Assessment of particle pollution from jetliners: from smoke visibility to nanoparticle counting

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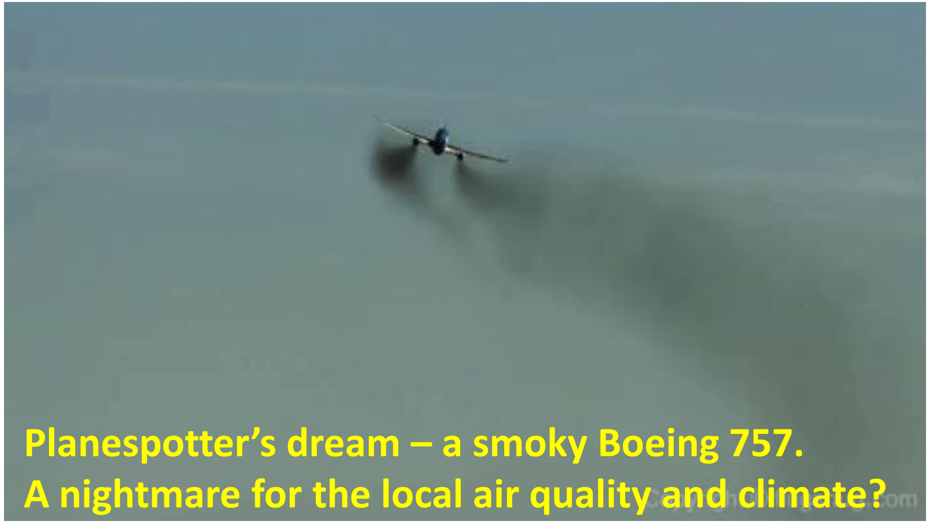
3 SR Technics Switzerland AG
4 Swiss Federal Office of Civil Aviation

Empa
Materials Science and Technology

Smoke inside of the aircraft disappeared before the smoke outside of the aircraft (nowadays a rare sight)

Source: pinterest

Poster #18 - effect of engine deterioration on BC emissions

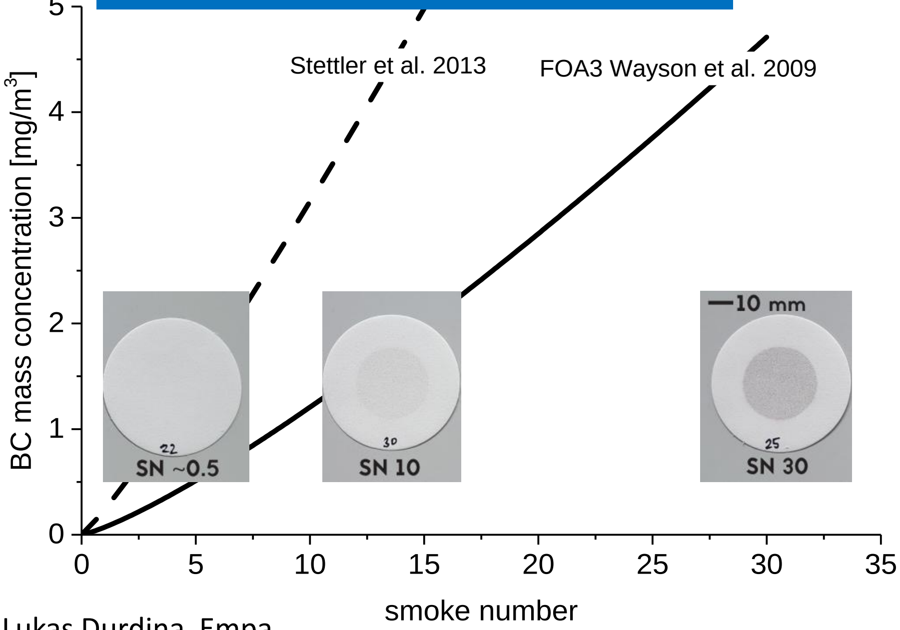


Source: YouTube / flugsnug.com

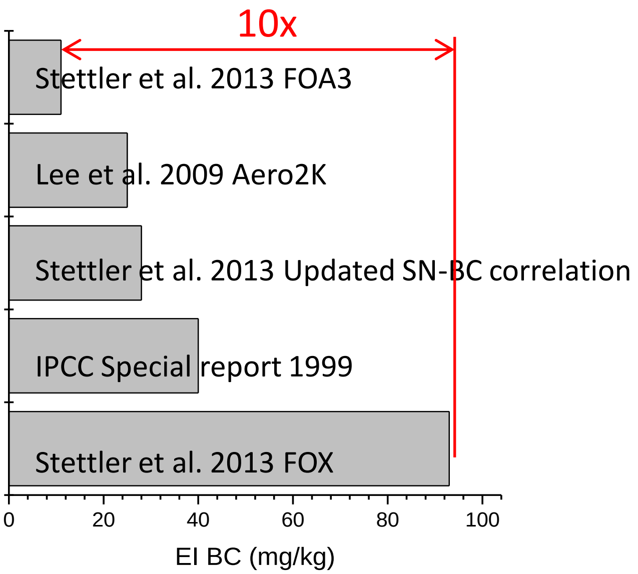
Smoke number (filter reflectance) has been the standard for estimating black carbon emissions from jet engines

- Various models have been developed (with / without smoke number correlation) to predict aviation black carbon emissions **(mass-based only)**

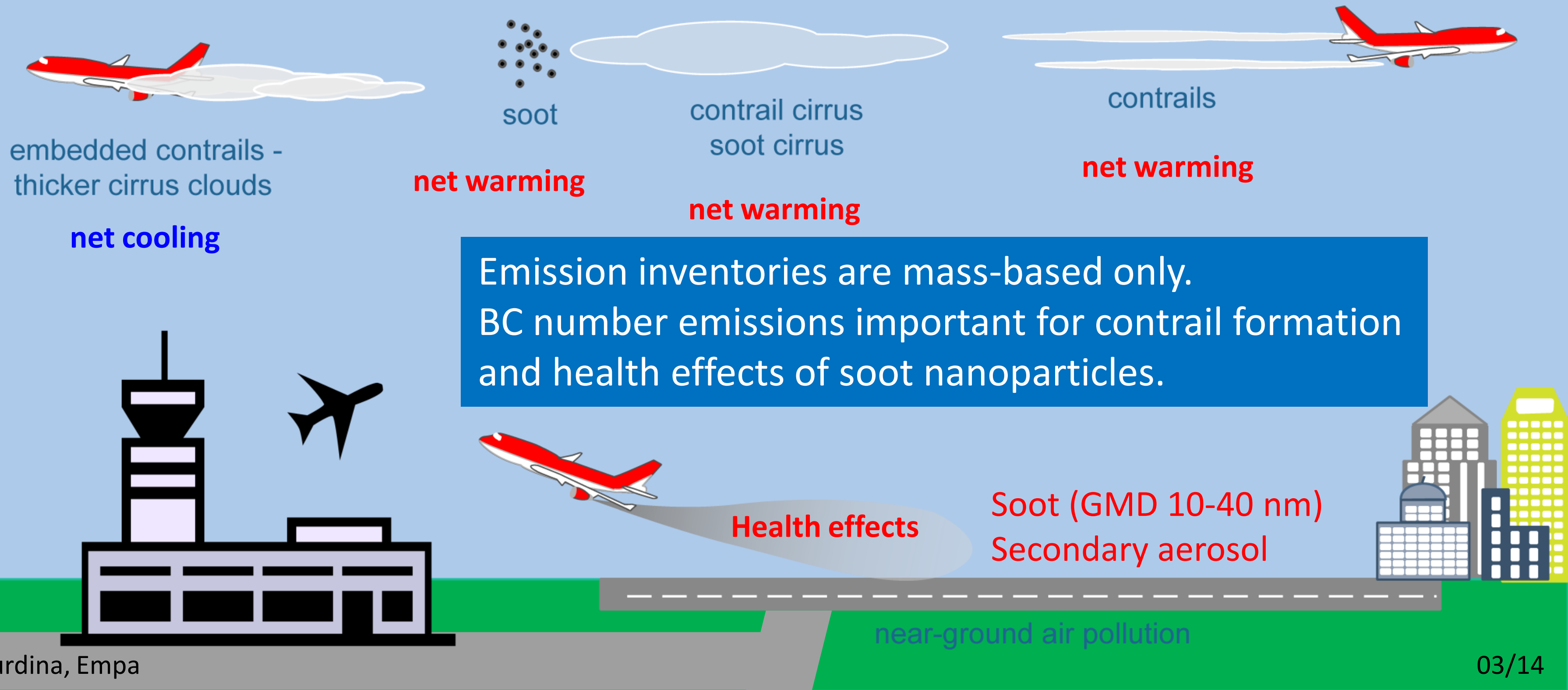
Poster #19 - smoke number – BC correlations



- the average fleet emission index changes with the chosen correlation by up to an order of magnitude



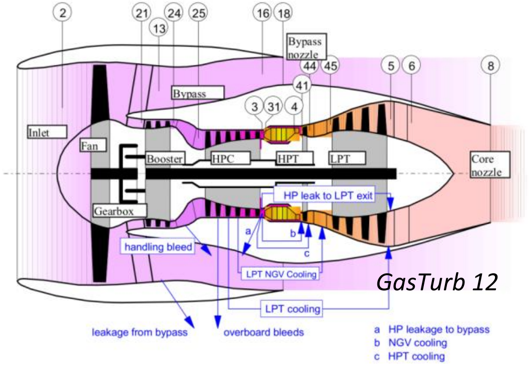
Better BC emission inventories needed for impact assessment of the growing airline industry (+5% / year)



Emission inventories are mass-based only.
BC number emissions important for contrail formation and health effects of soot nanoparticles.

Our approach: emission measurements compliant with future emission standard and engine performance modeling

SR Technics



→Particle number and mass emissions corrected for sampling artifacts
→ Known effects of fuel composition
→ Known particle morphology

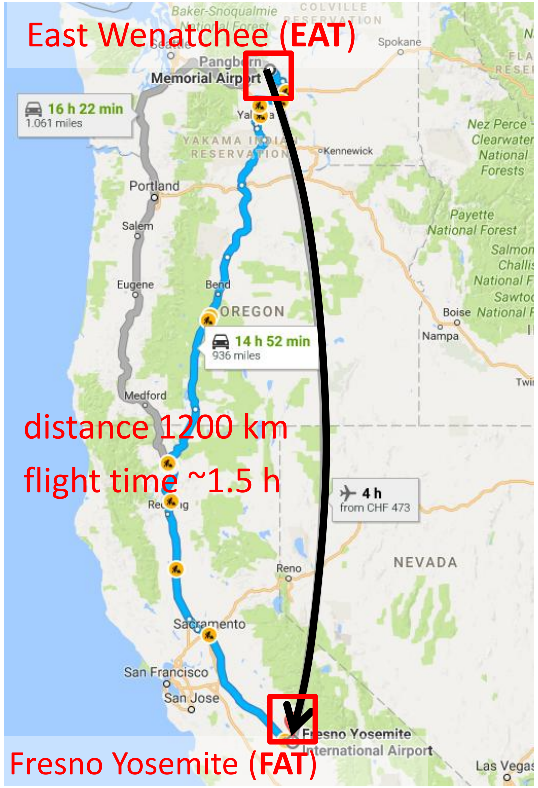
→ Emissions from the landing and take-off cycle (LTO)

→ Correction method of ground measurements to flight conditions
→ Engine control parameters

→ Calibrated engine performance model that matches engine operating parameters on the ground and during flight

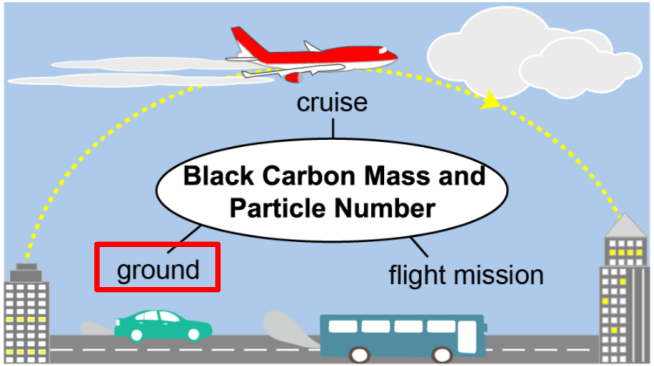
→ Cruise emissions
→ Overall flight emissions

Particle emissions race: do aircraft emit more soot particles (mass and number) per passenger-km than road vehicles?



- **Model aircraft: Boeing 737-800 (130 passengers) with the CFM56-7B/3 engines (certified 2006)**

30% of all commercial airliners are 737 Next Generation



- **Car (2 passengers)**

Direct injection gasoline (GDI)

Port fuel injection gasoline (PFI)

Diesel (D)

Diesel with a particle filter (DPF)

- **Bus (30 passengers)**

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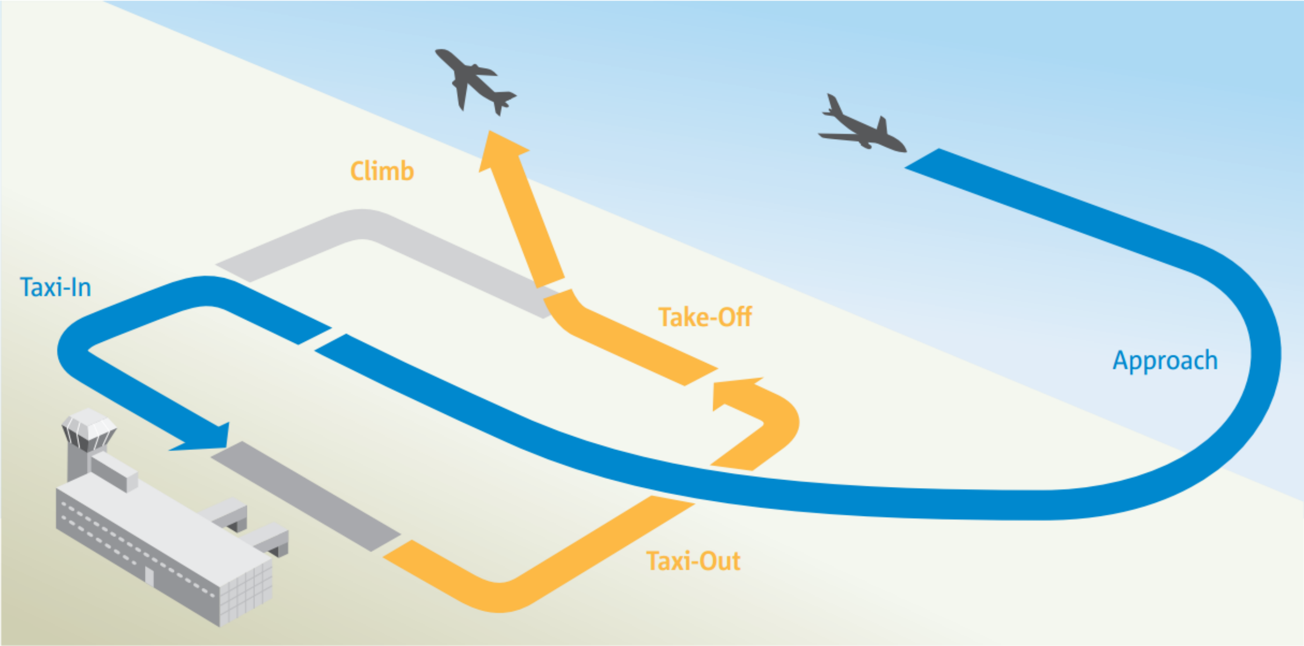
Literature data

Regulated emissions are reported for the reference landing and take-off cycle (LTO) – emissions < 3000 ft



- The LTO emission indices and smoke number in the ICAO databank are used to compute emissions of NO_x, HC, CO, and PM

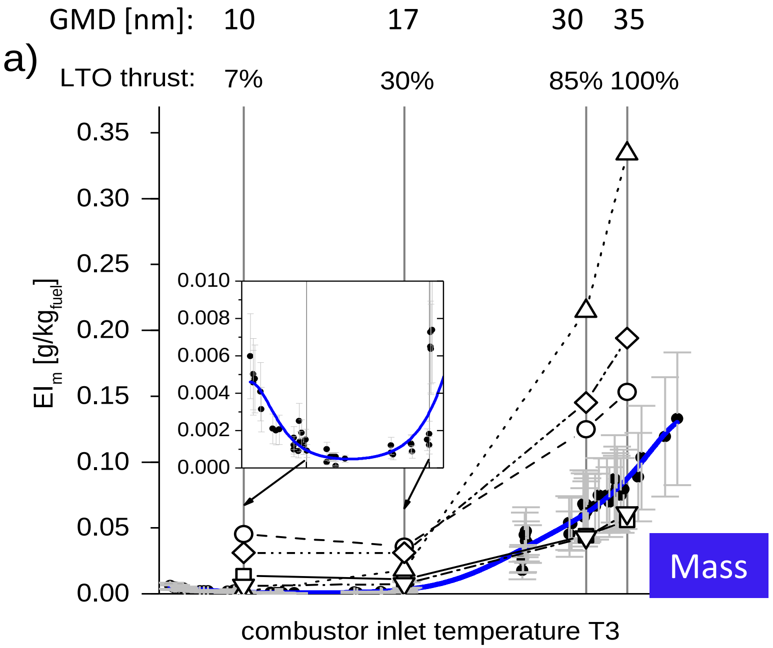
LTO cycle

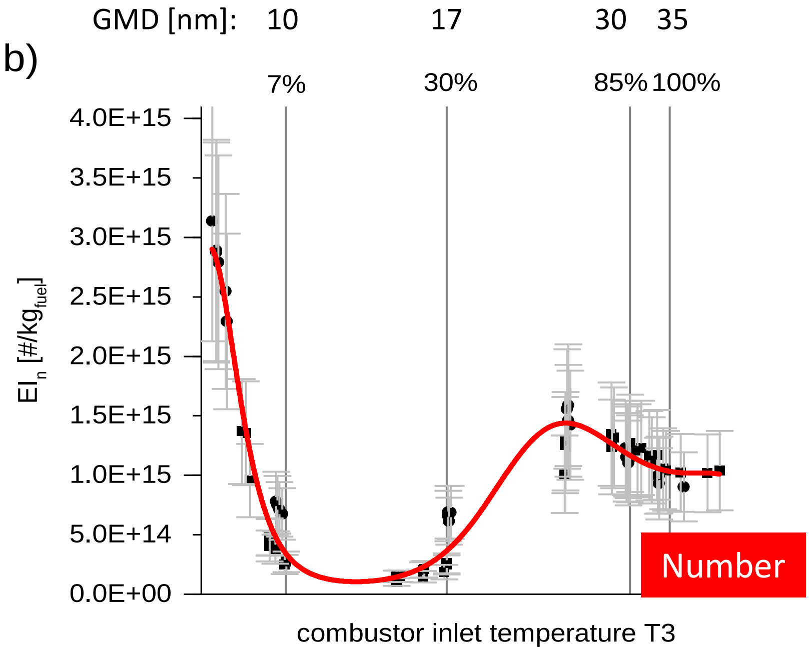
Mode	Thrust	Time
Take-off	100%	0.7 min
Climb	85%	2.2 min
Approach	30%	4.0 min
Taxi	7%	26 min

Source: European Aviation Environmental Report 2016

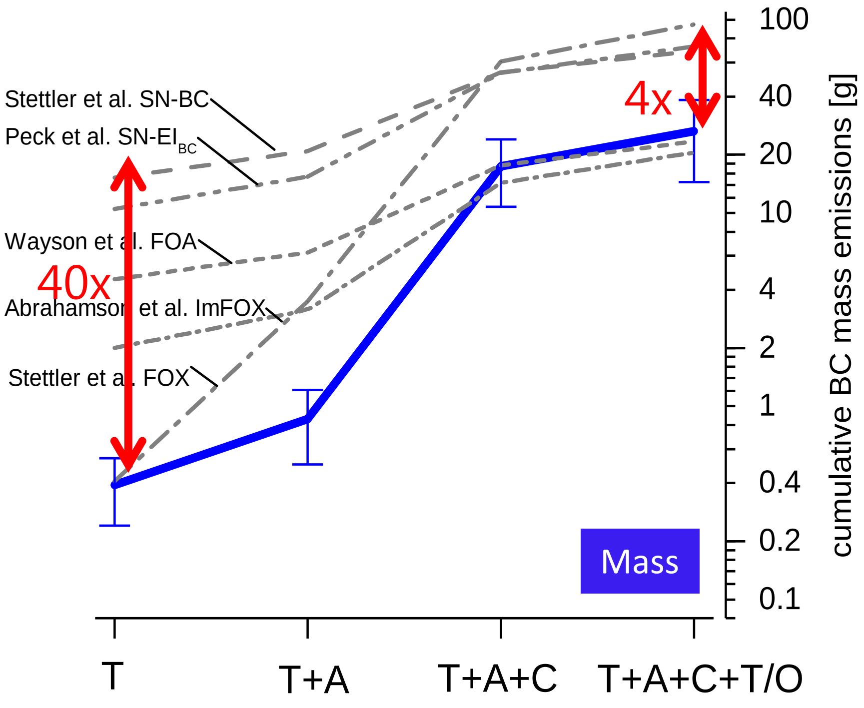
Particle emission characteristics of gas turbine engines strongly depend on engine power

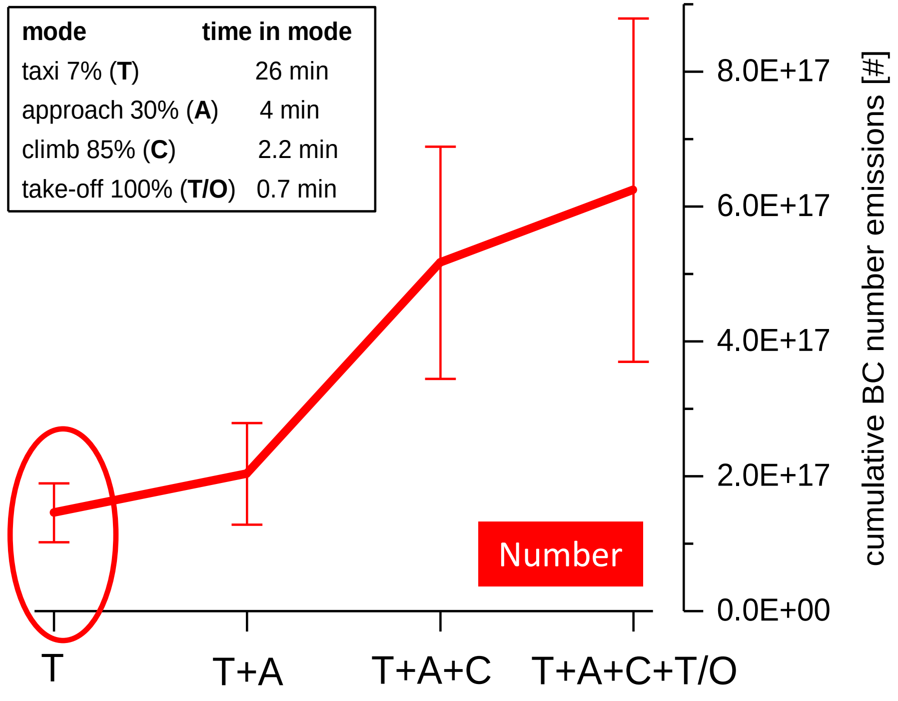
- Mass-based emissions peak at max. thrust, number-based emissions peak at idle
- Symbols in a) are results calculated with published methods



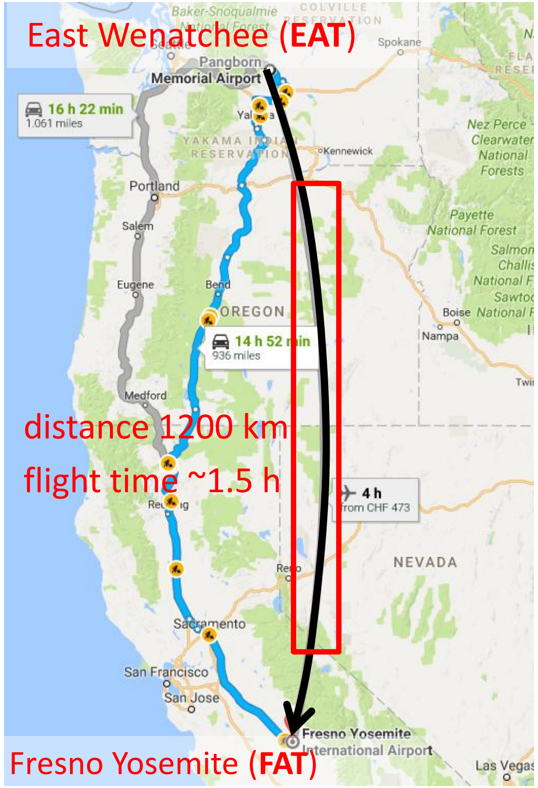


Published methods tend to overestimate BC mass emissions; number emissions at taxi and approach are up to 30% of LTO total





Particle emissions race: do aircraft emit more soot particles (mass and number) per passenger-km than road vehicles?



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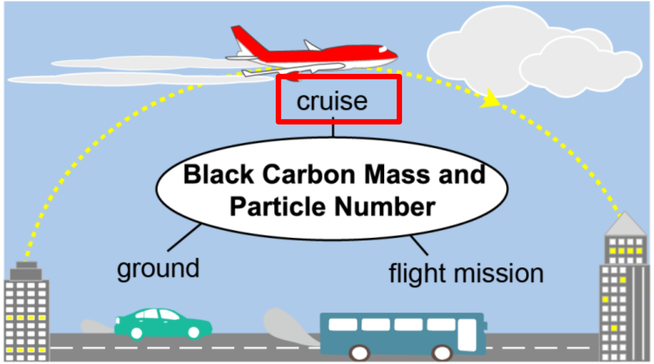

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Literature data

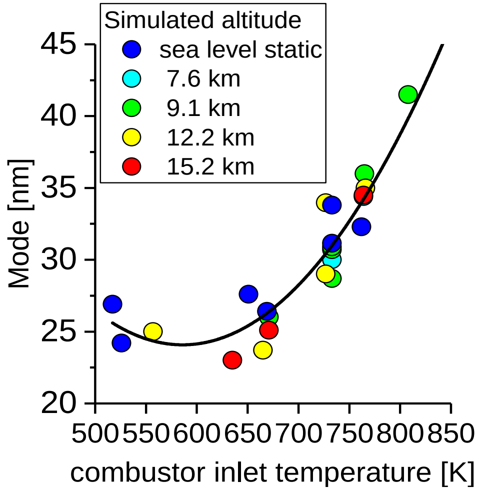
Correction of sea level data to flight conditions (air-fuel ratio and combustor inlet pressure p3) – "DLR Method"[1]

Parameter at cruise	Corresponding sea level thrust
Combustor inlet temperature T3	~45-70% (55% for reference cruise)
Combustor inlet pressure p3	~20-35% (30% for reference cruise)
Air-fuel ratio AFR4	~60-75% (70% for reference cruise)

$$EI_{m,T3} = EI_{m,ground,T3} \times K_{P3} \times K_{AFR}$$

$$EI_n = EI_{n,ground,T3} / EI_{m,ground,T3} \times EI_{m,T3}$$

Simulated altitude tests



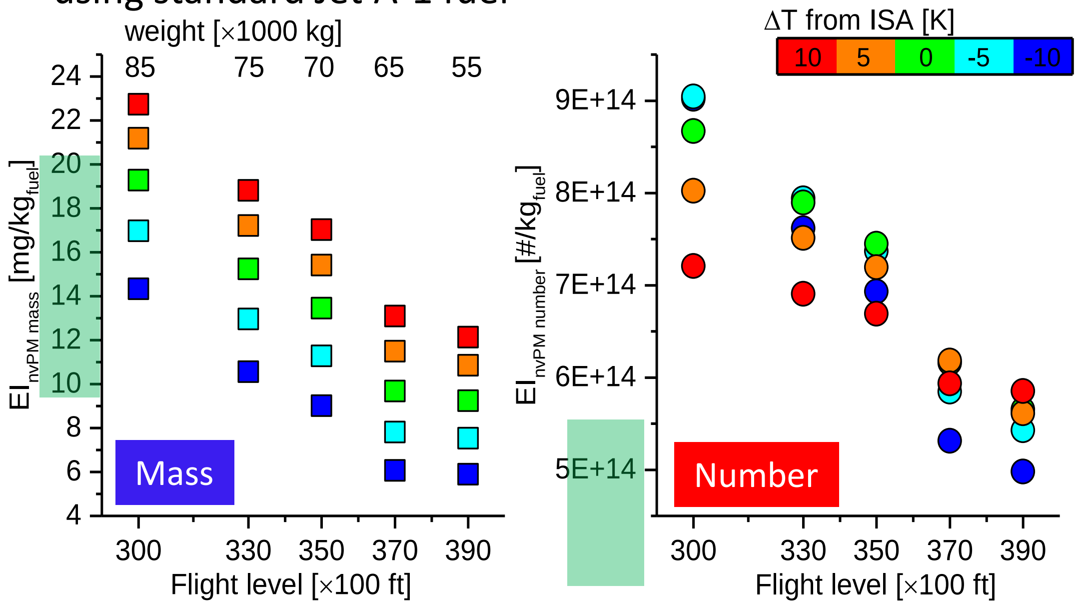
Howard et al. AEDC-TR-96-3 1996

GMD is a function of T3 independent of altitude

1 Döpelheuer, A.; Lecht, M. Influence of engine performance on emission characteristics. In RTO AVT Symposium on Gas Turbine Engine Combustion Emissions and Alternative Fuels; Lisbon, Portugal, 1998; p. RTO MP–14.

Emissions at cruise in agreement with chase studies; sensitive to fuel composition, ambient conditions, and aircraft weight

- Graph shows the effect of ambient temperature for optimum weight- altitude combinations using standard Jet A-1 fuel

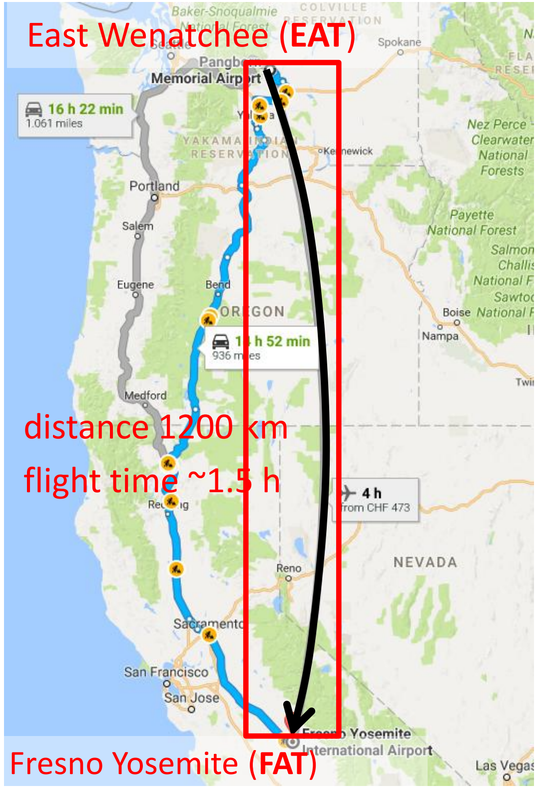


Representative emission indices for ISA, 35000 ft, Mach 0.8, and nominal aircraft weight:

EI_m (mg/kg)	**EI_n (10^{14}/kg)**
11	7

Moore *et al.* (2017), Nature – ACCESS campaigns, CFM56-2 engines at around max. range fuel flow and Jet A-1 fuel

Particle emissions race: do aircraft emit more soot particles (mass and number) per passenger-km than road vehicles?



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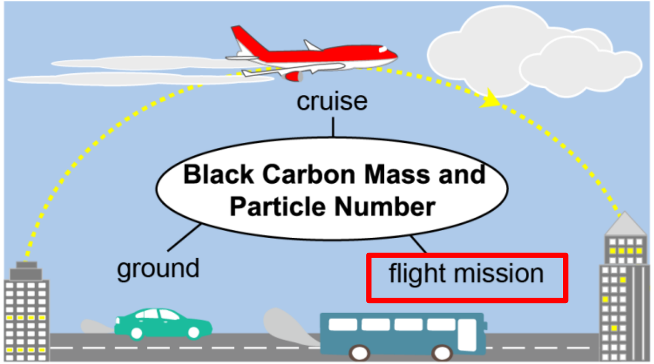

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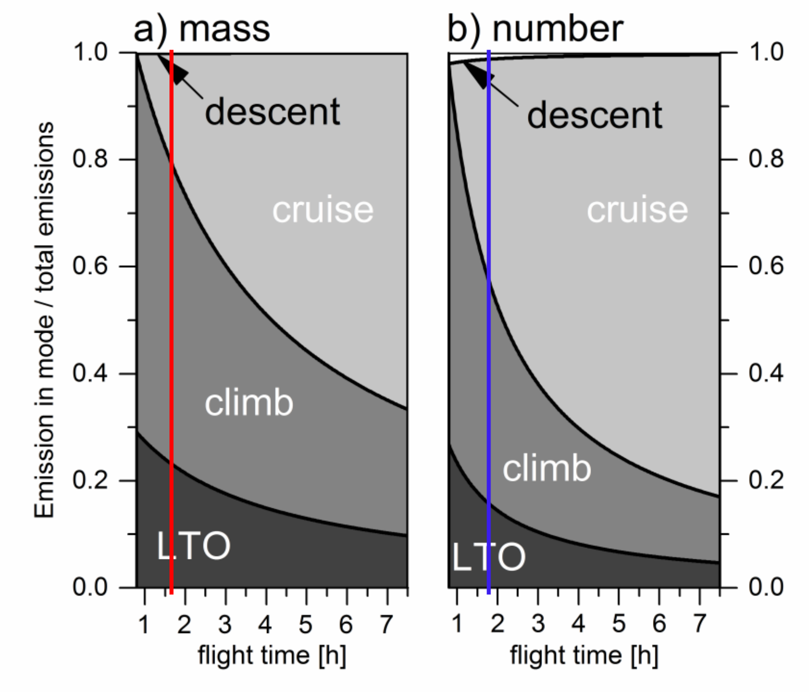
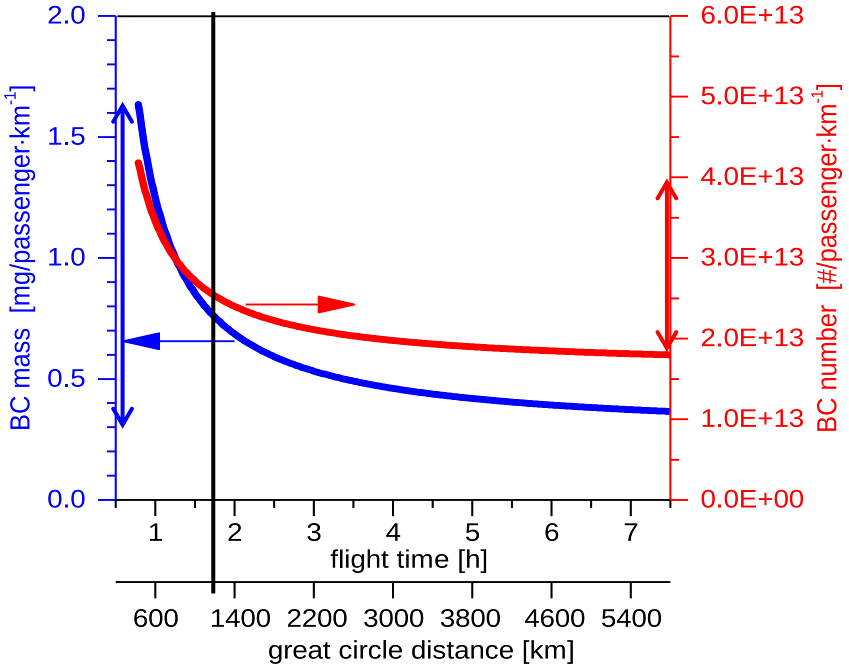
Literature data

Emissions per passenger-km depend on flight time

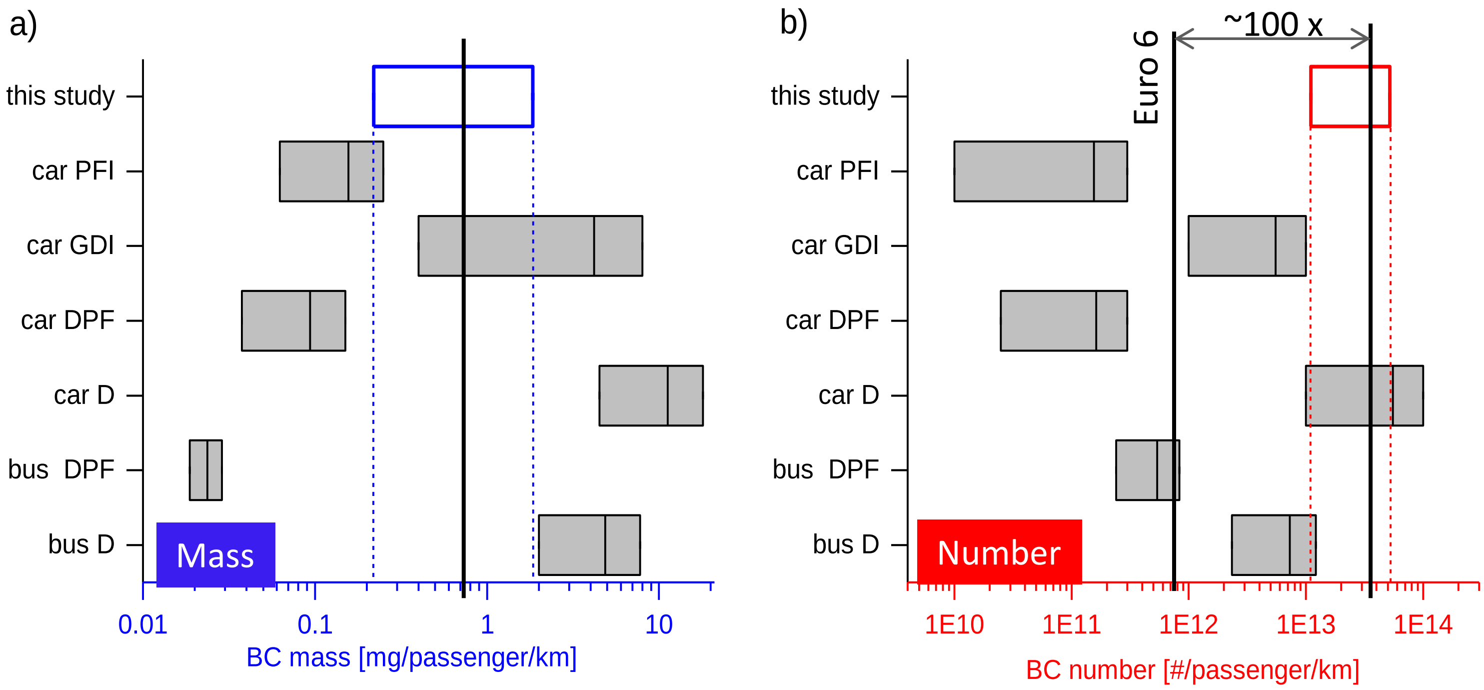
- Flight profile (climb, descent) based on flight radar data for Boeing 737 flights and realistic engine control
- LTO and climb emissions are dominant for short flights





A typical airliner may emit up to 100-times more soot particles (number) per passenger-km than a Euro 6 car

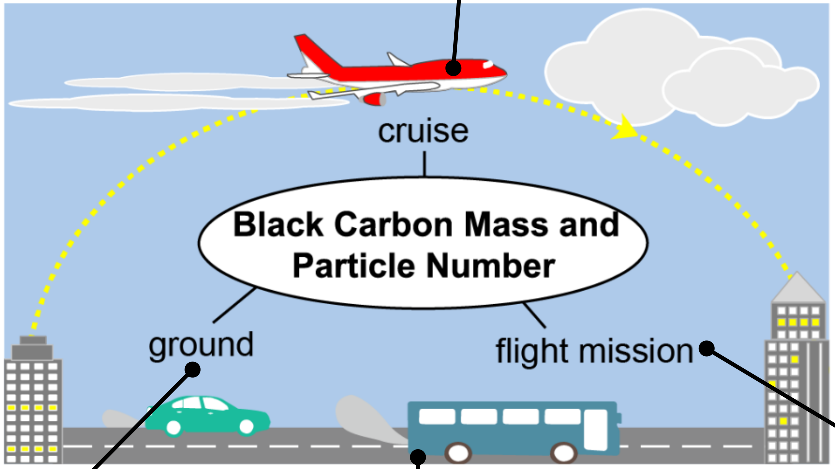
- Vehicle emissions data: Giechaskiel *et al.*, AST, 2012; Hallquist *et al.*, ACP, 2013
- “Perfect” comparison impossible *e.g.* due to different measurement techniques (CPC cutoff)

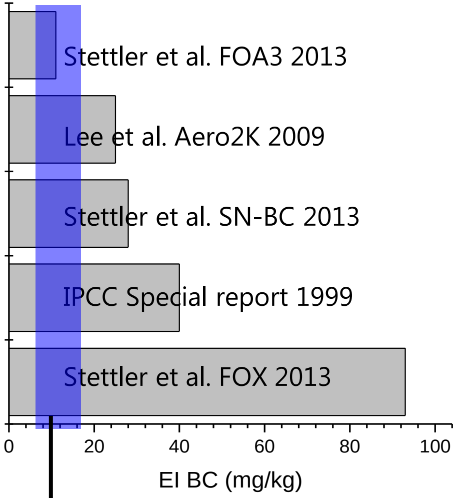


Summary

We characterized and assessed BC mass and **number** emissions of the most popular airliner, B737.

- Representative cruise emissions:
  - GMD ~25 nm, EI_m 11 mg/kg, **EI_n 7×10^{14}/kg**





- EI_m 6 – 15 mg/kg
- **EI_n 3 – 9×10^{14}/kg**

- BC mass emissions lower than predicted by most models
- **Number emissions significant at low power**

- BC mass / passenger ~ gasoline car
- **BC number / passenger ~ old diesel car**

Durdina, L. et al. (2017). *Environ. Sci. Technol.*, *51*(6), 3534–3541.

Acknowledgements

- **Empa** – Beni Brem, Ari Setyan, Jing Wang, Anthi Liati, Andrea Fischer
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- **PSI** – Dogushan Kilic
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- **NRC Canada** – Greg Smallwood, Kevin Thomson
- **Sample III consortium** – Andrew Crayford, Paul Williams, Mark Johnson
- **SAE E-31 committee**

A-PRIDE 5 campaign photo, July 2013

SR Technics

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Aviation Administration

EASA
European Aviation Safety Agency

Transport Canada
Canada

GE Aviation

SAFRAN
Snecma

SF Aviation

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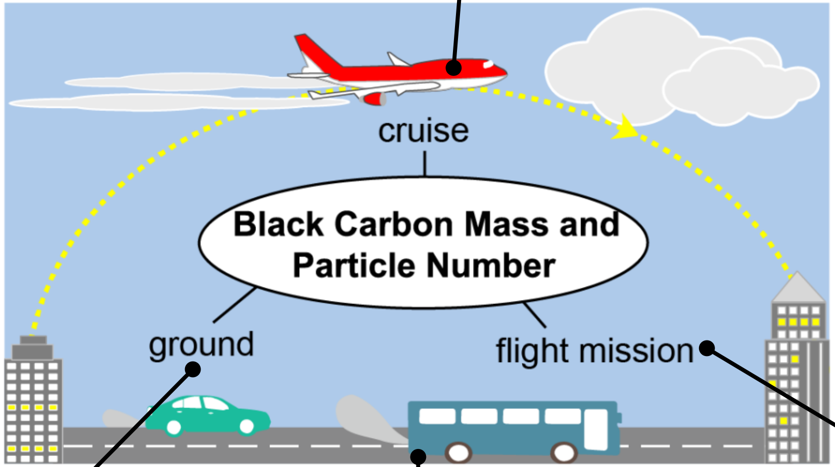

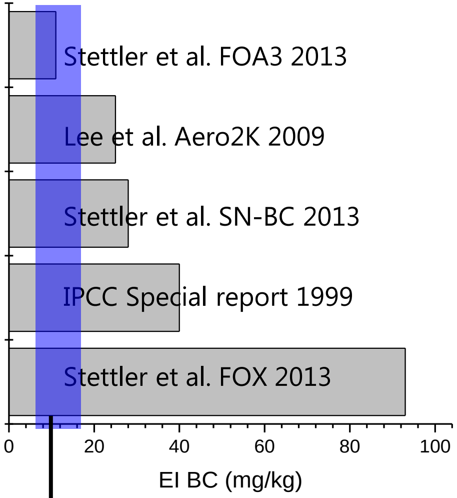

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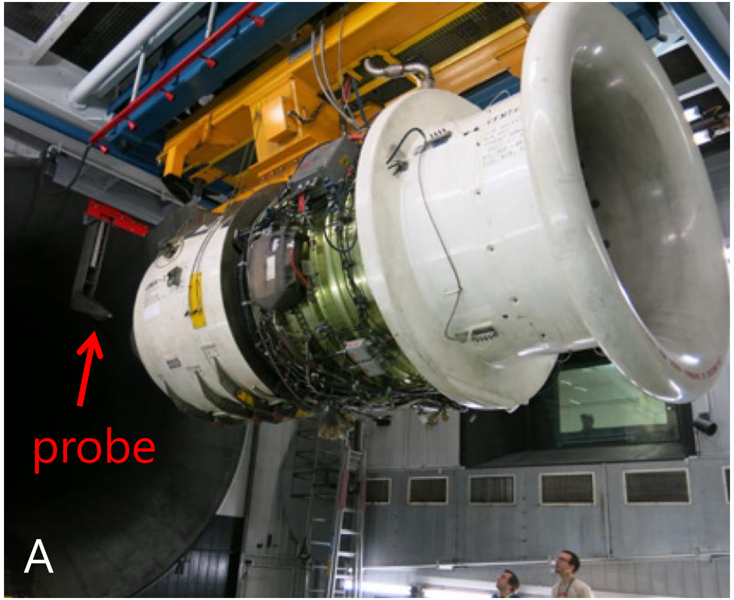
Backup slides

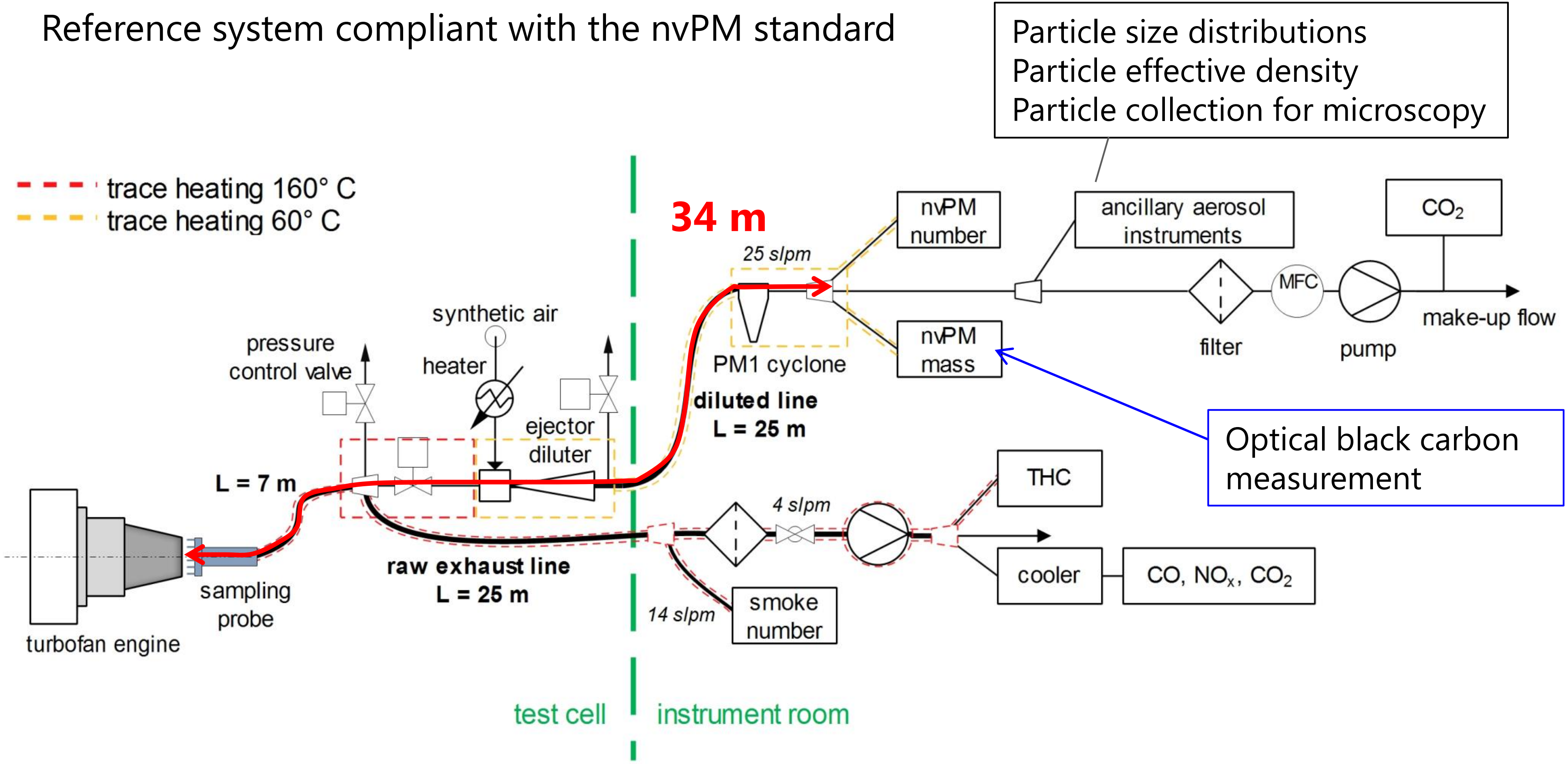
Reference measurement system of aircraft engine non-volatile PM emissions at SR Technics, Zurich airport



- A CFM56-7B engine in the test cell
- B Detail of the single-orifice sampling probe
- C PM measurement system

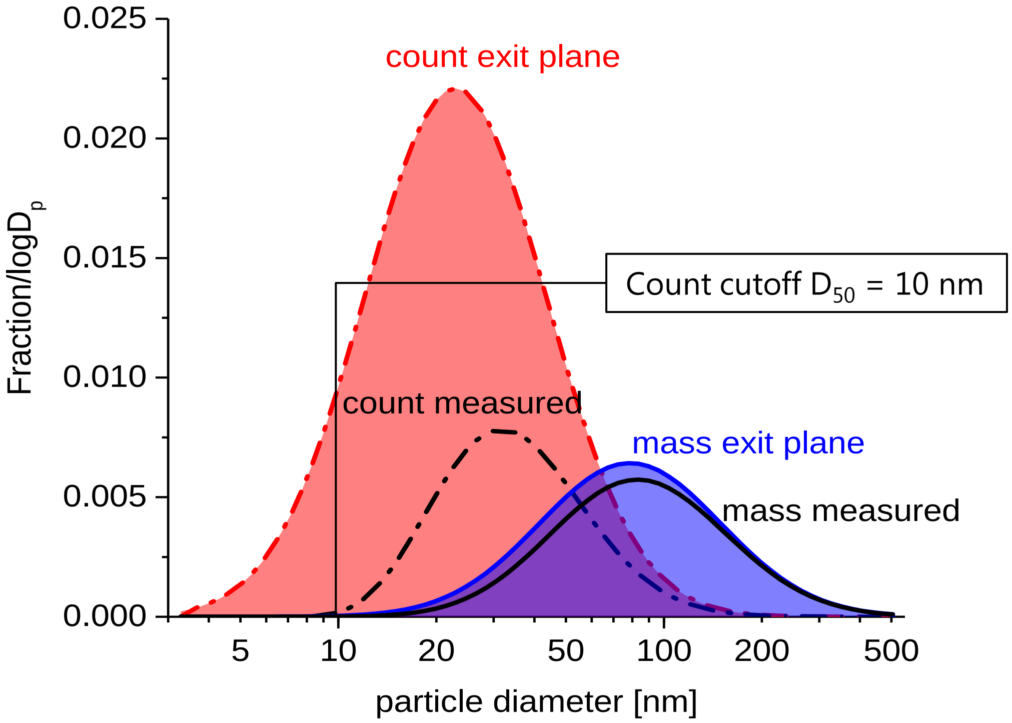
Emissions measurement system at SR Technics

- Reference system compliant with the nvPM standard



A large fraction of particles is lost to the inner walls of the sampling system

- Particle size distribution at take-off thrust (log-normal distribution), no dilution correction

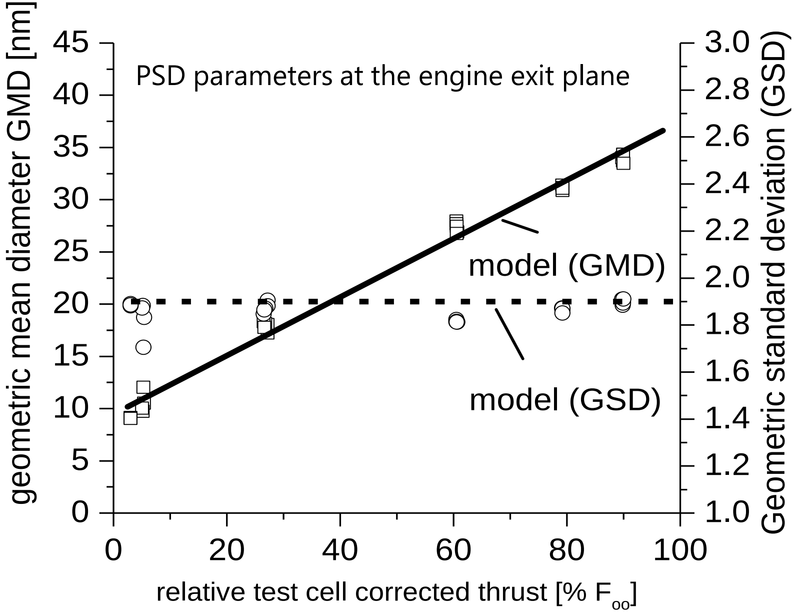


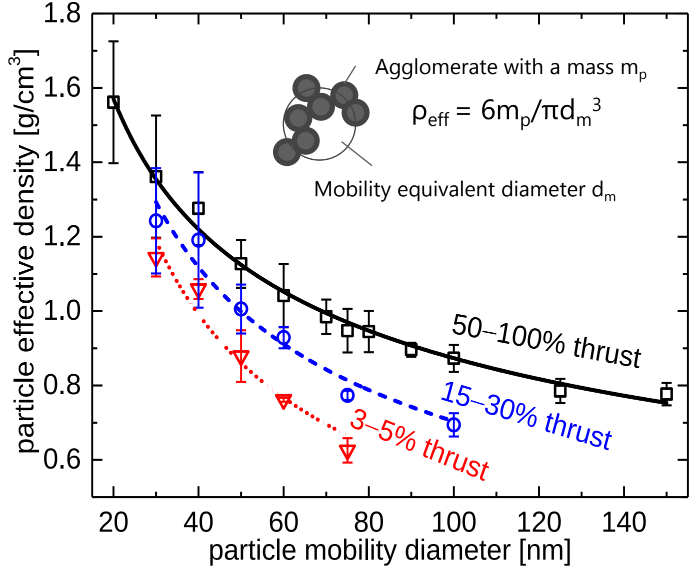
Loss correction takes particle size and effective density into account

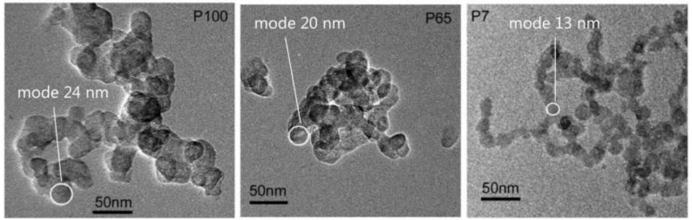
- GMD and effective density increase with engine thrust

$$dN = \frac{1}{\sqrt{2\pi}\ln GSD\, D_p} e^{-\frac{(\ln D_p - \ln GMD)^2}{2\ln^2 GSD}}$$

$$\rho_{eff} = C_\rho d_m^{D_{fm}-3}$$





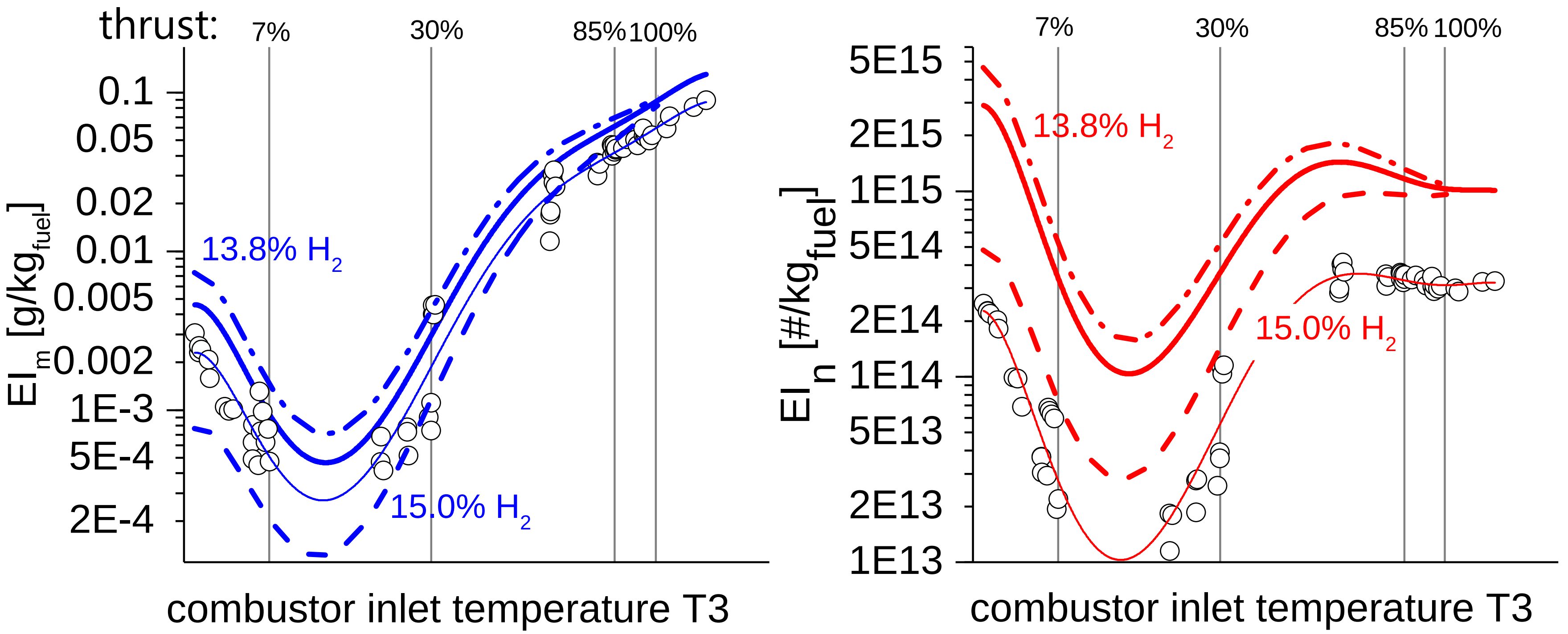


Mean effective density ~1 g/cm^3

Durdina et al. Atm. Env. 2014, Durdina et al. EST 2017 (submitted), Liati et al. EST 2014

Particle emission indices after fuel and line loss correction

- ↑H content →cleaner burning fuel, higher heating value; worldwide variability 13.8 – 15.0% (Zurich 14.3%)
- Fuel effects increase with decreasing thrust (↓ combustion efficiency)



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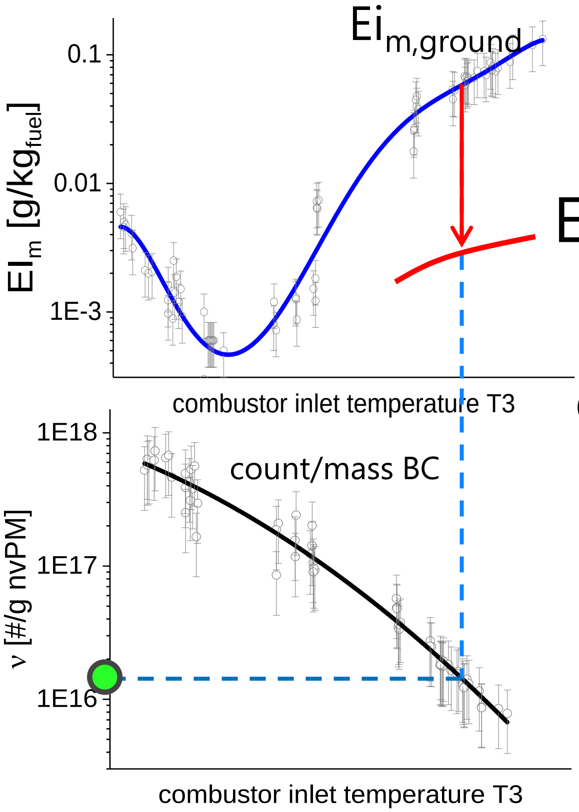
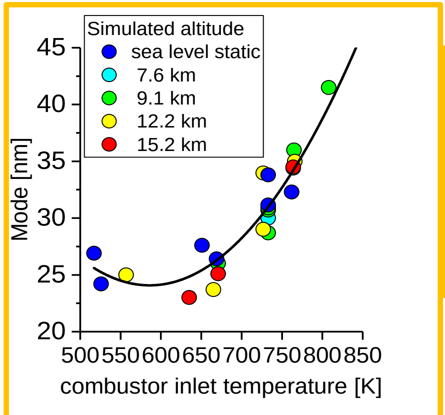


$$EI_m = EI_{m,ground} \times K_{P3} \times K_{AFR}$$

Combustor inlet pressure effect

Air-fuel ratio effect

$$EI_n = \nu(T3) \times EI_m$$



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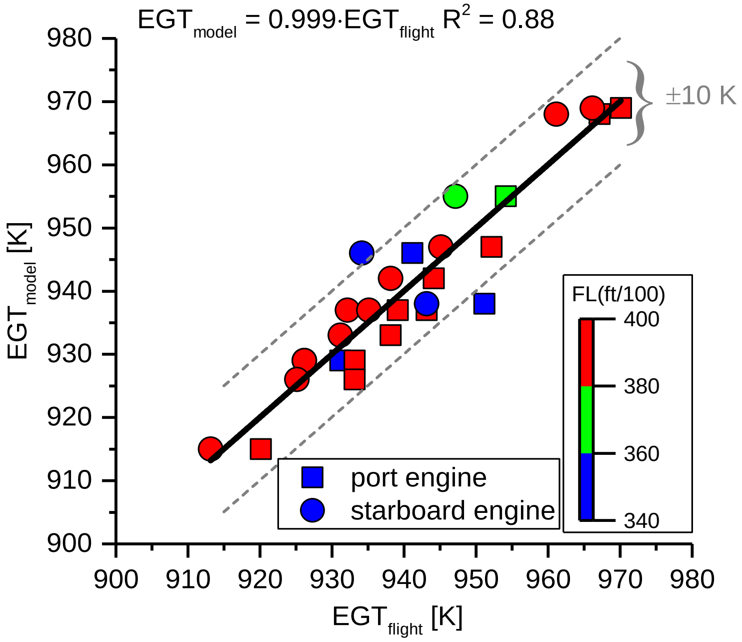
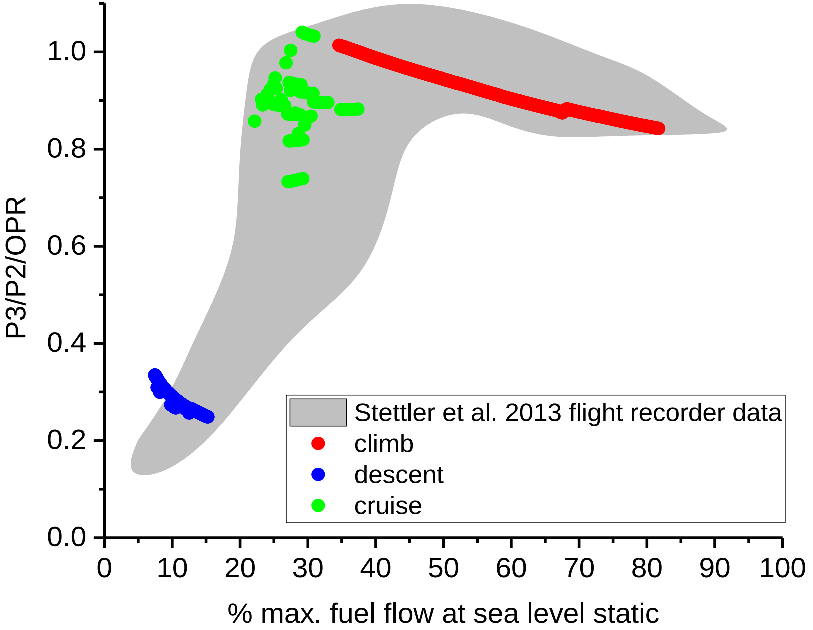
Engine performance model

- Model exhaust gas temperature (EGT) matches data from the Boeing 737 cockpit



- Engine performance parameters agree with flight data recorder measurements of similar engines over all the flight phases



Climb and descent profiles from the model