.45m, y= –0.45m, z= 0.10m) more affected by car speeds showing increasing PNDs and a fresh nucleation mode
- P_d (x =0.45m, y= –0.45m, z= 0.50m); PNDs quite similar irrespective of any speed; nucleation mode not evident
- Similar shape, as for P_d, was seen for points in the centre and at far end of tailpipe, showing a missing nucleation mode
- Similar to P_a, a less pronounced nucleation mode was observed at P_b (closer to tailpipe)

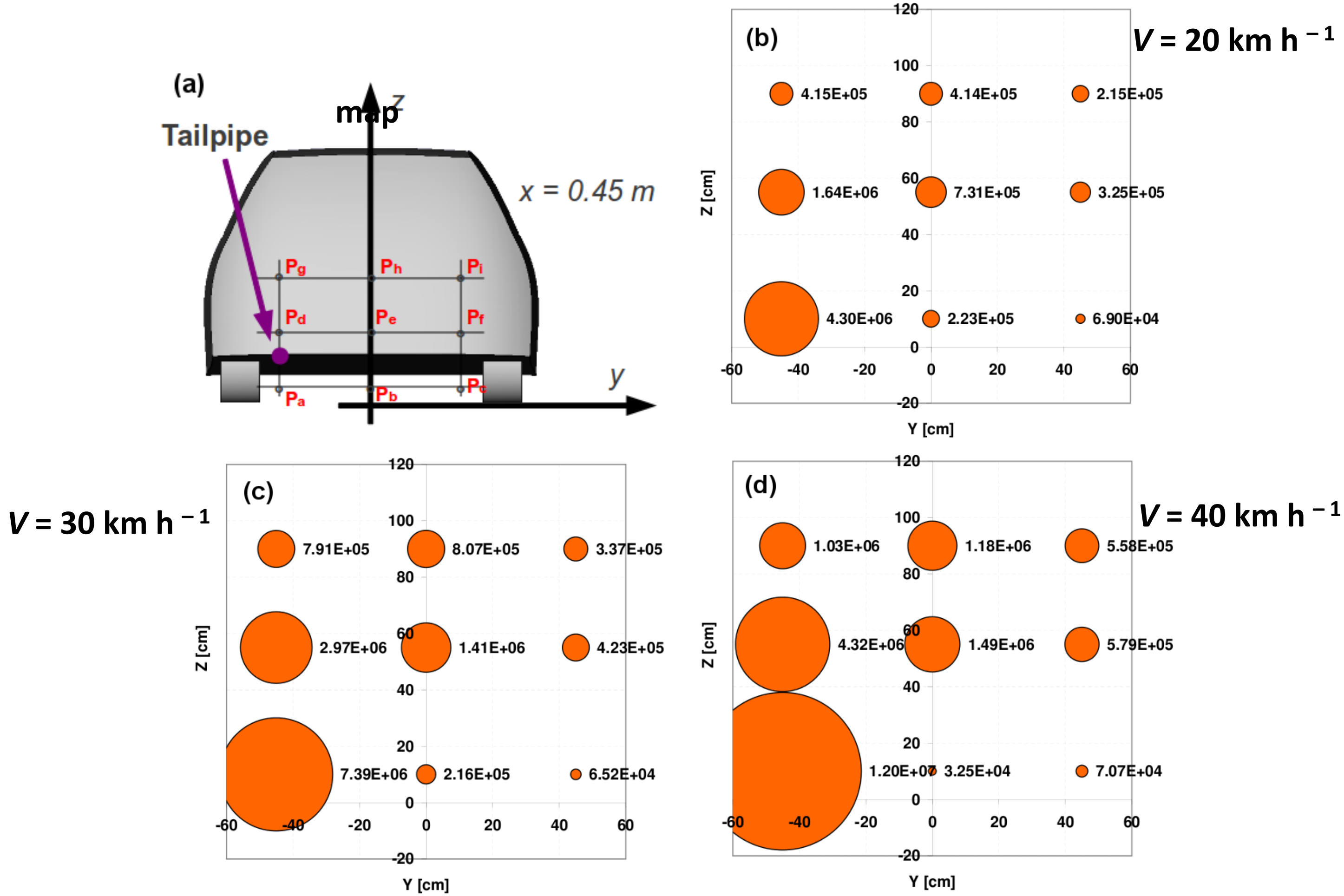
- Combined analysis showed two separate groups experiencing different transformation processes just adjacent to the back of a moving car
  - New particles (with nucleation mode), which are freshly emitted and come directly from tailpipe in recirculation longitudinal vortex at the side of tailpipe, and
  - Relatively aged particles (without nucleation mode), which are entrained within the recirculation (flow reversal) wake and reside for a longer time



- Other zones further away from car showed a mixture of both patterns

VEHICLE WAKE (On–board; an example)

PNCs (# cm^{-3}) measured at x=0.45 m. Size of each bubble corresponds to magnitude of PNCs at that point.



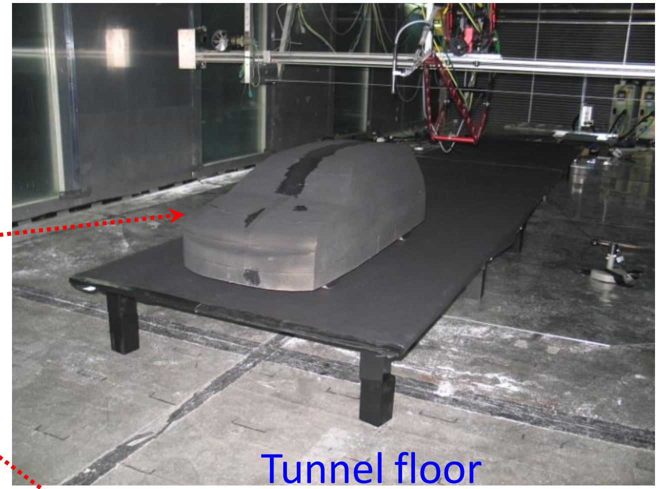
- Size of bubble expanding with the increased vehicle speed, verifying the fact that PNC emissions increases with vehicle speed.
- As expected, concentrations were higher in x-direction close to tailpipe which are being recirculated towards the centre points resulting in larger concentrations than those on the extreme far end from tailpipe

Objectives

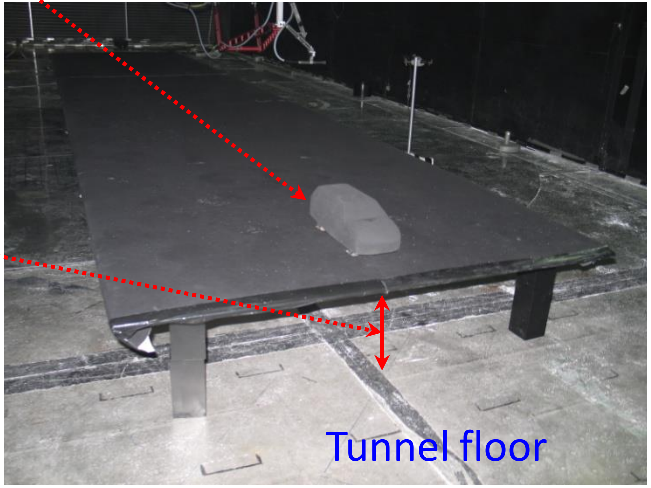
- Determining detailed flow and dispersion characteristics in the wake of moving vehicle, mimicking the field experiments, for developing fast parameterisation mathematical model to be used with operational nanoparticle dispersion model

Methodology

- Experiments carried out in the EnFlo (Environmental Flow Research Centre) wind tunnel. Reduced scale models (**1:20** and **1:5**) of the diesel car used mimicked our field experiments

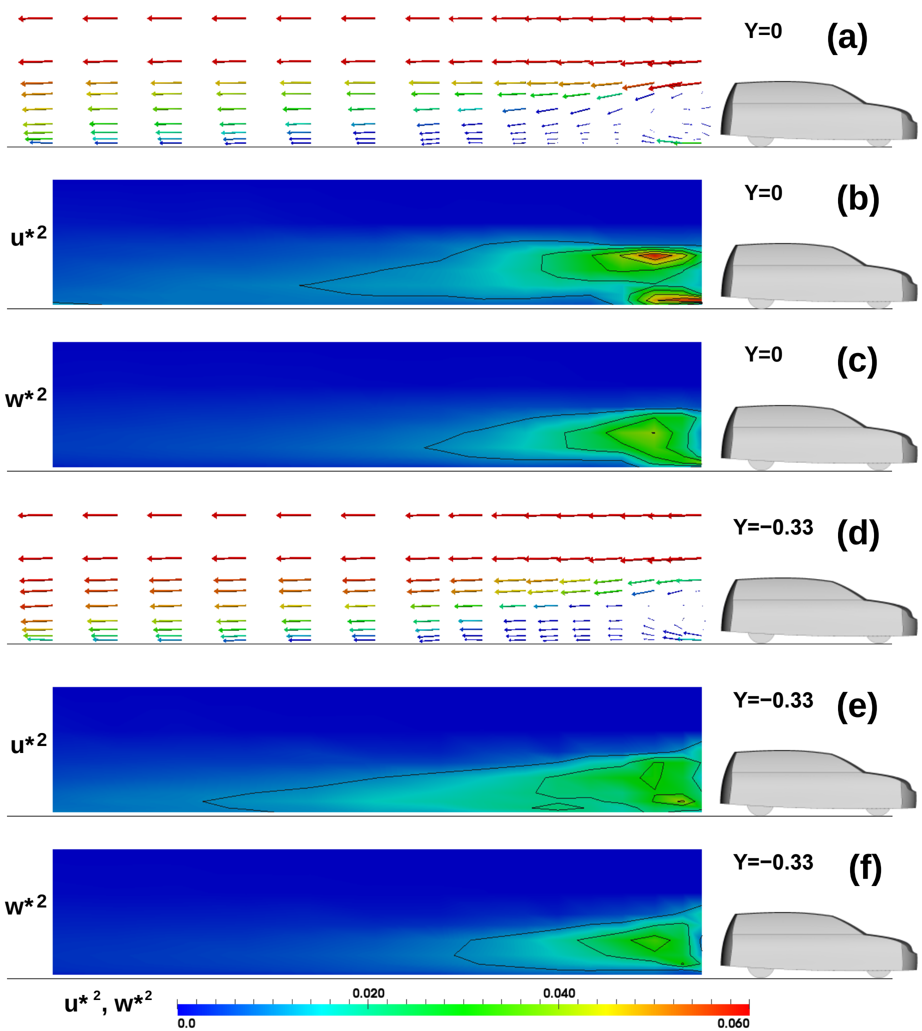


- For reducing the unrealistic effects of a growing boundary layer at the wind tunnel surface, the models were placed at the leading edge of a false floor (i.e. 0.23 m above the tunnel floor)



*Carpentieri, M., **Kumar, P.,** Robins, A., 2012. Wind tunnel measurements for dispersion modelling of vehicle wakes. *Atmospheric Environment* 62, 9-25.

VEHICLE WAKE (WIND TUNNEL EXPERIMENTS*)



U^*-W^* vector plot at Y=0

- Recirculating flow up to ~2*h*
- High speed at lowest level, airflow below vehicl

Longitudinal turbulence at C/L of car

- High in recirculation zone
- Maximum at upper and lower car edges due to flow separation and shear layer

Vertical turbulence at C/L of car

- Signification turbulence within recirculation region

U^*-W^* vector plot at C/L of tailpipe

- Similar characteristics

Longitudinal turbulence at C/L of tailpipe

- High in recirculation zone
- Extending in far wake

Vertical turbulence at C/L of tailpipe

- Similar but relatively less than at *Y* = 0

LDA measurements on the 1:5 model, vertical planes. *Y* = 0 in the centreline of the vehicles & *Y*=–0.33 is approximately in line with the tailpipe.

Taken from: Carpentieri, M., **Kumar, P.,** Robins, A., 2012. Wind tunnel measurements for dispersion modelling of vehicle wakes. *Atmospheric Environment* 62, 9-25.

What happens inside car cabins?

*Joodatnia, P., **Kumar, P.,** Robins, A., 2013. The behaviour of traffic produced nanoparticles in a car cabin and resulting exposure rates. *Atmospheric Environment* 65, 40--51.

*Joodatnia, P., **Kumar, P.,** Robins, A., 2013. Fast response sequential measurements and modelling of nanoparticles inside and outside a car cabin. *Atmospheric Environment* 71, 364-375.

INSIDE CAR CABIN

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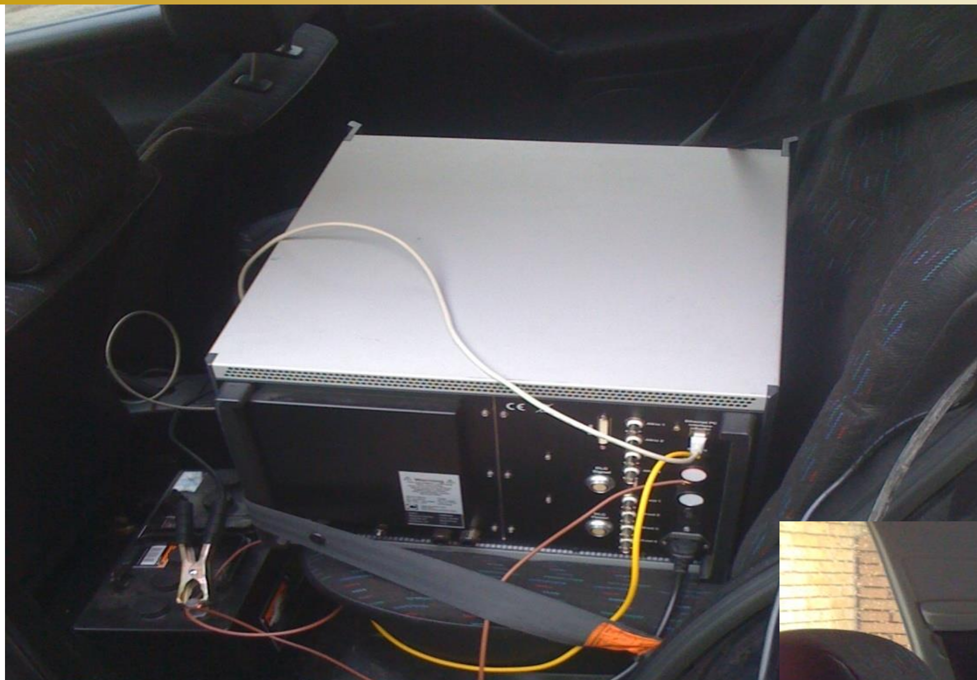

DMS50 on–board

Passenger exposure to nanoparticulate pollution inside car cabin with A/C ON & Windows closed

***Aim:* Determining particle dynamics inside the car cabins**

Route: University to City Centre

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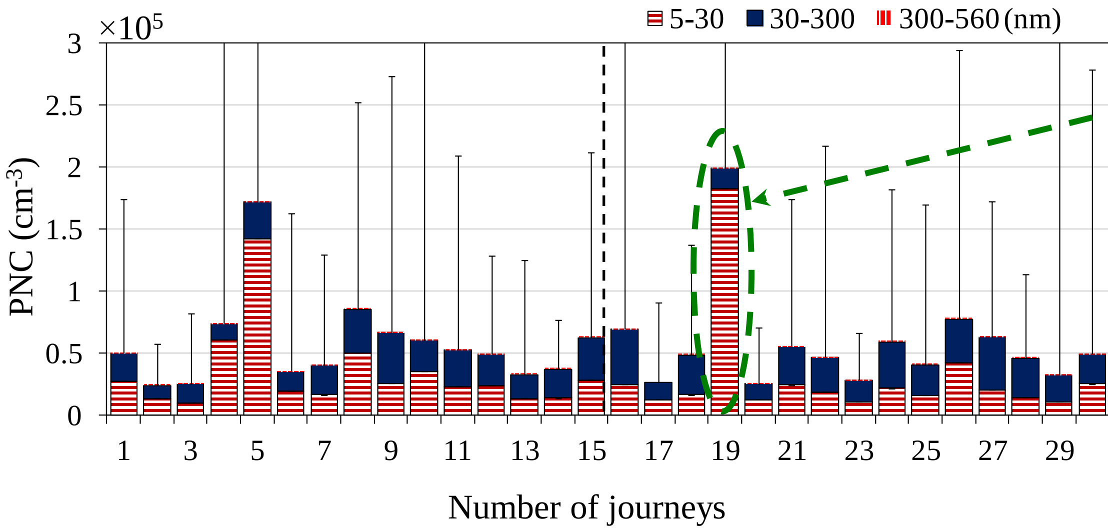
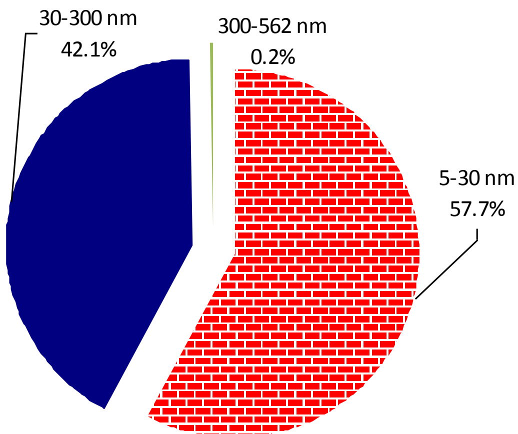
Overall averaged PNCs 5.78±3.86×10^4 cm^{-3}

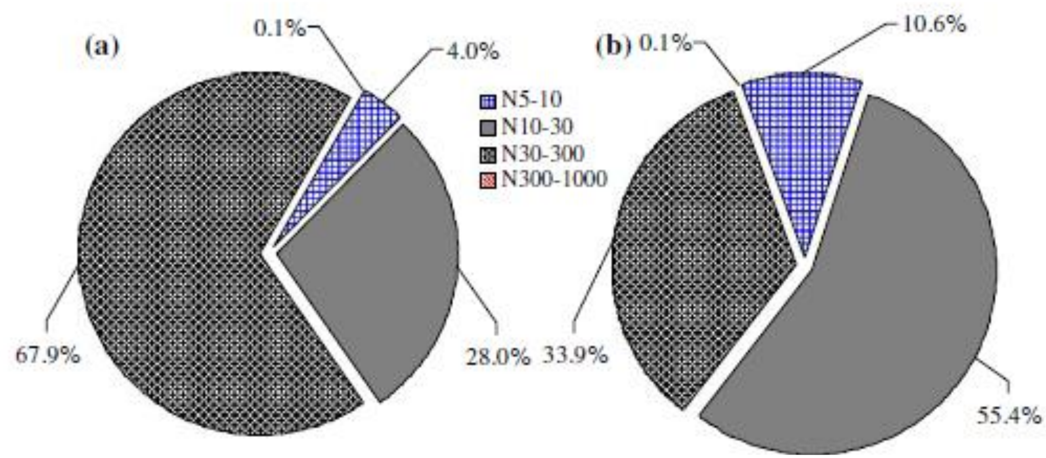


- When the car was behind a bus, as seen in next slide
- Greater fresh exhaust emissions (i.e. 5-30 nm)

In any case, negligible particles by number above 300 nm



Car cabins (~60/40%)



Street (roadside; ~35/65%)

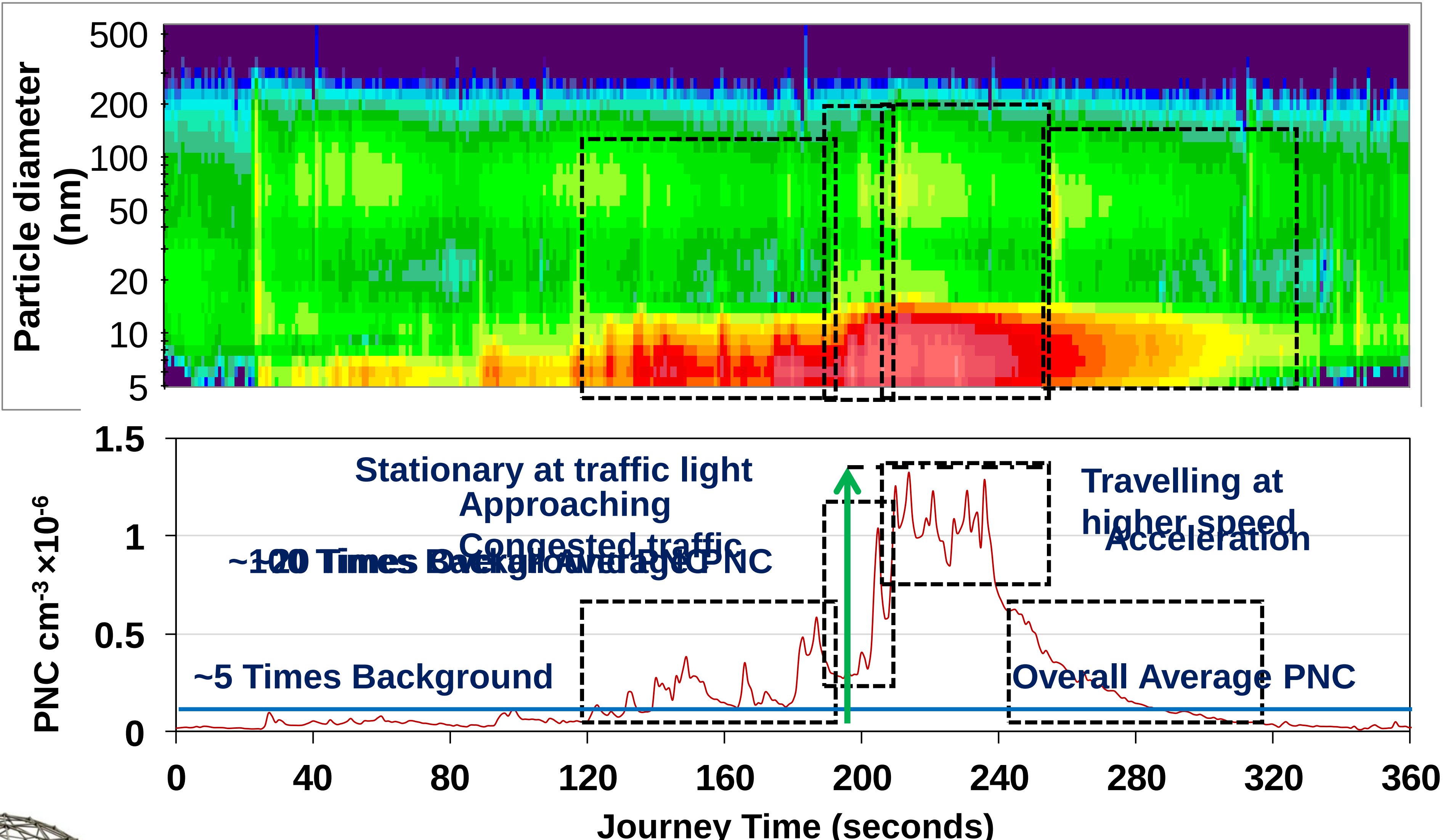
Above rooftop (~65/35%)

PNCs inside the car cabin during a typical car journey in a typical UK town

Driving behind (~3 m) a Bus inside Guildford Town Centre

Short–term instantaneous exposure can increase up to 4 orders to magnitude (i.e. ~10^4 times)

Driving on a Road just outside Guildford Town with no Traffic ahead


Particle diameter (nm)
500
200
100
50
20
10
5
PNC cm^{-3} ×10^{-6}
1.5
1
0.5
0
Stationary at traffic light
Approaching
Congested traffic
~120 Times Background PNC
~20 Times Overall Average PNC
Travelling at higher speed
Acceleration
~5 Times Background
Overall Average PNC
0
40
80
120
160
200
240
280
320
360
Journey Time (seconds)

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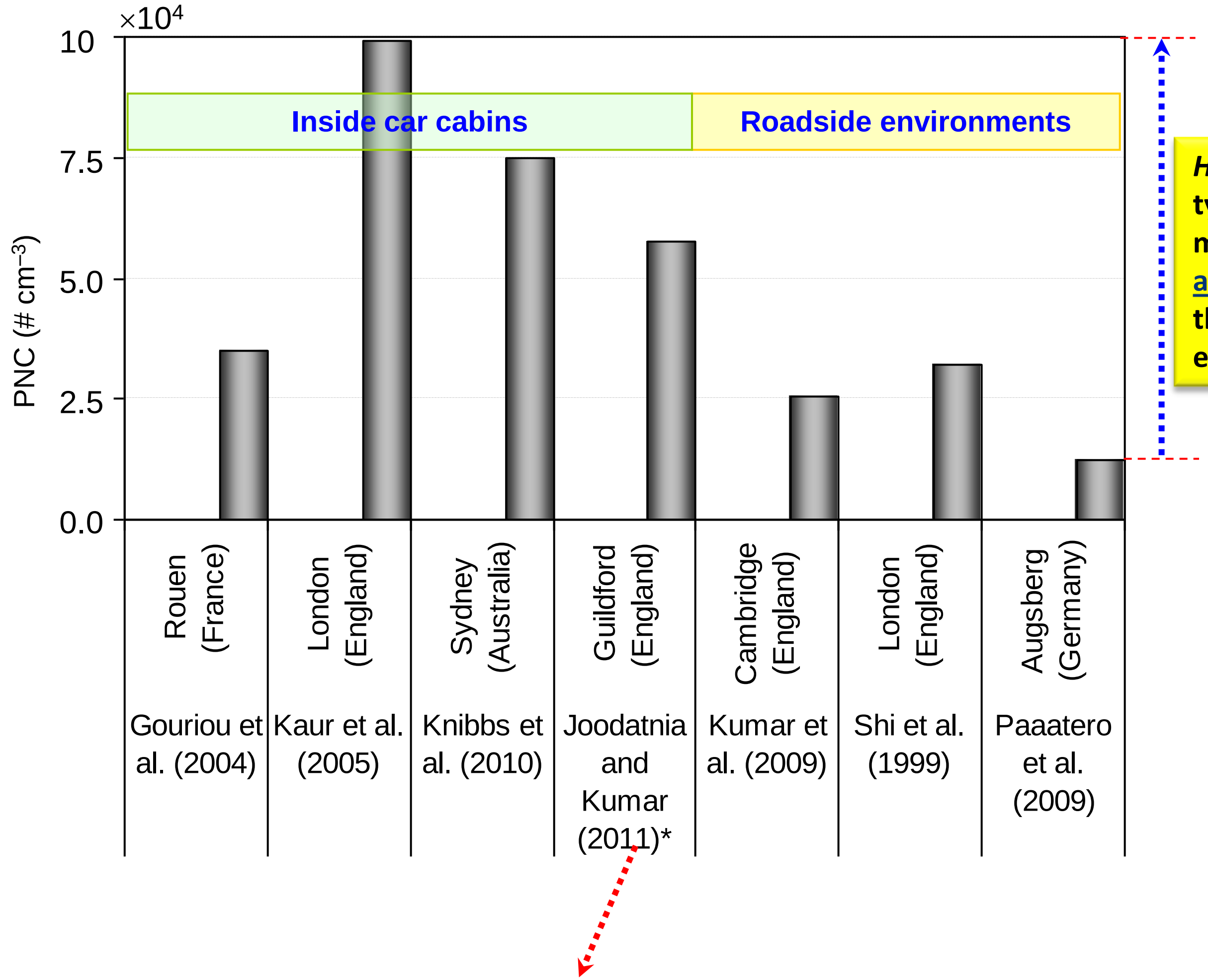
How does PNCs compare with other studies?



Hourly average PNCs **during typical journeys in car cabins may have up to a factor of about 5 higher PNCs than those in urban roadside environments.**

*Joodatnia, P., **Kumar, P.,** Robins, A., 2013. The behaviour of traffic produced nanoparticles in a car cabin and resulting exposure rates. *Atmospheric Environment* 65, 40-51.

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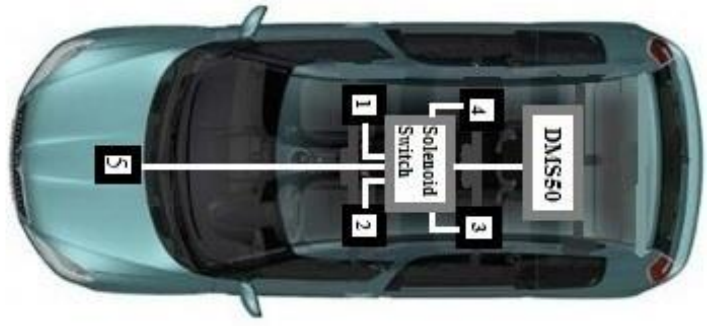
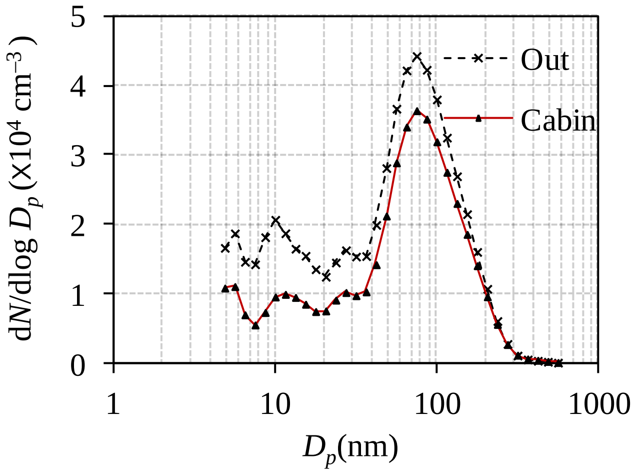
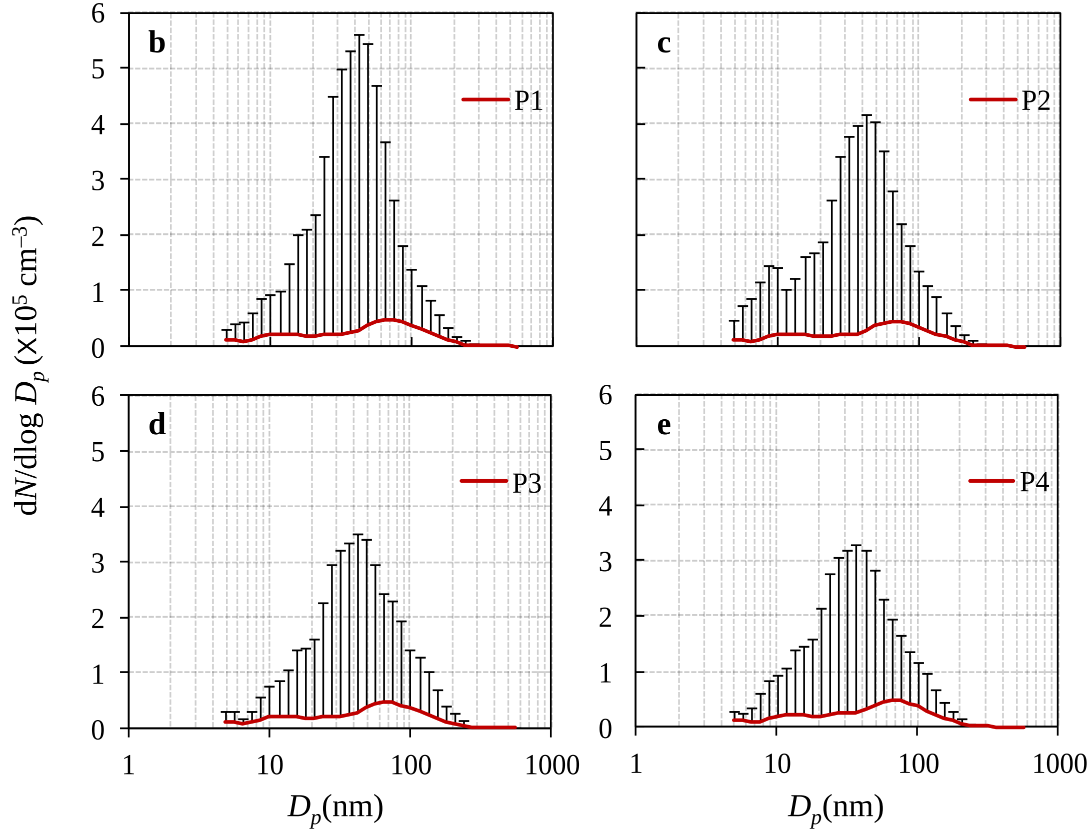
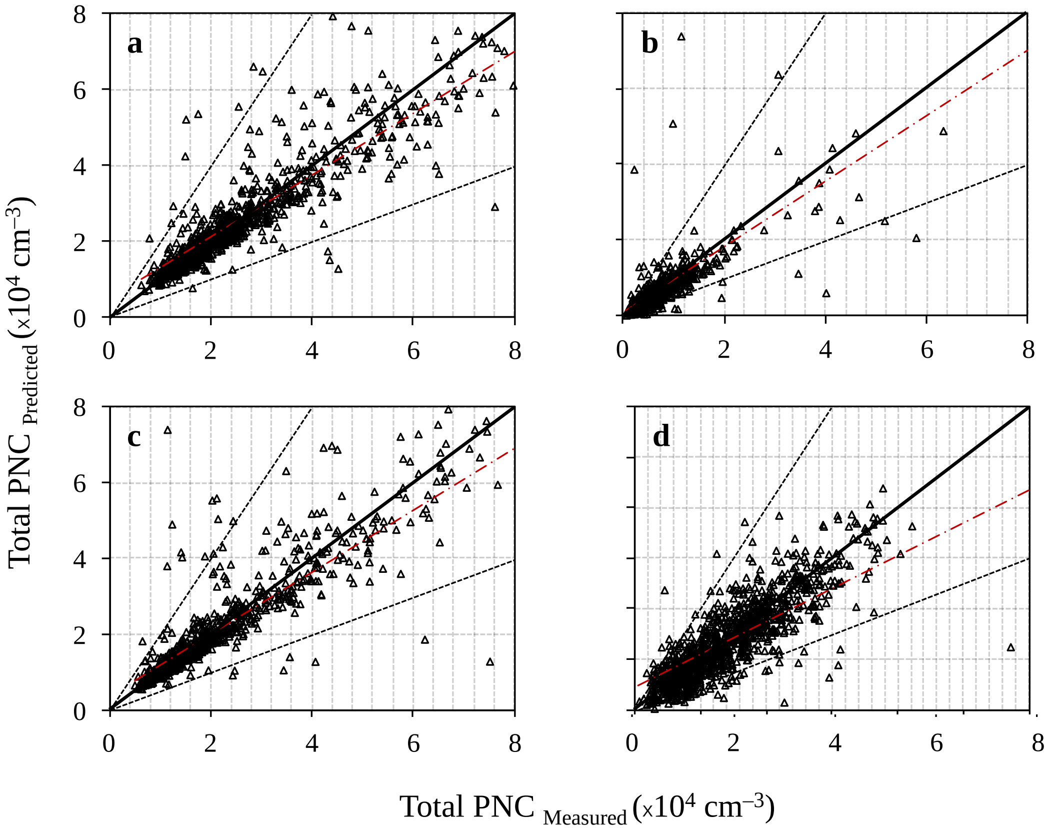
INSIDE CAR CABIN (MODELLING)







INSIDE CAR CABIN (MODELLING)*



$$N_{ci}(t_{n+1}) = N_{oi}(t_n) \times (I/O)_i + (N_{ci}(t_n) - N_{oi}(t_n) \times (I/O)_i) \times e^{-A_E(\Delta t)}$$

I/O = 0.72 (from experiments); A_E (=7.7x10^2 m^3 s^{-1}; air exchange rate, estimated using gas experiment; inflow rate into vehicle 4.2x10^2 m^3 s^{-1})

*Joodatnia, P., **Kumar, P.,** Robins, A., 2013. Fast response sequential measurements and modelling of nanoparticles inside and outside a car cabin. *Atmospheric Environment* 71, 364-375.

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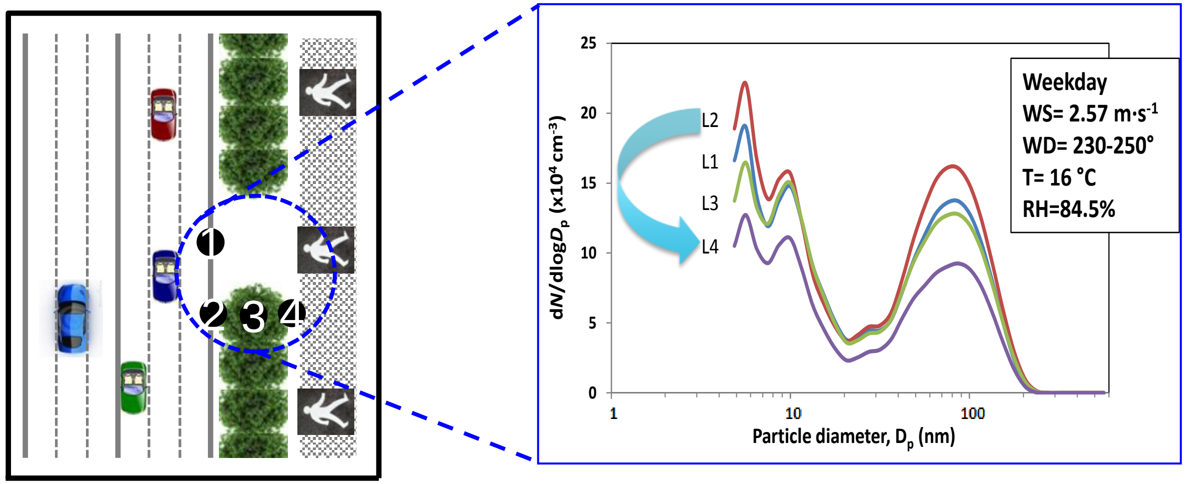
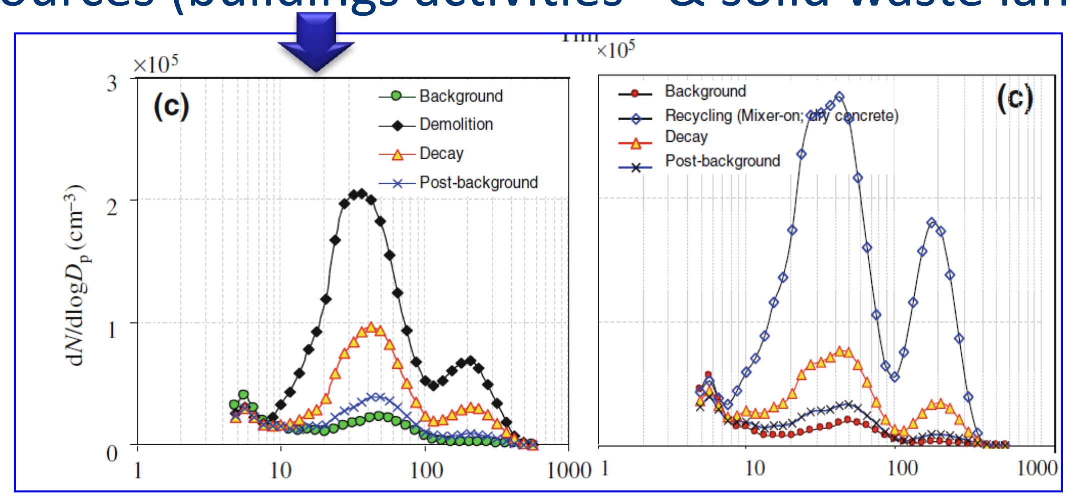
INSIDE CAR CABIN (SUMMARY)

- Pseudo–simultaneous measurements at all 4 seats in car, and inside–outside taken.
- Identical PNCs at all 4 seats indicated car cabin air is well–mixed.
- Ratio of in–cabin to outside PNCs is not uniform for different particle sizes.
- Time scale analysis highlights dilution as a dominant process.
- A proposed semi–empirical model predicted inside cabin PNC adequately well

- Dispersion model for the near wake; model linking wake and cabin
- Vegetation barriers



- Non-vehicle sources (buildings activities* & solid waste landfills)



***Kumar, P.,** Mulheron, M., Som, C., 2012. Release of ultrafine particles from three simulated building processes. Journal of Nanoparticle Research 14, 771, doi: 10.1007/s11051-012-0771-2.

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Review

Nanoparticle emissions from 11 non-vehicle exhaust sources – A review

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[*Most downloaded article*]

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  - Prof. Liisa Pirjola (*UoH, Finland*)*;*
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THANK YOU

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