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Non-volatile particulate matter mass and number emissions of an aero gas turbine fueled with alternative fuel blends

22nd ETH-Conference on Combustion Generated Nanoparticles, June 18th, 2018

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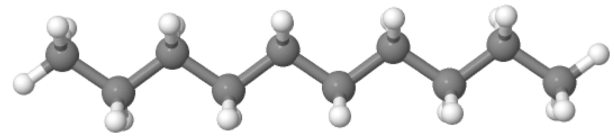
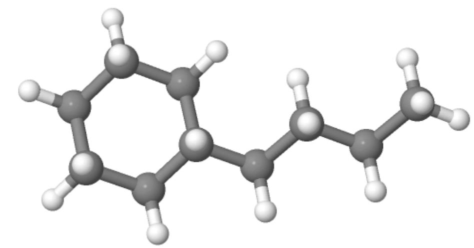
Standard Jet Fuel (Jet A-1)

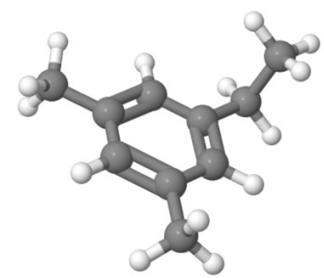
- Major components:
  - Alkanes (C_nH_{2n+2}) ~ 60% v/v
    - High energy content at a low density
    - Low sooting propensity
    - Low reactivity



  - Cycloalkanes (C_nH_{2n}) ~20% v/v
    - Low energy content
    - Low freezing point



  - Aromatics ~ 20% v/v
    - High sooting propensity
    - Swell seals to prevent fuel leaks



  - Sulfur (<0.1% v/v):
- Formulated for operational stability and safety!

Alternative Jet Fuel Types

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- **F**ischer- **T**ropsch (FT)
  - Fully synthetic from any carbon feedstock – most common feedstock is coal! (South Africa)
  - Contain mainly n-alkanes
- **S**ynthesized **I**so- **P**araffins (SIP)
  - Derived from sugar cane (Brazil) with subsequent hydro processing (removal of oxygen)
  - Contain mainly C15 iso-alkanes
- **H**ydro Processed **E**sters and **F**atty **A**cids (HEFA)
  - Derived from vegetable oils which are hydro processed to remove oxygen and to isomerize
  - Contain mainly n- and iso- alkanes

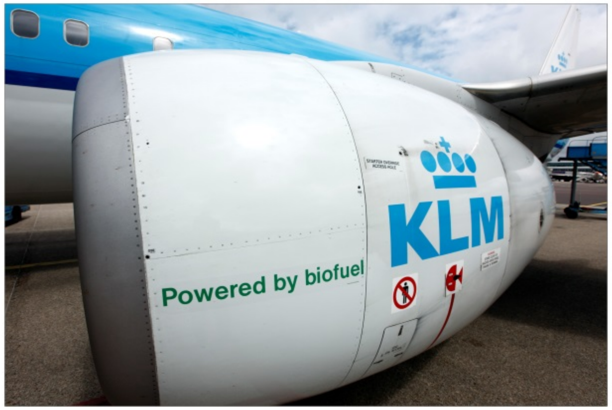
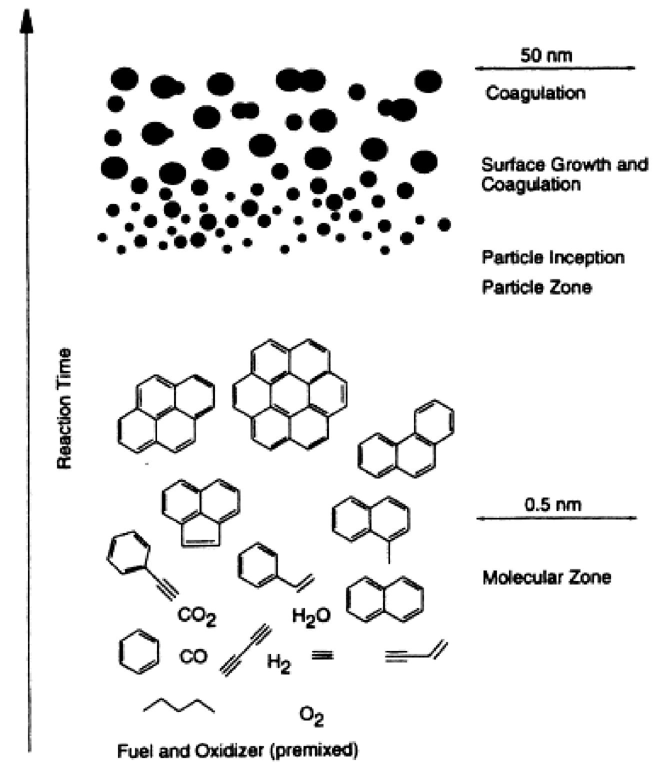


Photo: KLM

Fuel chemistry - soot emission link

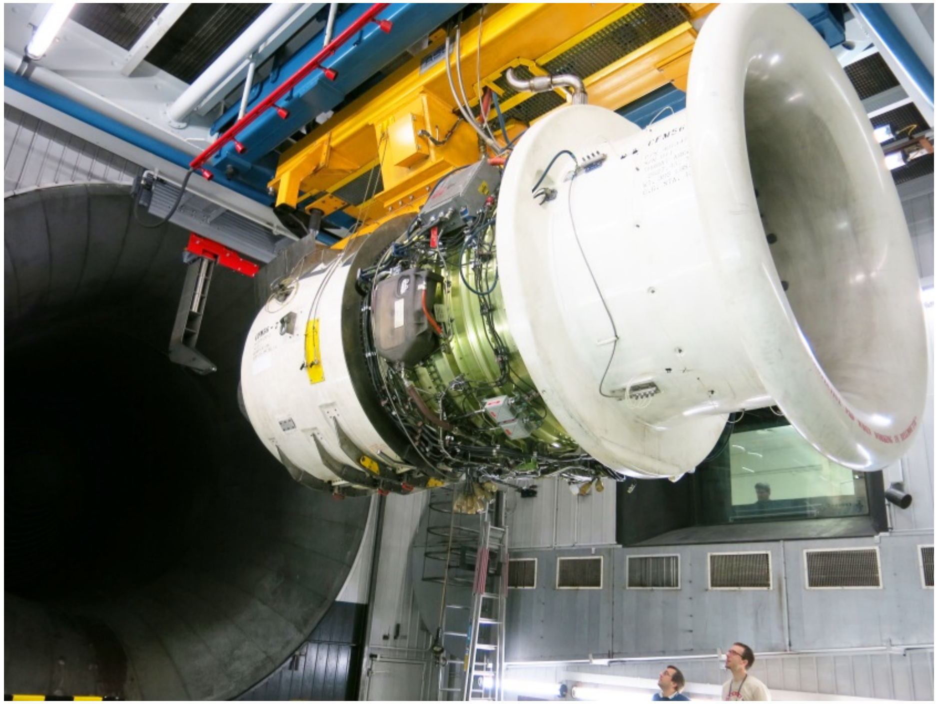
- In the focus of research for more than half a century
- Fuel rich pockets within the flame promote the formation of heavy PAHs which pyrolyze and form soot PM
- Fuel aromatic content is critical
- Aliphatic species can also form PAHs, but reaction rates are typically slower than reactions on already present aromatic species
- PAHs and soot have typically short lifetimes and most of them are oxidized in fuel lean zones



Soot formation mechanism in premixed flames (Bockhorn 1983)

Objectives

1. Investigate the effect of alternative HEFA fuels on non-volatile PM mass and number emissions of an in-production aircraft engine
2. Evaluate the previously developed parameterization that links the non-volatile PM emissions to fuel hydrogen mass content



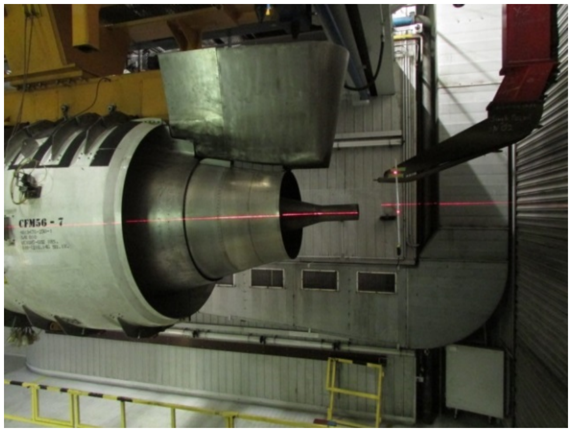
Experiments performed

1. Fuel “doping” experiment with HEFA originating from used cooking oil
   - This experiment addressed low blending ratios (5 and 10%) of alternative fuels
   - Test cell occupation: 2 days

2. Alternative fuel experiment with 42 m^3 of commercially available JET A-1 – HEFA blend (as an airline would buy it)
   - The HEFA content of this fuel was 32% v/v
   - The HEFA fraction also originated from used cooking oil (California)
   - Test cell occupation: 4 days

Engine and test matrix

- An airworthy CFM56 engine was used for these experiments:



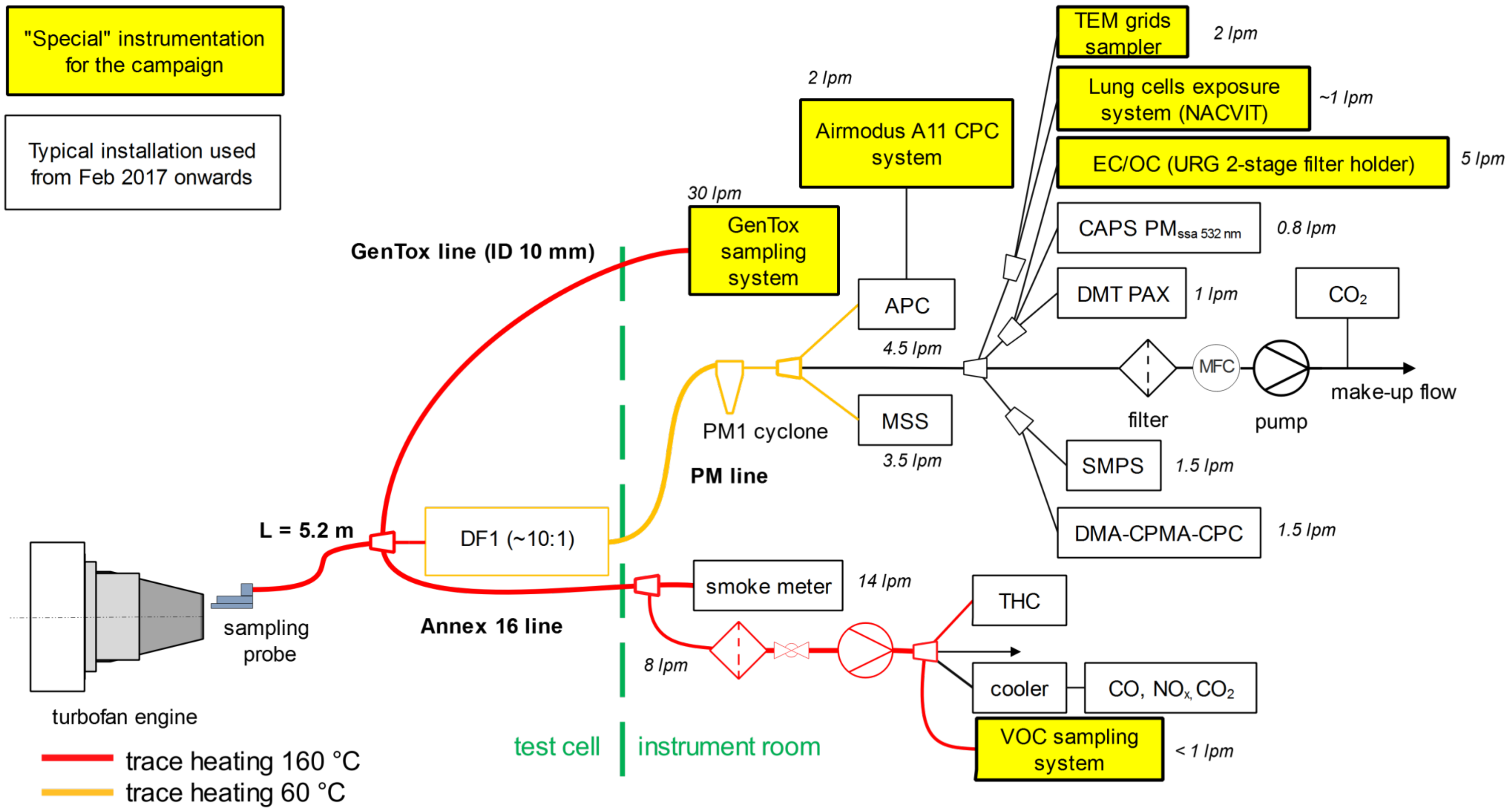
Hours of operation	32297
Engine cycles	15271
Performance	Typical performance
Oil consumption	High (0.3 l/h)

- Typical test matrix consisted of the following test points:

Engine thrust (%)	Targeted flight phase	Approx. fuel flow (kg/s)
Warm-up	N.A.	N.A.
100	Take -off	1.24
85	Climb-out	1.02
65	Cruise (High)	0.74
50	Cruise (Low)	0.55
30	Approach	0.33
7	Taxi	0.12
Idle	Tramac Idle	0.09

- The combustor inlet temperature (T3) was used as the engine control variable

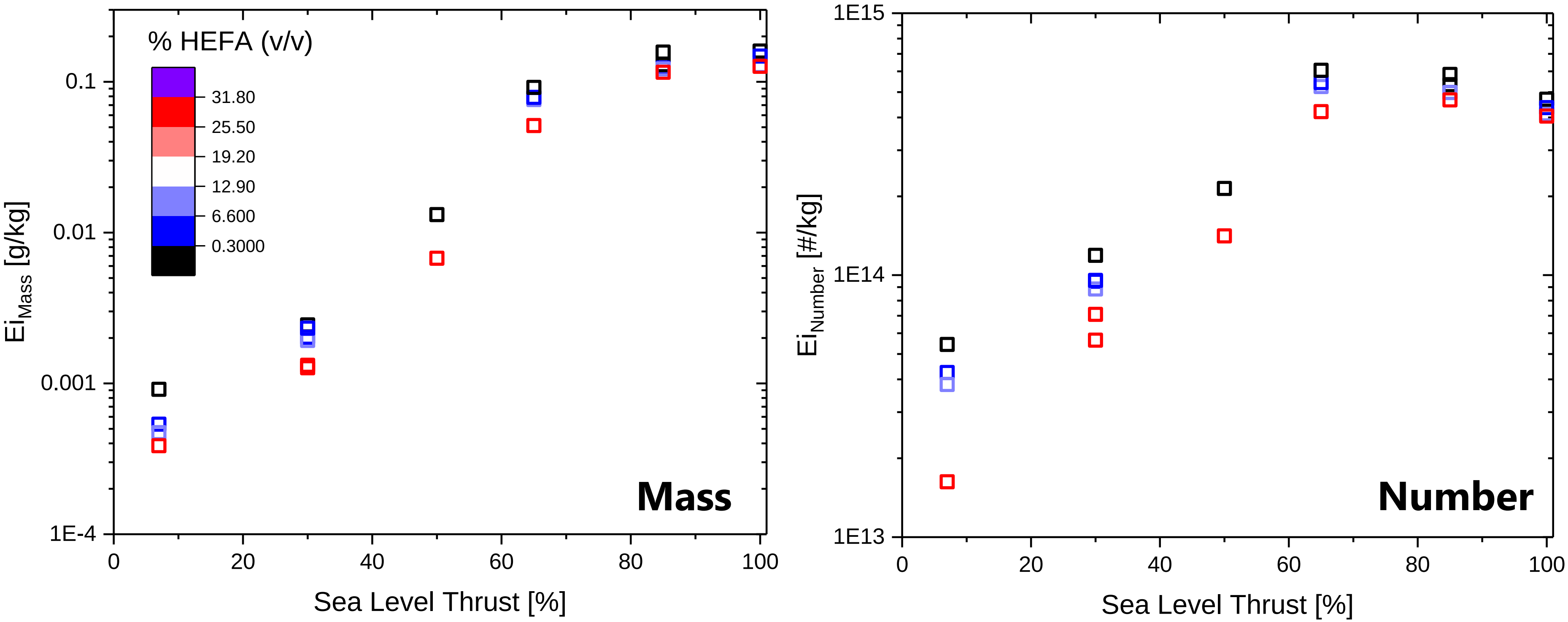
Experimental setup



(figure credit Lukas Durdina)

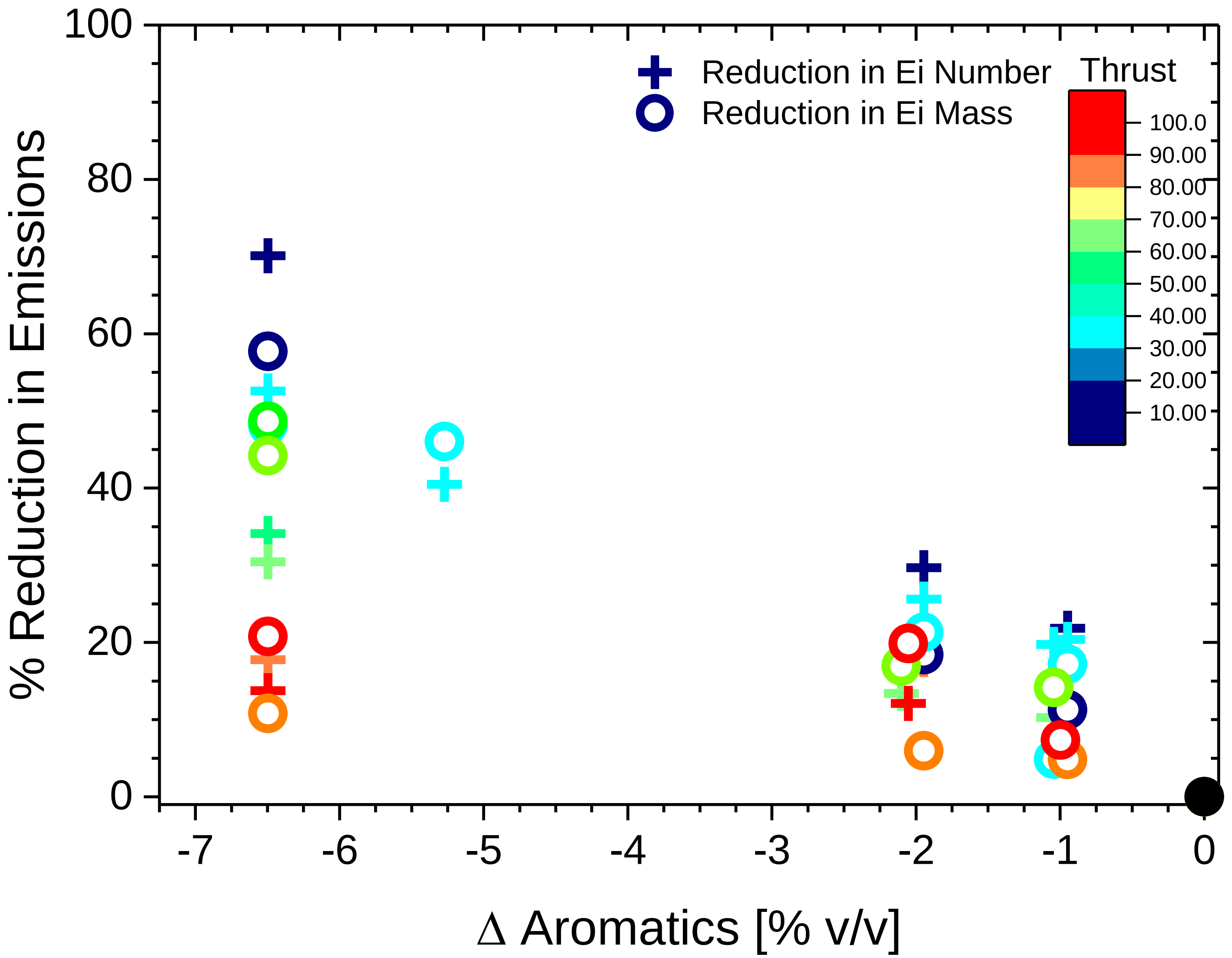
Experimental setup

Fuel effect on nvPM emissions



- Clear effect of HEFA fraction visible for both mass and number emissions
- Clear thrust dependence observed
- Effect on mass and number is comparable

Change in nvPM emissions vs. change in aromatics



- Fair linear dependency
- Effect on mass and number comparable (at high engine thrusts)

Fuel hydrogen content as a predictor for non-volatile PM emissions

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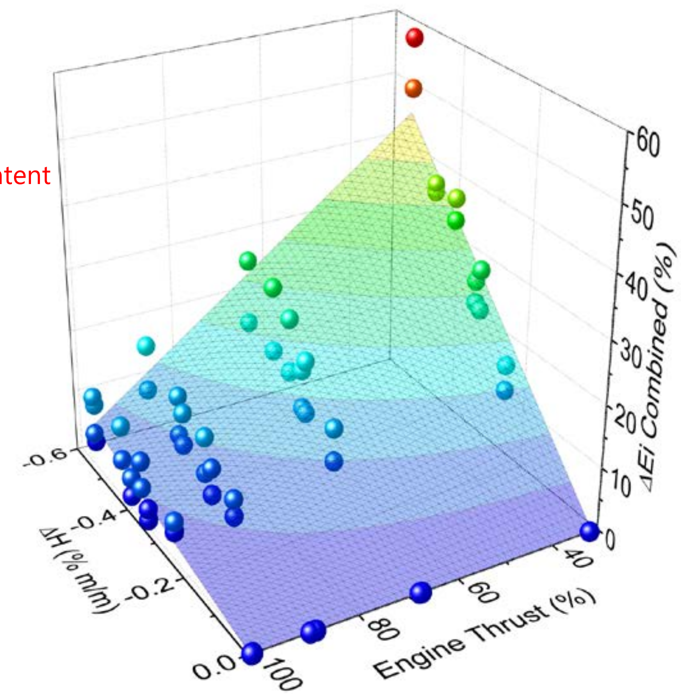
- Lumping complex aromatics chemistry into one predictor
- A simple model was developed:

$$\Delta Ei_x = (\alpha_0 + \alpha_1 \times \hat{F}) \times \Delta H$$

Change in emission index (ΔEi_x); Fitting parameter (α_0, α_1); Engine thrust level ($\hat{F}$); Change in hydrogen mass content (ΔH)



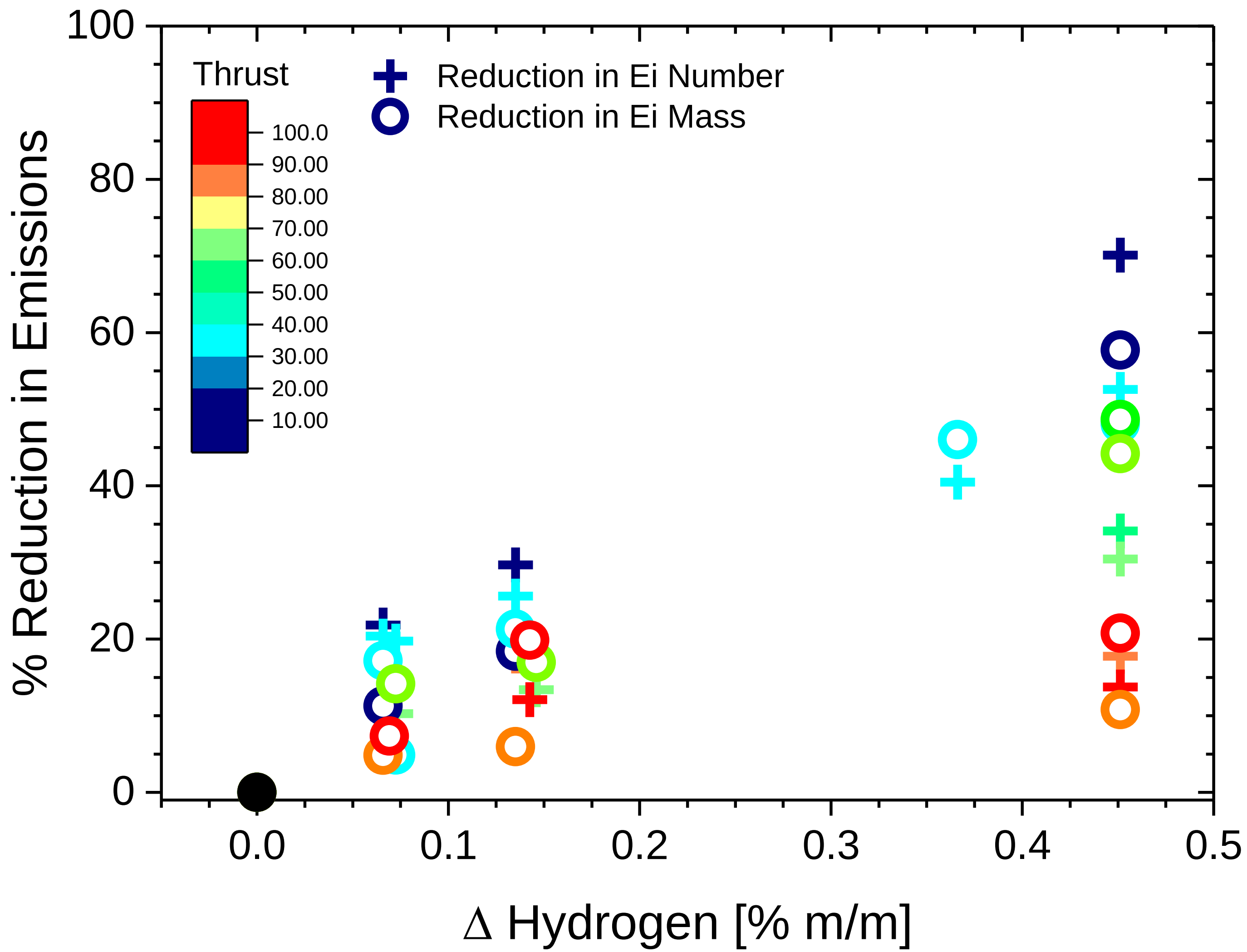
- The following fitting parameter were determined to predict the combined changes in mass and number

Variable	α_0	α_1	Adjusted R^2
ΔEi Combined	-119.31± 3.94	1.03 ± 0.05	0.92

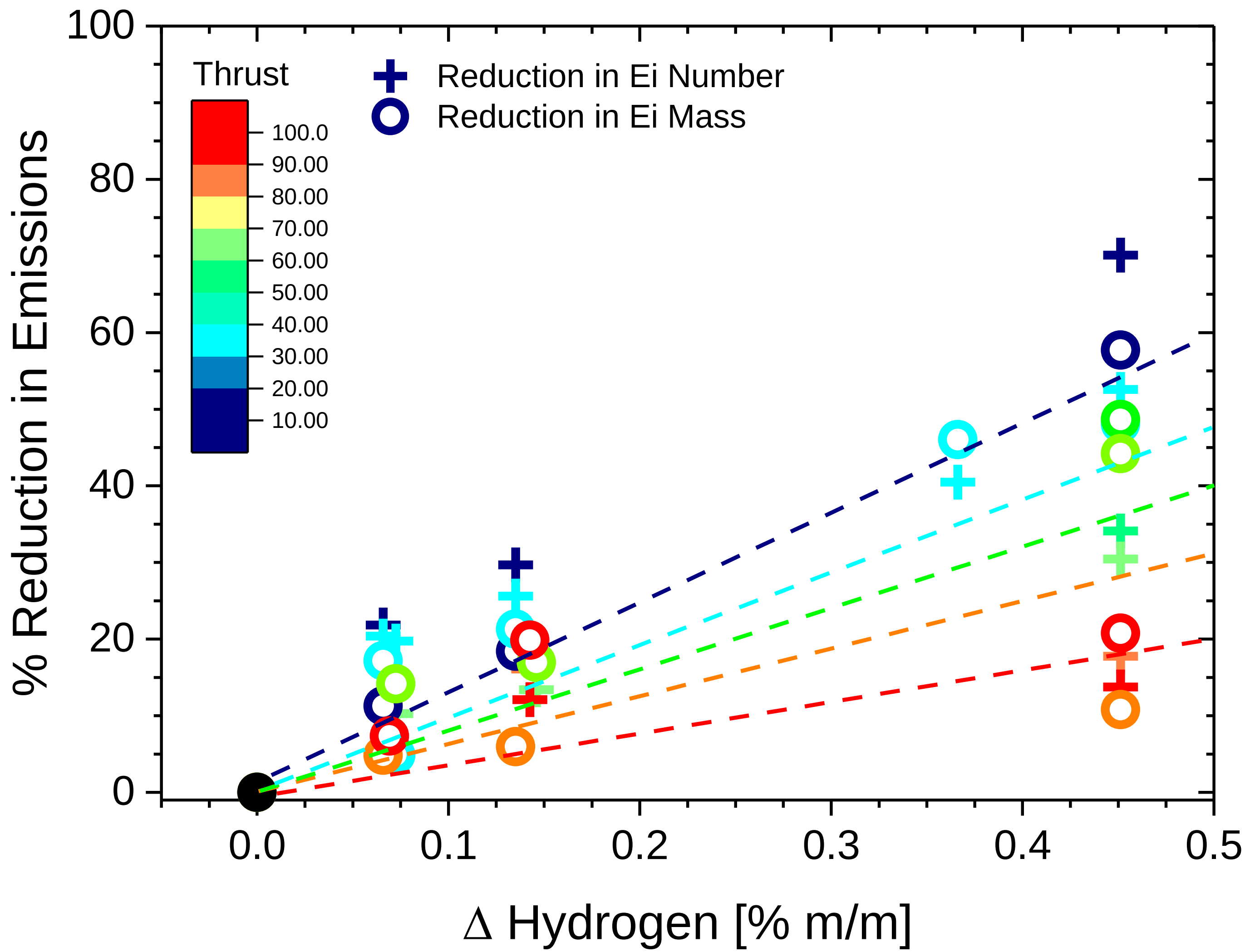
- Requires very accurate measurement of fuel hydrogen mass

More Information: Brem *et al. Environ. Sci. Technol. 2015, 49, 13149−13157*

Change in nvPM emissions vs. change in fuel hydrogen

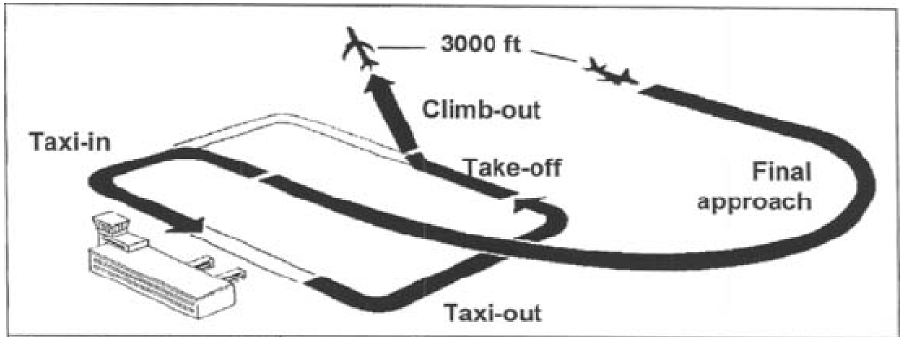


Applying parameterization



- At small changes in fuel chemistry, parameterization underpredicts changes in emissions

Implications for the landing and take-off cycle of a Boeing 737 jetliner



Operating mode	Power setting	Time in mode
1. Taxi / idle	7% take-off thrust	26.0 minutes
2. Take-off	100% std day take-off thrust	0.7 minutes
3. Climb	85% take-off thrust	2.2 minutes
4. Approach	30% take-off thrust	4.0 minutes

HEFA fraction (%)	nvPM mass emissions (g)	nvPM number emissions
0	25.63	1.14E+17
5	24.10	1.03E+17
10	22.87	1.01E+17
32	21.90	8.98E+16

- Improvements are marginal, emissions are dominated by high thrust settings

Summary and conclusions

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- Particle emissions of a current technology turbofan fueled with standard Jet A-1 and three HEFA – JET A-1 blends of 5, 10 and 32% were measured in a test cell setting
- HEFA fuel has the biggest impact at low engine thrusts where its reduced total aromatic content lowers the emissions (up to 70% for the 32% HEFA blend)
- The previous developed emission parameterization using fuel hydrogen mass content is qualitatively applicable but generally under predicts the reduction in emissions
- LTO cycle emissions are only marginally affected by the use of HEFA fuels

Acknowledgements

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- SR Technics: Frithjof Siegerist, Mike Weiner, test cell crew and engine leasing department
- Empa Administration
- Empa 504: Christian Bach, Roland Graf (fuel import know-how and permits)
- Funding: Swiss Federal Office of Civil Aviation SFLV 2015-113

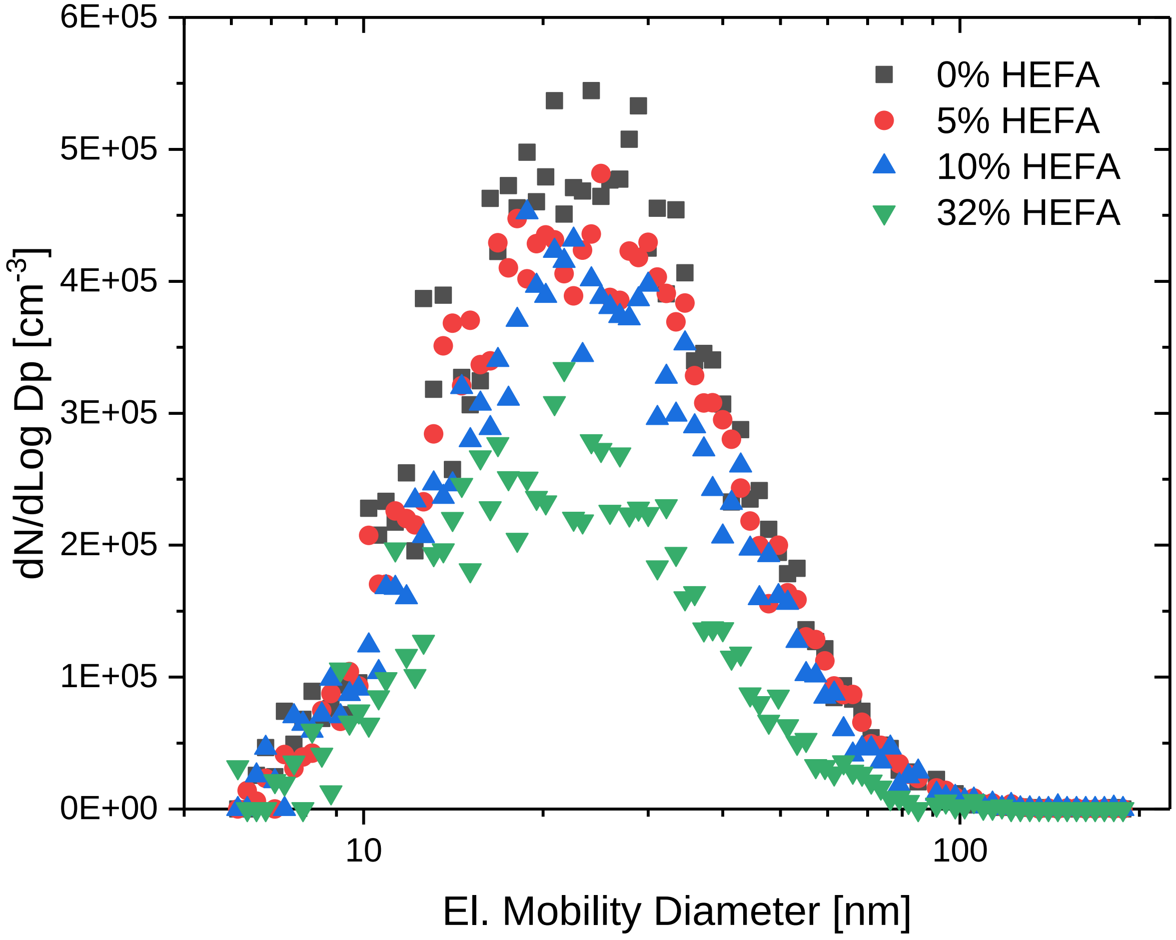
Thank you for your attention!

Appendix: Fuel compositional parameters associated with soot emissions

Property	Unit	ASTM Method	Jet A-1	ICAO Annex 16	Typical Value (ZRH)	Alternative Fuel Blends
Total Aromatics	% v/v	D 1319	< 25	15 - 23	17.9 +/-0.34	8 - 25
Smoke point	mm	D 1322	> 18	20 - 28	21.6+/-1.3	>18
Naphthalenes	% v/v	D 1840	< 3	1 – 3.5	0.79+/-0.11	<3
Hydrogen	% m/m	D 5291	N.A.	13.4 – 14.3	14.1+/-0.25	N.A.

- Standard Jet A-1 shows little compositional variation
- ICAO specifications were made that visible smoke emissions are not affected by compositional variations
- For alternative fuels a minimum total aromatics content of 8% is prescribed

Appendix: Fuel effect on the PSD at 30% engine thrust



- Clear fuel effect on the particle concentration is observed
- Slight (2%) shift towards smaller diameters with increasing HEFA fraction