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Variability in non-volatile particulate matter mass and number emissions of aircraft gas turbine engines

Benjamin Brem[1,2], Lukas Durdina[1,2], Jing Wang[1,2], Alice Suri[3], Theo Rindlisbacher[3] , Frithjof Siegerist[4]

[1]Laboratory for Analytical Chemistry, Empa Dübendorf
[2]Institute of Environmental Engineering, ETH Zurich
[3]Swiss Federal Office of Civil Aviation, FOCA, Bern
[4]SR Technics, Zürich Flughafen

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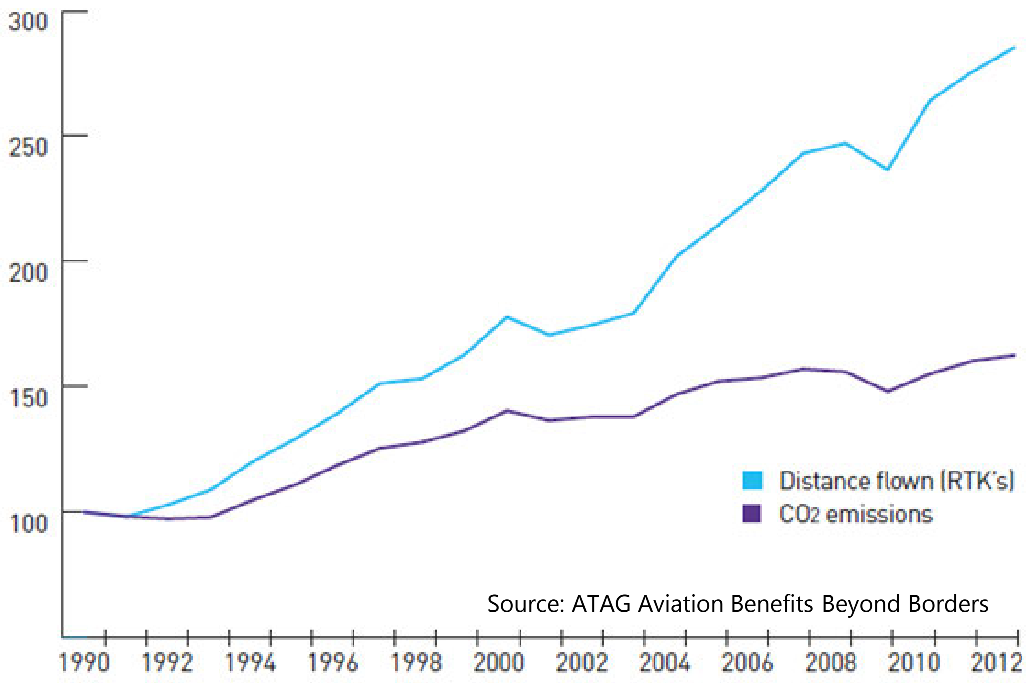
Increasing Efficiency: Aviation Spurs its Own Growth with Potential Consequences



- Revenue ton kilometers (RTKs) have tripled since 1990, CO_2 emissions have increased by 50% since 1990
- Transport efficiency has increased drastically, lowering prices result in increased demand
- Global demand is expected to grow at 5 to 8% per year in this decade, resulting in increased fuel consumption and increased emissions

Emissions: Components, Transformation and Impact

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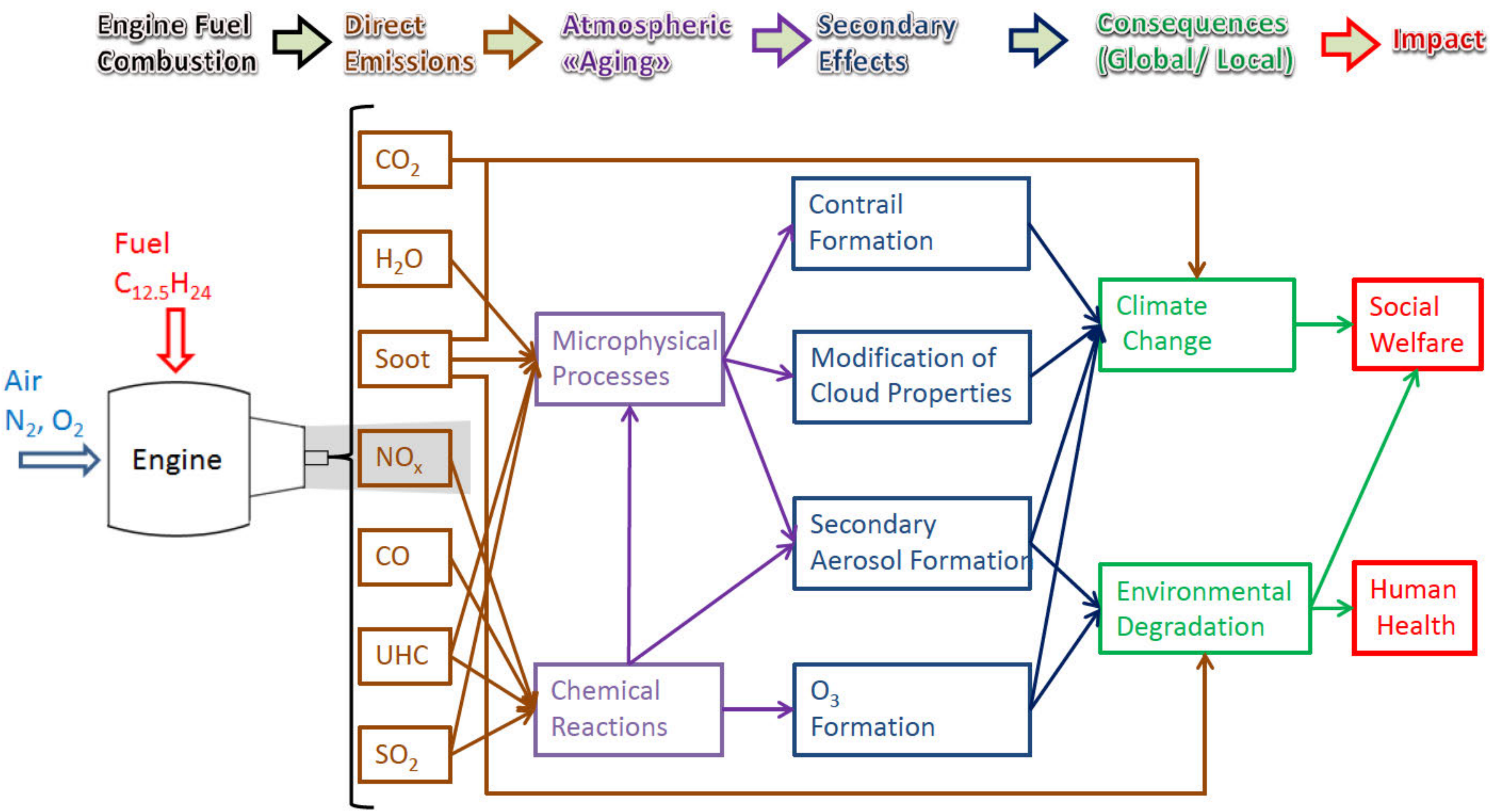


Objectives

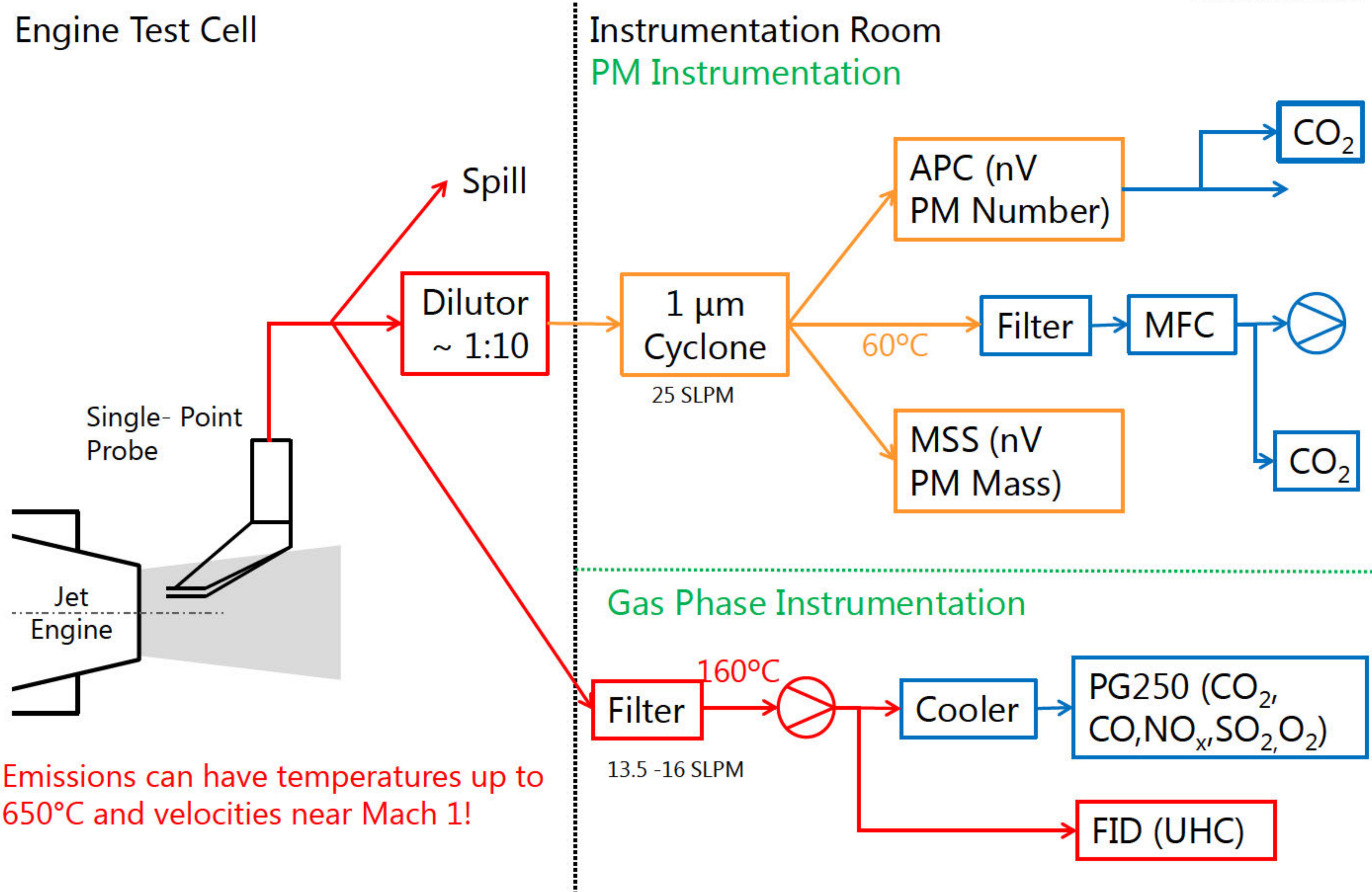
PM Measurement Standardization (FOCA, SAE-E31 and EMPA)

- Development of a sampling system for the representative measurement of non-volatile PM number and mass in aircraft gas turbine exhaust
  - Selection of suitable measurement technologies
  - Calibration and certification
  - Intercomparison with other sampling systems

PM Emission Characterization (EMPA, PSI and ETH)

- Effects of:
  - Engine type
  - Thrust level
  - Ambient conditions
  - Fuel composition
- Chemical and physical properties
- Volatile emissions and secondary aerosols
- Climate relevant properties

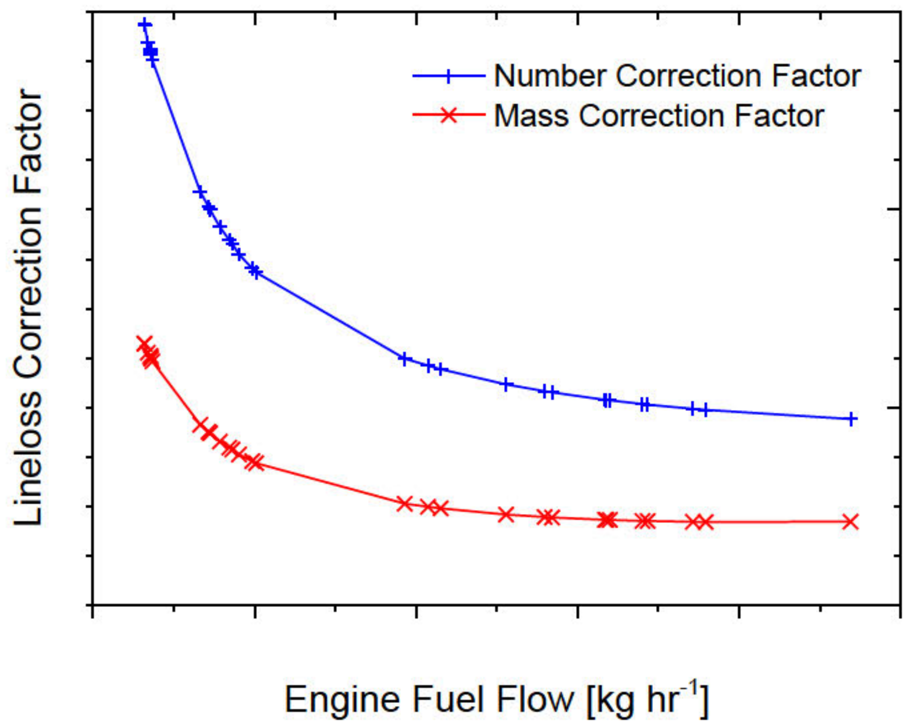
Sampling System Overview



Emissions can have temperatures up to 650°C and velocities near Mach 1!

Data Processing

1. Determination and averaging of stable sampling periods
2. Correction of dry measured gases to actual wet exhaust condition
3. Line loss correction for PM mass and number (modelled according to Liscinsky *et al.* (2010) based on measured parameters)



4. Calculation of emission indices, *e.g.* mass PM/mass fuel

Non-volatile PM Mass & Number Emissions: 90s Technology Mid-Size Turbofan

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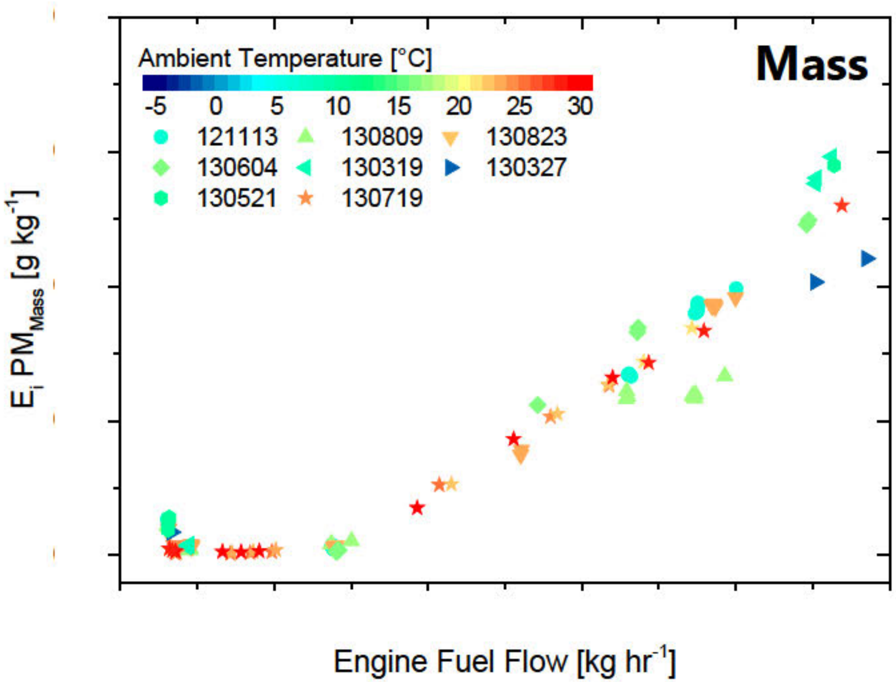
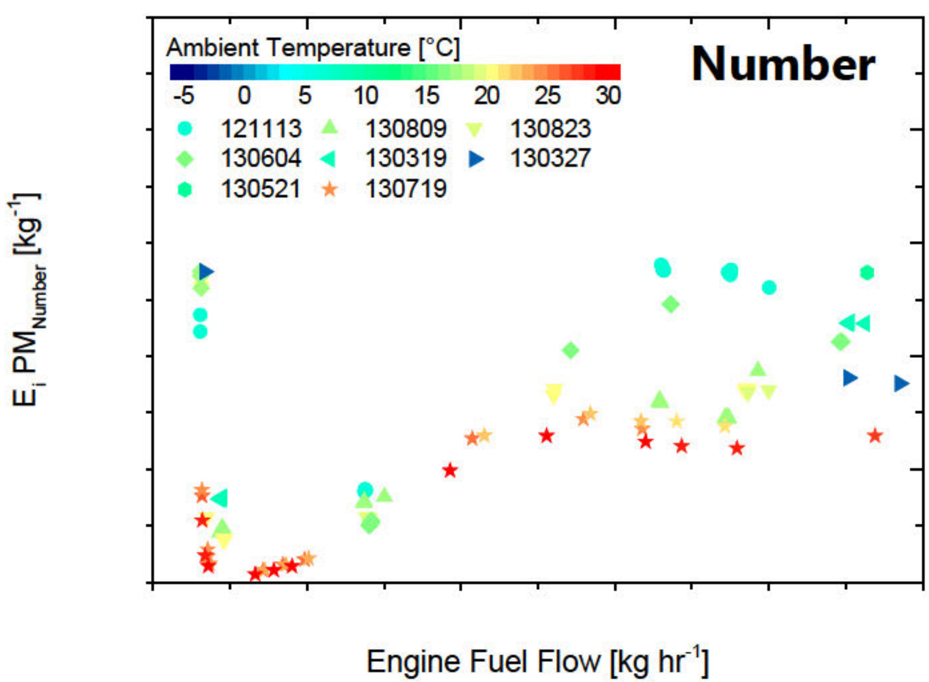
- One of the most common aircraft engine in the world, with more than 20,000 units built





- High number emissions at low engine fuel flow that do not correlate with mass emissions
- Temperature effect visible in the number emissions

Non-volatile PM Mass & Number Emissions: 90's Technology Large-Size Turbofan

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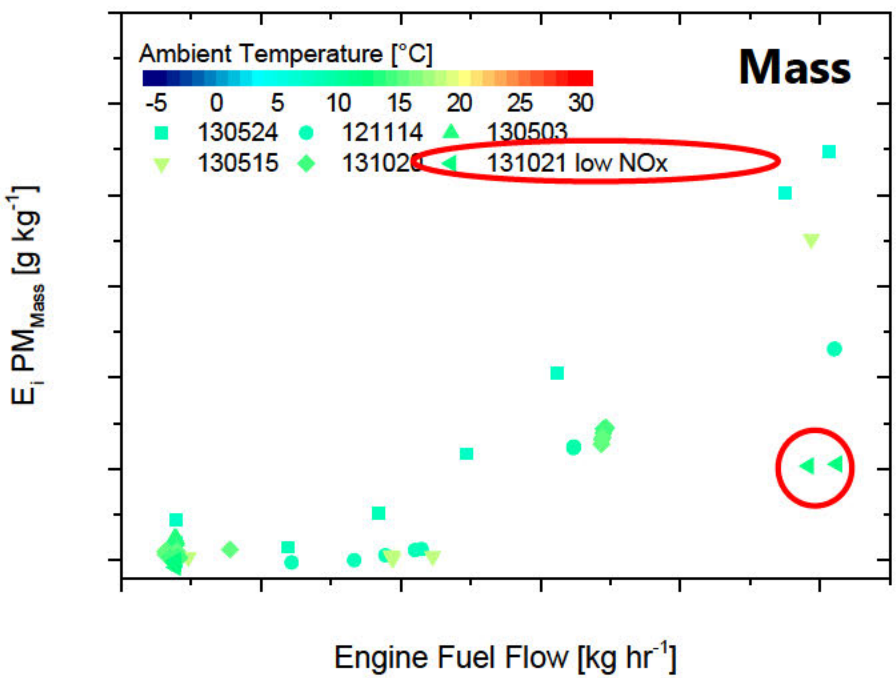
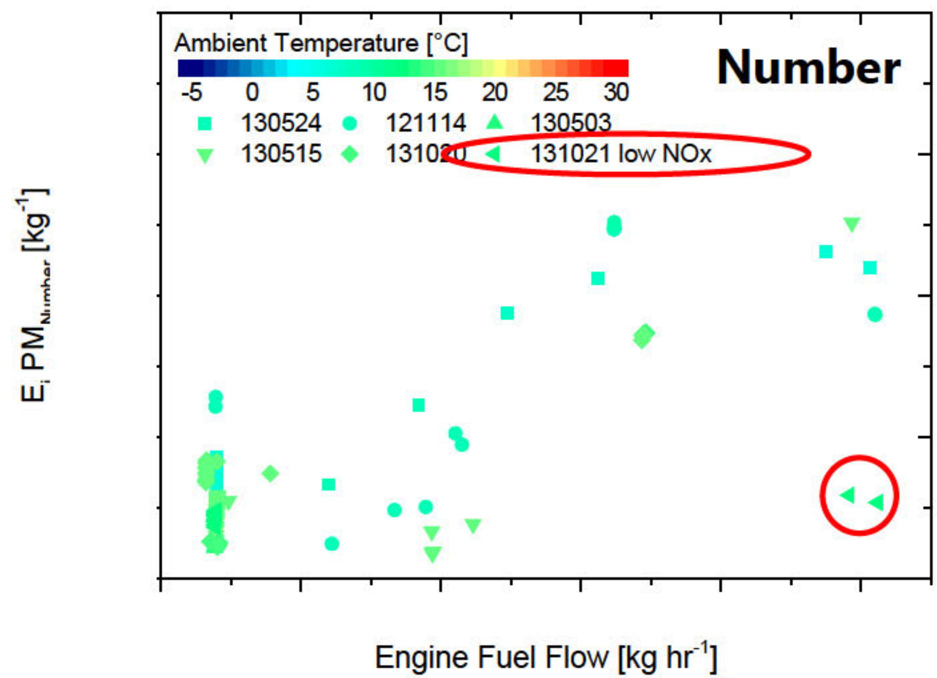
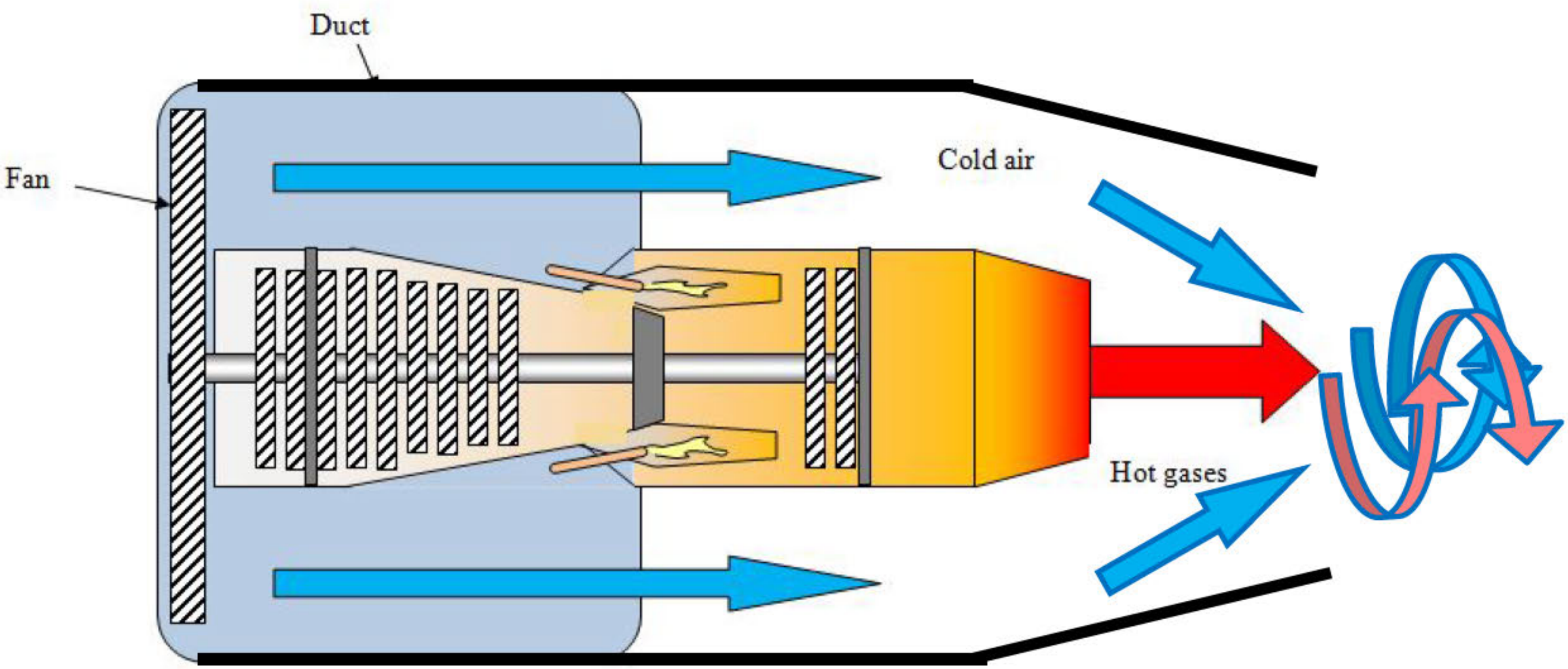
- Largest engine that is tested at SR Technics





- All tests performed at temperatures between 7 and 17°C
- Reasons for variability not clear and could be variability in combustor type or engine degradation
- Low NOx combustor has the lowest mass and number emissions at take-off

Special Case 1: Mixed-Flow Turbofan



- Mixing provides higher thermal efficiency and lower acoustic emissions at certain frequencies
- Low concentrations in mixed exhaust cause higher uncertainty for emissions measurements (in particular for PM mass)

Non-volatile PM Mass & Number Emissions: 90s Technology Mixed Flow Turbofan

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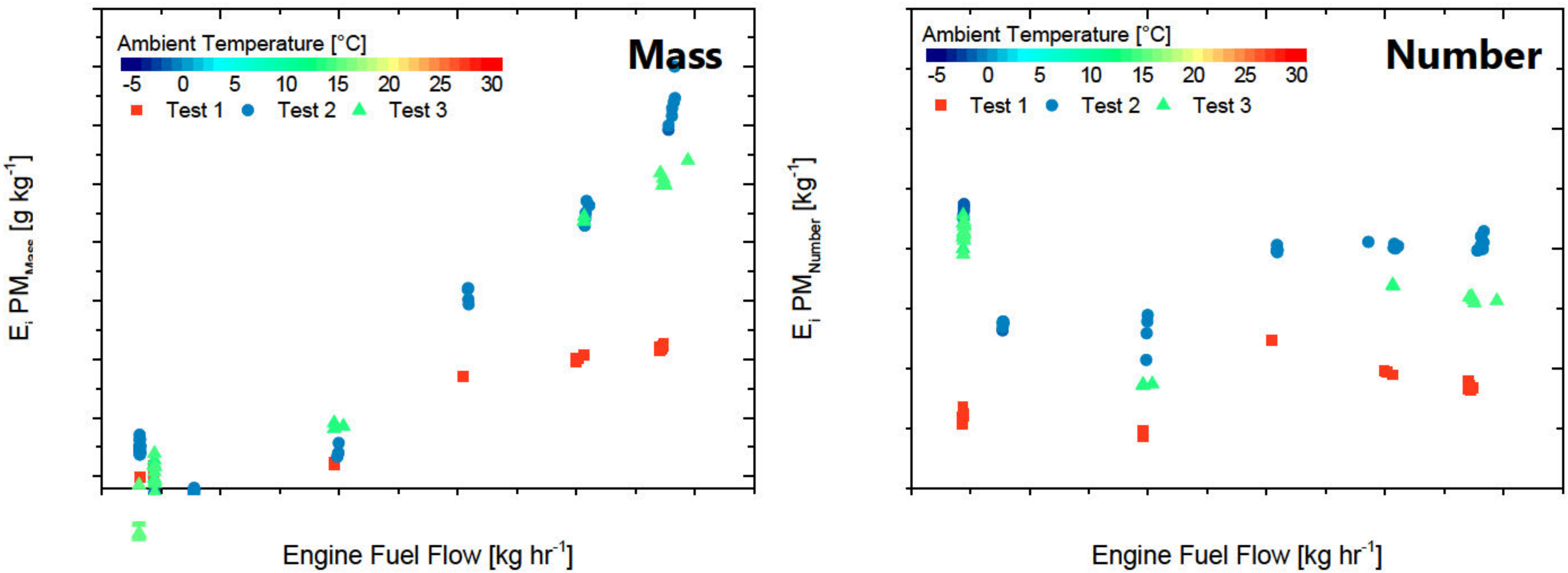

- Variability in mass data likely caused by uncertain calibration of mass instrument at low concentrations (measured mass concentration in the range of 30- 40ug/m^3 at take-off)
- Ambient temperature effect observable for number emissions

Special Case 2: Double Annular Combustor (DAC) Engine

- Radial staging of two combustor zones
  - Rich pilot stage with low through flow velocities for stable operation at relative thrusts < 25%
  - Lean main stage with high through flow velocities and low residence time kicks in at relative thrusts > 25%
- About half the NO_x emissions of a traditional engine
- Swissair and Austrian Airlines provided the initial impetus to incorporate DAC technology into their fleet
- Newer technologies are incorporating the staged approach into one combustor ring, *e.g.* GE Twin Annular Premixing Swirler (TAPS) combustor

Non-volatile PM Mass & Number Emissions: Late 90s Technology DAC Turbofan

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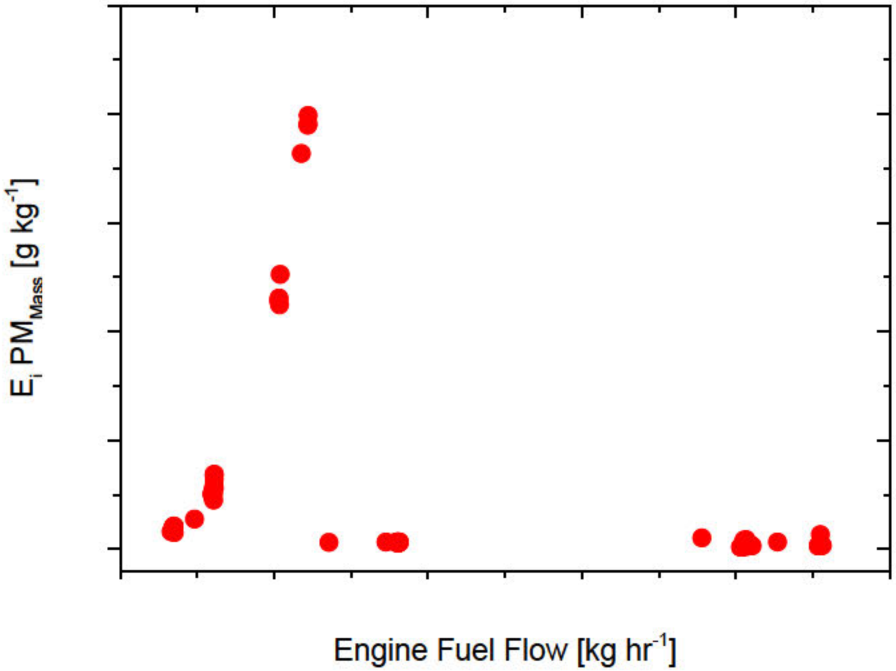

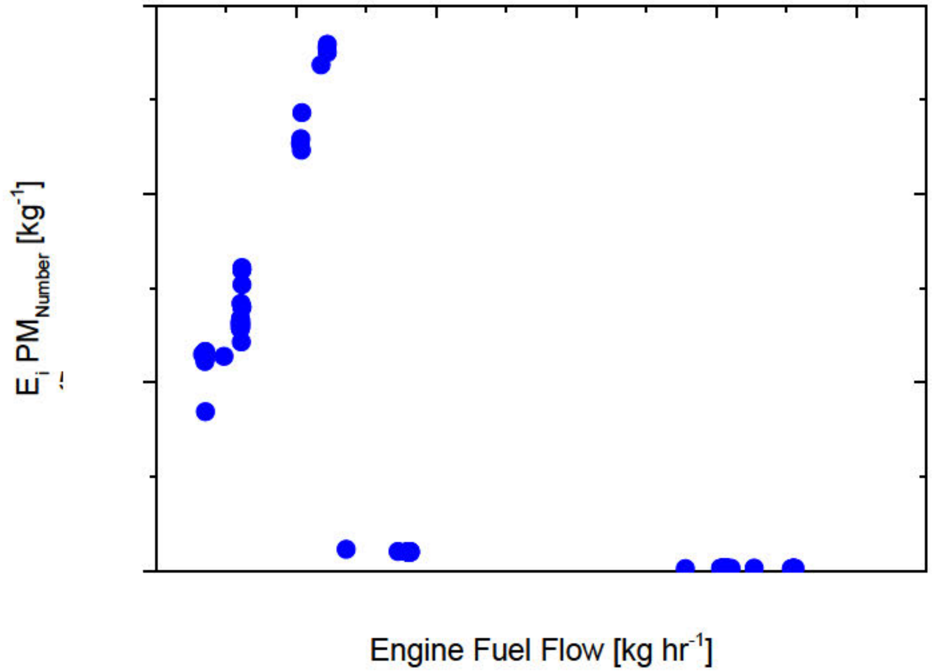

- High number and mass emissions when pilot stage is solely operating
- Mass emissions at the detection limit of instrumentation when both combustor stages are engaged
- High emissions only occur during transients, but not during typical flight operation engine settings

Assessment of nV PM Mass and Number Emissions: Zürich Tel Aviv Route

- Aircraft Assumptions:
  - Airbus A 330-200 equipped with 2x 90s Technology Large Size Turbofans
  - Travelling distance of 2803 km (linear)
  - 236 passengers
  - Cruise emissions approximated according to Döppelheuer and Lecht (1998) and Stettler *et al.* (2013)

- Bus and Car Assumptions:

	Bus Euro IV	**Bus Euro VI**	**Car Euro 4**	**Car Euro 6**
Travelling Distance (Google Maps)	4135 km	4135 km	4135 km	4135 km
Passengers	60	60	4	4
PM_{Mass} emissions	0.03 g kWh^{-1}	0.01 g kWh^{-1}	0.025 g km^{-1}	0.0045 g km^{-1}
PM_{Number} emissions	3.50E+13 kWh^{-1}	6.00E+11 kWh^{-1}	6.00E+13 km^{-1}	6.00E+11 km^{-1}

Total nV PM Mass and Number Emissions

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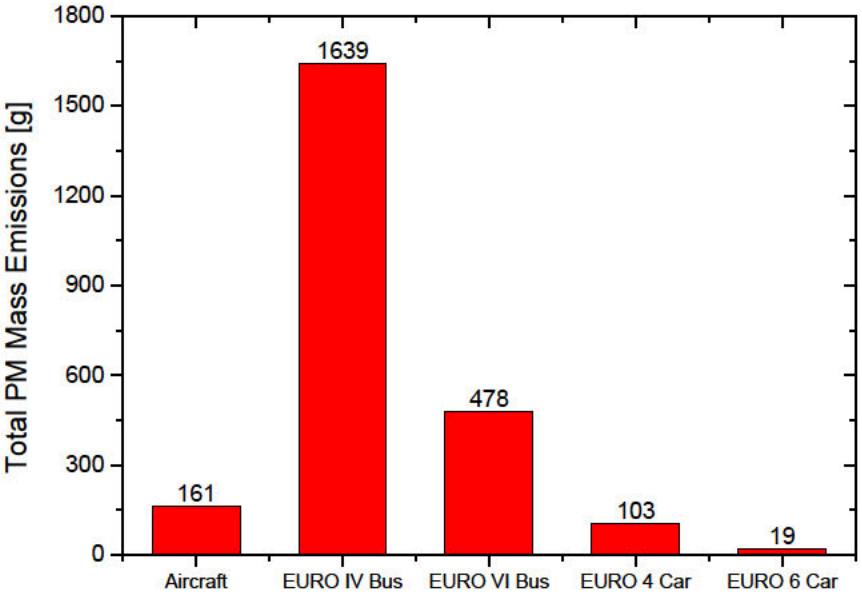
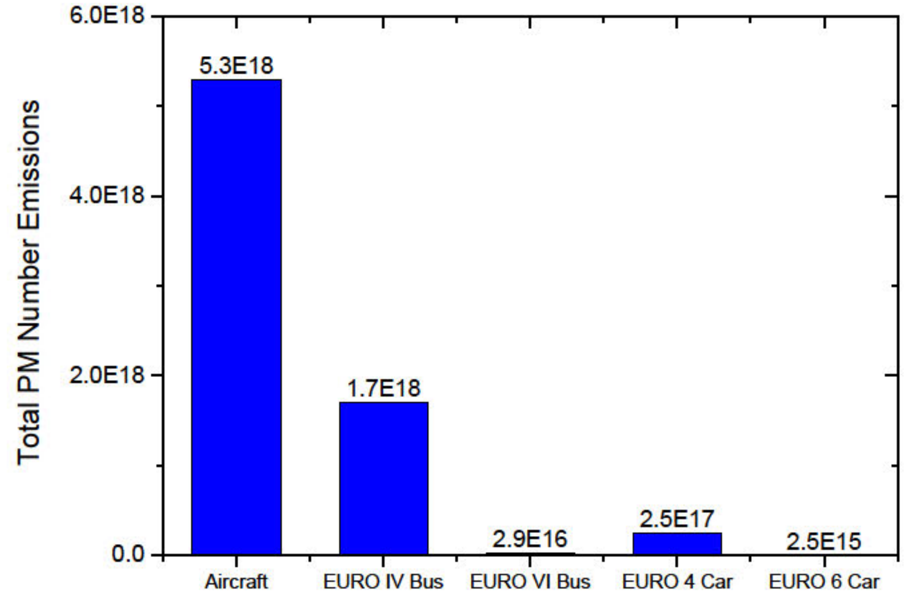


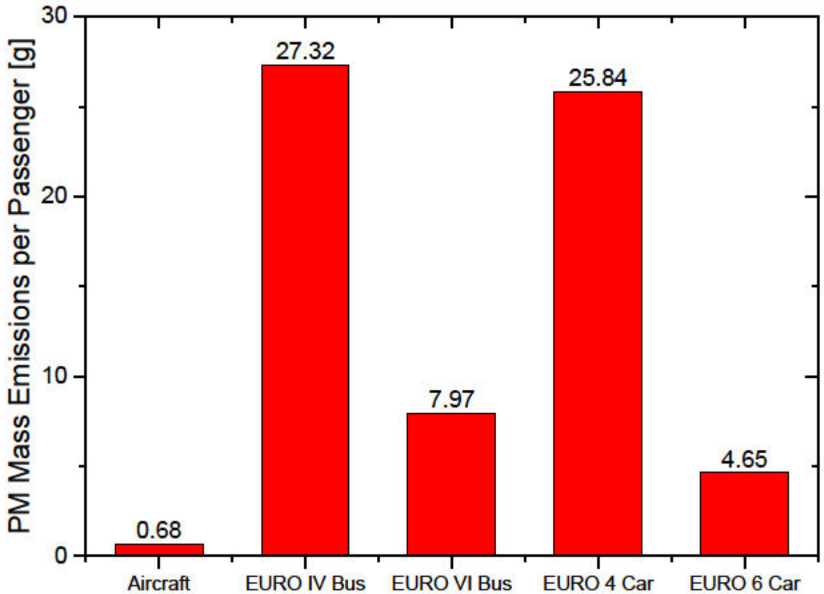


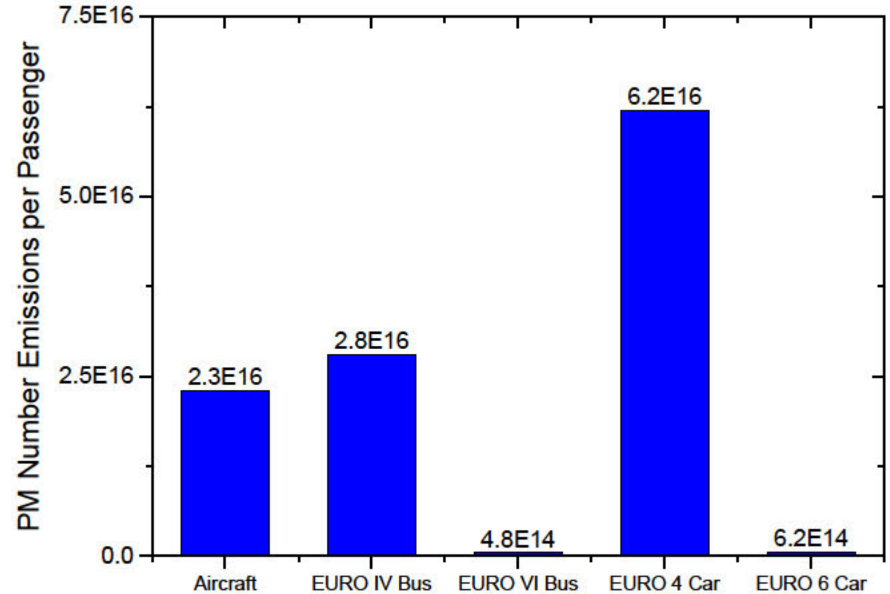
- Total aircraft nV PM mass emissions comparable to a EURO 4 passenger car
- ~~Total aircraft nV PM number emissions almost an order of magnitude higher~~

Not a fair comparison: aircraft CPC counting efficiency of ≥50% at 10nm vs. PMP CPC counting efficiency of ≥50% at 23nm

Spatial Distribution of Aircraft Emissions		
Location of Emission	**Mass [g]**	**Number**
Zürich & vicinity (< 1000 m)	77.22	1.53E18
Cruise (> 1000 m)	82.12	3.23E18
Tel Aviv & vicinity (< 1000m)	2.02	5.46E17

nV PM Emissions per Passenger





- Aircraft nV PM mass emissions per passenger an order of magnitude lower
- EURO 6 vehicles have an order of magnitude lower nV PM number emissions
- Newer, low NOx aircraft engine technologies would lower nV PM mass emissions further, but the effect on nV number emissions is currently not clear

Conclusions & Outlook

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- The aviation industry spurs its own growth
- For traditional combustor types nV PM mass emissions increase with increasing engine fuel consumption/power. Number emissions show U-shaped emission profiles
- Low NO_x combustor technologies such as the DAC have unique emission profiles with lower nV mass and number emissions at high thrust
- Mixed flow turbofan engines pose a measurement challenge
- nV PM mass emissions per passenger are an order of magnitude lower than the ones of the cleanest diesel powered vehicles

Current work focuses on:

- Understanding variability
- Studying fuel effects on emissions

Acknowledgements

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Questions?

Thank you for your attention!

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