CTU

CZECH TECHNICAL UNIVERSITY IN PRAGUE

27th ETH Nanoparticles Conference
June 11, 2024, Zurich, CH

Mobile test rig for field measurement of small jet engine particle emissions

Michal Vojtíšek[1], Miloslav Emrich[2], Tomáš Sommer[2], Martin Valach[2], Petr Vodička[3], Martin Pechout[4]

1 Center for Vehicles for Sustainable Mobility, Faculty of Mech. Eng., Czech Technical University in Prague, CZ
2 Center of Aviation and Space Research, Faculty of Mech. Eng., Czech Technical University in Prague, CZ
3 Institute of Chemical Processes Fundamentals of the Czech Academy of Science, Prague, CZ
4 Department of Vehicles and Ground Transport, Czech University of Life Sciences, Prague, CZ

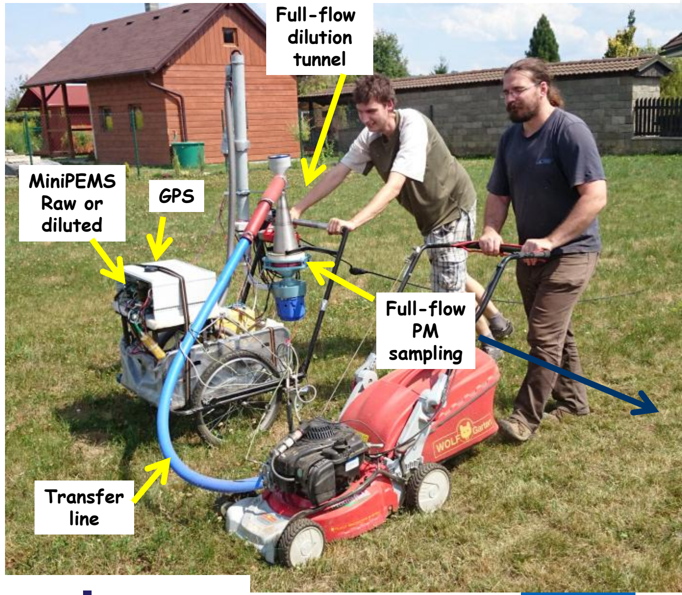
Contact: michal.vojtisek@fs.cvut.cz, michal.vojtisek@tul.cz +420 774 262 854

Czech (Prague) real driving emissions group

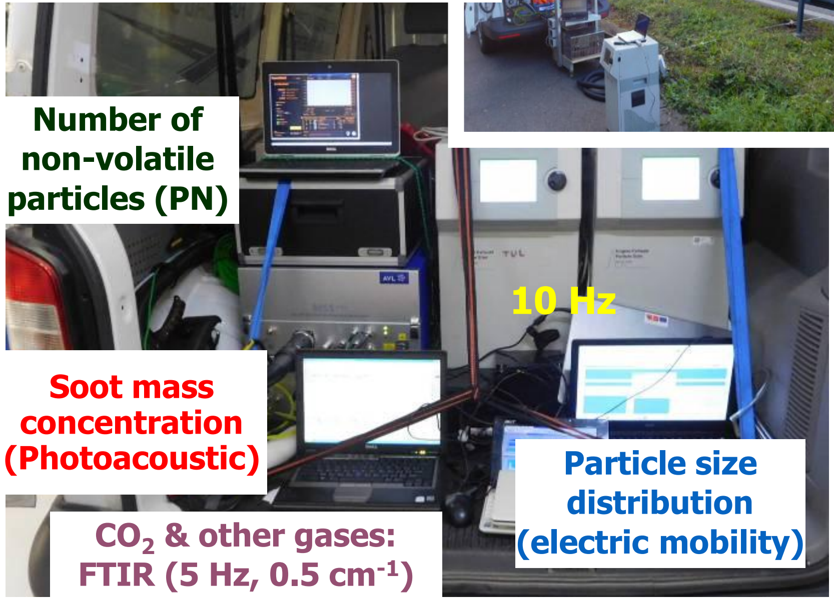
Czech Technical University (CTU) – Automotive Engineering
Czech University of Life Sciences (CULS) - Dept of Vehicles and Ground Transport
TU Liberec – Faculty of Mechatronics
Institute of Experimental Medicine of the Czech Academy of Sciences

Key competences: engines, fuels, combustion, emissions, air quality real driving emissions – testing and instrumentation

„Real gardening emissions" measurement with „off-board" system with full-flow dilution tunnel



Roadside PN & soot measurement to identify bad/no DPF

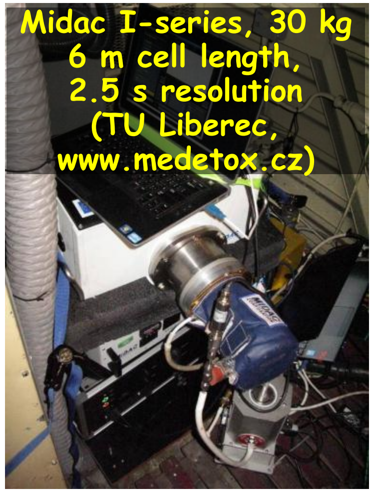


Poor man's PEMS & Mini-PEMS

NO, NO2, CO, CO2
qualitative: PM, PN, HC
calculated exhaust flow
9 kg, 3 hr run time

Portable on-board FTIR analyzers

(NO, NO2, NH3, …, CO2, CH4, N2O)



Nicolet Antaris IGS, 70 kg
5 m cell length, 1 s resolution

Goal: Practical, affordable measurement.

Variances among engines and magnitude of excess emissions are much higher than instrument uncertainty

We drive cars (mopeds, trucks, locomotives, …) to show that driving cars is bad for the environment.

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

On-board FTIR for small motorcycle emissions measurement

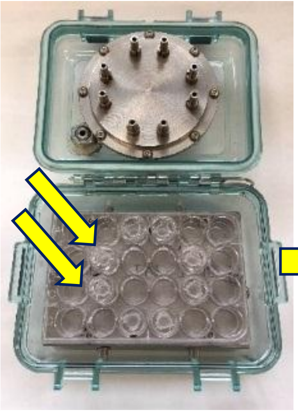
35 kg, 5 Hz @ 0.5 cm^{-1}
~250 W @ -10 C

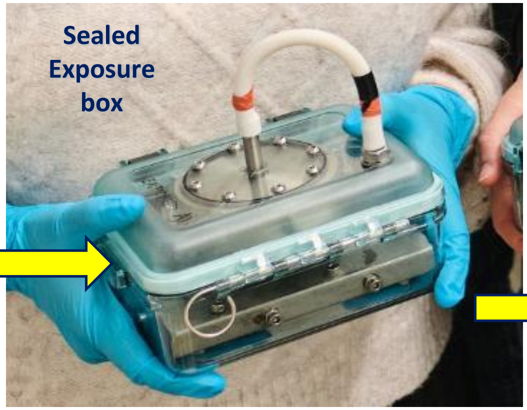
Full Euro 7 suite: CO, HCHO, NO, NO_2, NH_3, CO_2, CH_4, N_2O

To come … was not sure it will work -> did not submit an abstract

On-board ALI exposure chamber for toxicity studies

Cell cultures in 8 inserts in a standard 24-well plate





Poster 12D Thursday

Aviation emissions, climate and human health

Health relevant pollutants

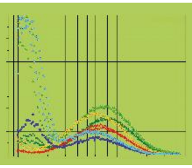
- Primary emissions of soot, semi-volatile and volatile organics, NO_x
- Secondary emissions - particulate matter and ozone

Health effects

- Similar concern as with diesel exhaust (Bendtsen et al. Environmental Health, 2021, 20:10)
- Most of the risk in NOx – i.e., 91% of premature deaths (Arter et al., Environment International, 2022, 158, 106958)
- Ultrafine PM elevated in/around airports (Riley et al., City and Environment Interactions, 2021, 11: 100066)
- Increase of malignant brain cancer with airport-related ultrafine particles (Wu et al., Cancer Res 2021;81:4360–9)
- Increased risk of cardiovascular disease in elderly due to noise (Correia et al., BMJ 2013;347:f5561)

Climatic effects

- 2-3% of worldwide CO_2 emissions
  (post- vs. pre-CoVID; IEA https://www.iea.org/energy-system/transport/aviation; Bergero et al., Nat Sustain 2023, 6, 404–414)
- Additional positive and negative radiative forcing effects, just as important a CO_2 (or even more)
- Effective radiative forcing from contrail cirrus same order of magnitude as CO_2, from NO_x tens of % of CO_2
  (Lee et al., Atmos Environ 2021, 244, 177834)
- Cirrus radiative forcing affected by soot emissions
  (Burkhard et al., npj Clim Atmos Sci 2018, 1, 37; Voigt et al., Commun Earth Environ 2021, 2, 114; Kelesidis et al., Environ. Sci. Technol. 2023, 57, 28, 10276–10283)



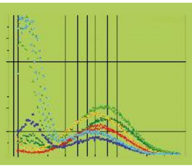
Aviation emissions mitigation

The big picture

- Reduction in travel demand
- Switch to high-speed rail on shorter routes
- Synthetic/renewable fuels (SAF – Sustainable Aviation Fuel), hydrogen, battery electric
- Ground emissions management
- Improved efficiency and reduced emissions
- CO_2 per passenger mile decreased 8 times since 1960 and approx. halved in last 30 years
  (Lee et al., Atmos Environ 2021, 244, 177834)
- Average CO_2 per revenue km / passenger km (2018-2019) estimated a) 104 g, b) 90 g, c) 88 g
  a) U.S. Federal Aviation Administration, https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf
  b) Turgut et al., International Journal of Sustainable Transportation, 2018, 13(3), 224–234.
  c) ICCT, 2020, https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf

Emissions regulations

- International Civil Aviation Organization (ICAO) Annex 16, Protection of the Environment, Volume II, 5th edition (2023), turbojet & turbofan engines, two categories: a) > 26.7 kN maximum thrust, b) smaller
- HC, CO, NOx – all engines from 1986 with > 26.7 kN
- "Smoke" by filter reflectance (smoke number) – all engines from 1983 until Jan 1, 2023, now only < 26.7 kN
- Non-volatile particulate matter by mass ("soot", by photoacoustic sensor) and number d50 = 10 nm
  – all production engines > 26.7 kN from Jan 1, 2020, new engines > 26.7 kN from Jan 1, 2023



This work: Emissions from a small aircraft engine

Motivation

Czech Republic – long history (100+ years) of aircraft and aircraft engine manufacturing

Dozens of small sport aircraft, ultralight, glider manufacturers, approx. 10-20 K employees, 85% is exported

Emissions from small aircraft sparsely covered in literature

Standard laboratory type-approval procedures costly and to some extent not possible to execute on small engines

Goal

To develop a relatively simple and inexpensive test procedure, in the field or at manufacturer site, applicable to small engines, covering regulations for all engine sizes for research, engineering and type-approval purposes

Test setup: 400 N sailplane auxiliary engine

Auxiliary 400 N thrust jet engine tested as installed on HPH sailplane at HPH, Kutná Hora, CZ

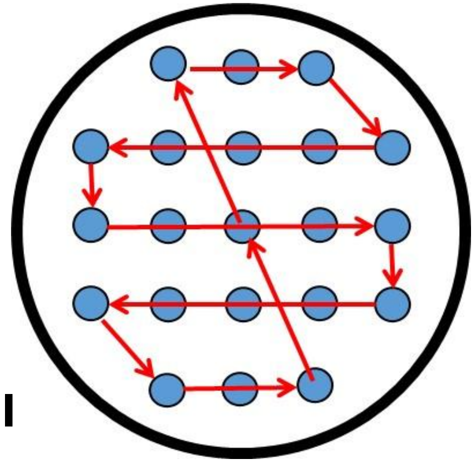
Wings removed, aircraft placed in noise-abatement location, secured.

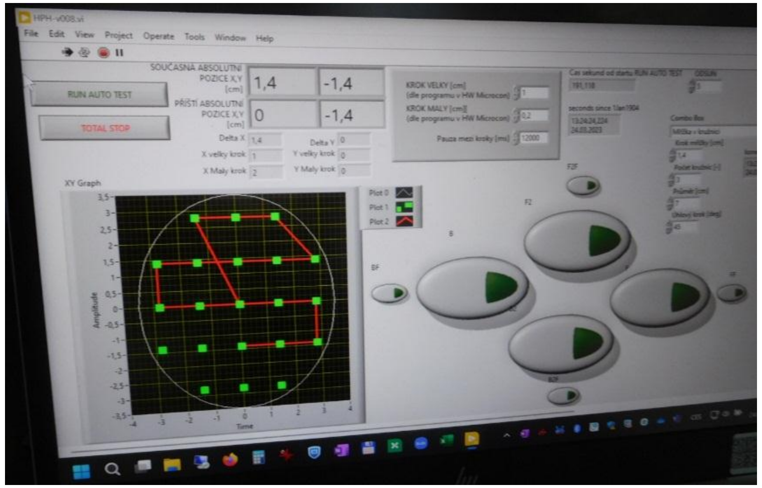
Fuel:
Commercial Jet A-1
with 5% oil
(Aeroshell Turbine Engine Oil 500)

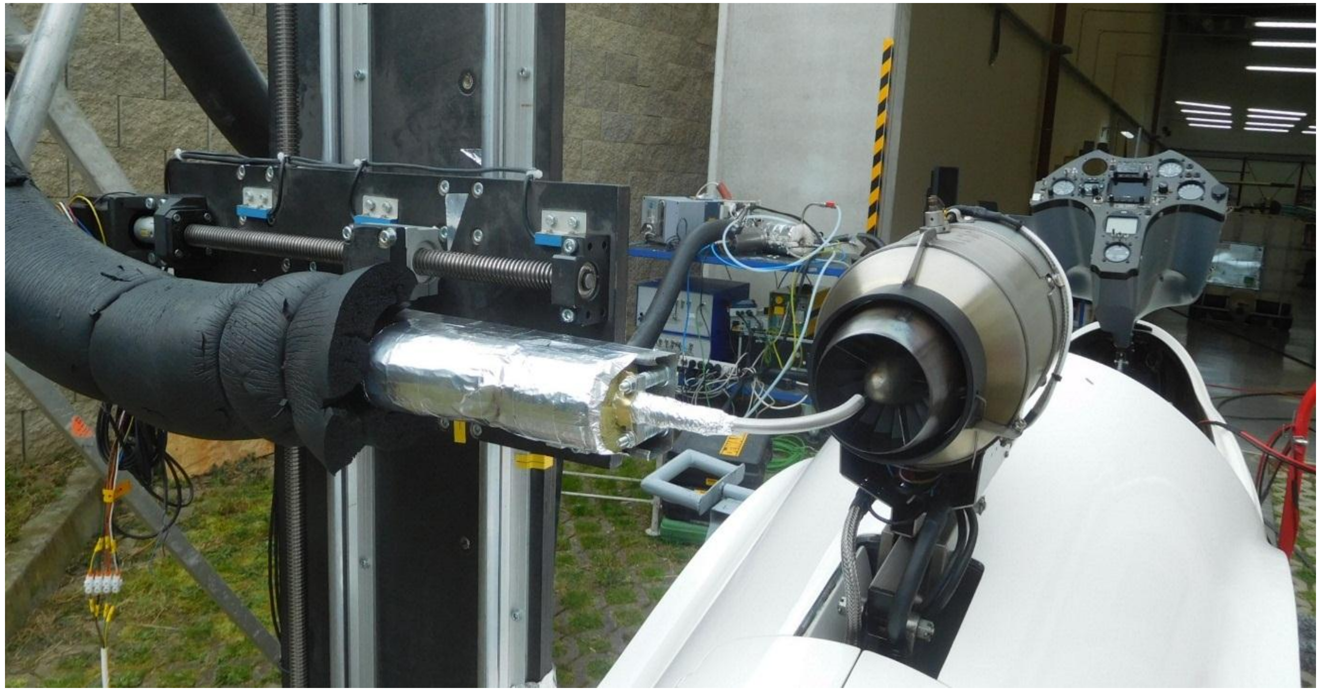
Instruments intended to be installed in a van, but for simplicity, installed on a cart in a warehouse

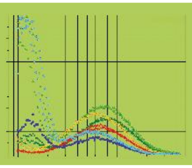
Exhaust sampling

Single probe, 6 mm diameter,
traversing the 7 cm diameter exhaust exit plane
to cover 21 points,
10 seconds per point, 2 s transfer,
Beginning and ending at center point, 300 s total

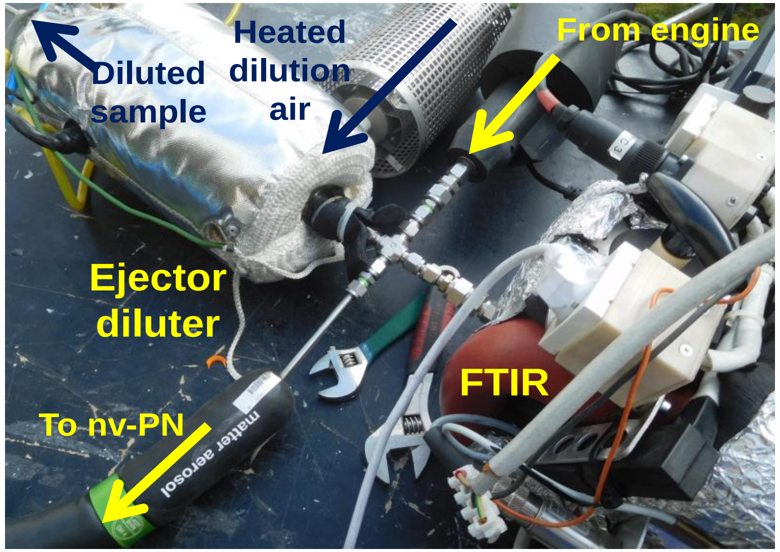


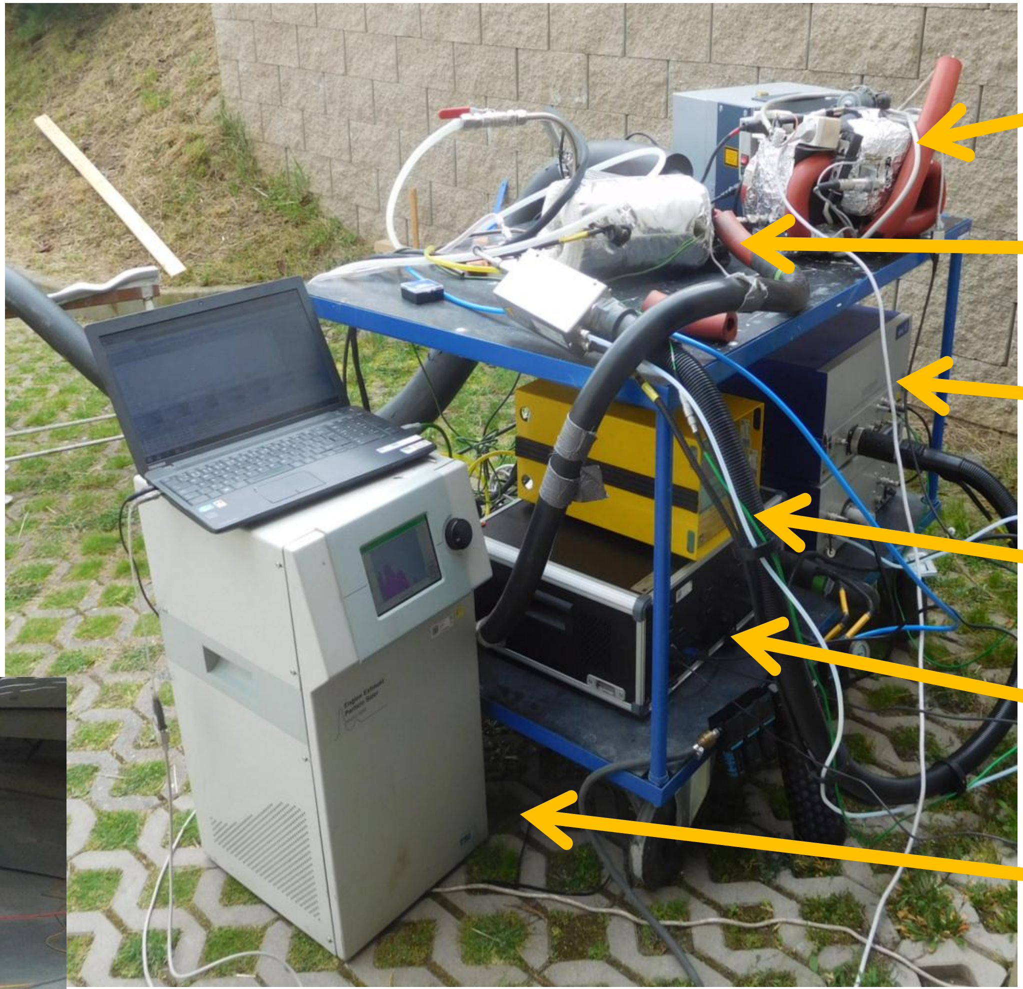






Instrumentation





FTIR undiluted all gases

Heated ejector diluter 8:1

AVL Microsoot Photoacoustic nvPM

NDIR diluted CO2

NanoMet3 nvPN 10-700 nm

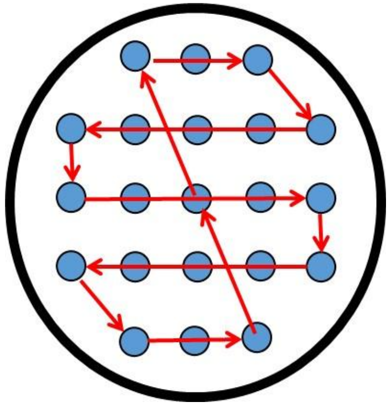
EEPS Particle size Distribution 5-560 nm

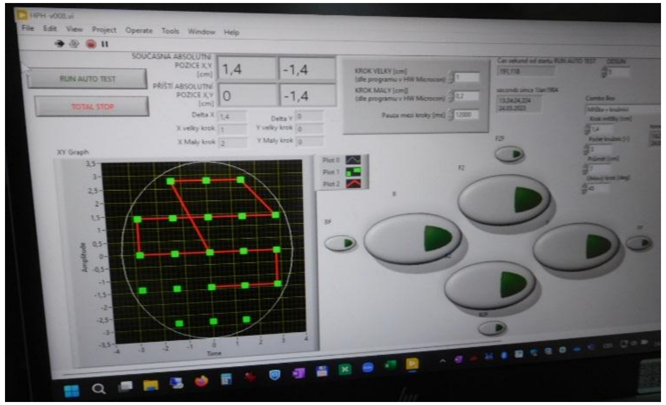
Sampling on 47 mm filters
Quartz fiber, Whatman QMA, EC/OC
PTFE coated glass fiber, smoke number

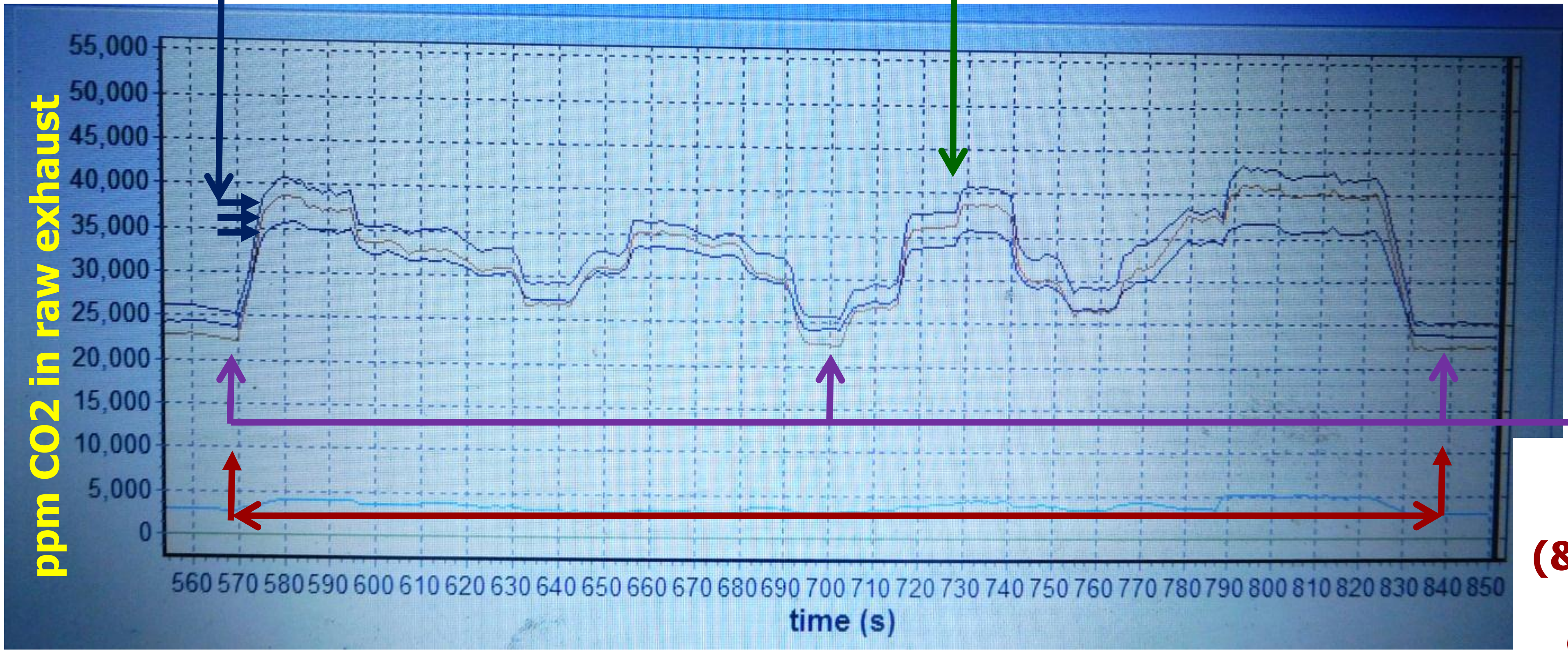
Exhaust exit plane traversing

Each engine operating point repeated three times to assess repeatability

10 s per point to characterize emissions at each probe position







Begin & end at the center to check for stability

Filter sampled continuously (& data averaged) as average of 21 positions

Filter flow rate set to achieve target total flow per operating point (16.2 kg/m2 for smoke number)

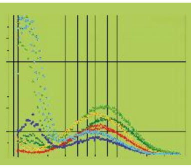
Test sequence

Warmup and instrument range check run:
7%, 30%, 85%, 100% of rated thrust
Run 1: 7%, 30%, 85%, 100% of rated thrust
Run 2: 7%, 85%*, 30%, 100%, 85%
Run 3: 7%*, 7%, 85%, 30%*, 30%, 100%*, 100%
*** test not successful**

Visual check of data continuously
and at the end of each point

Data processing for each point:
Online data averaged
(raw gases, diluted CO_2, nvPN, nvPM, particle size distributions)
Dilution ratio assessed (raw, diluted CO_2) and accounted for
Quartz filter analyzed using EC/OC (EUSAAR2 protocol)
- individual calibration for the very engine tested, not “general” “aviation” calibration
EC results used to calibrate photoacoustic soot sensor
Fiber filter reflectance measured (not done)

Cooling of the sample probe at high load



Test sequence

Warmup and instrument range check run:
7%, 30%, 85%, 100% of rated thrust

Run 1: 7%, 30%, 85%, 100% of rated thrust

Run 2: 7%, 85%*, 30%, 100%, 85%

Run 3: 7%*, 7%, 85%, 30%*, 30%, 100%*, 100%

*** test not successful**

Visual check of data continuously and at the end of each point

Data processing for each point:

- Online data averaged (raw gases, diluted CO_2, nvPN, nvPM, particle size distributions)
- Dilution ratio assessed (raw, diluted CO_2) and accounted for
- Quartz filter analyzed using EC/OC (NIOSH protocol)
  - individual calibration for the very engine tested, not "general" "aviation" calibration
- EC results used to calibrate photoacoustic soot sensor
- Fiber filter reflectance measured (not done)

Cooling of the sample probe at high load

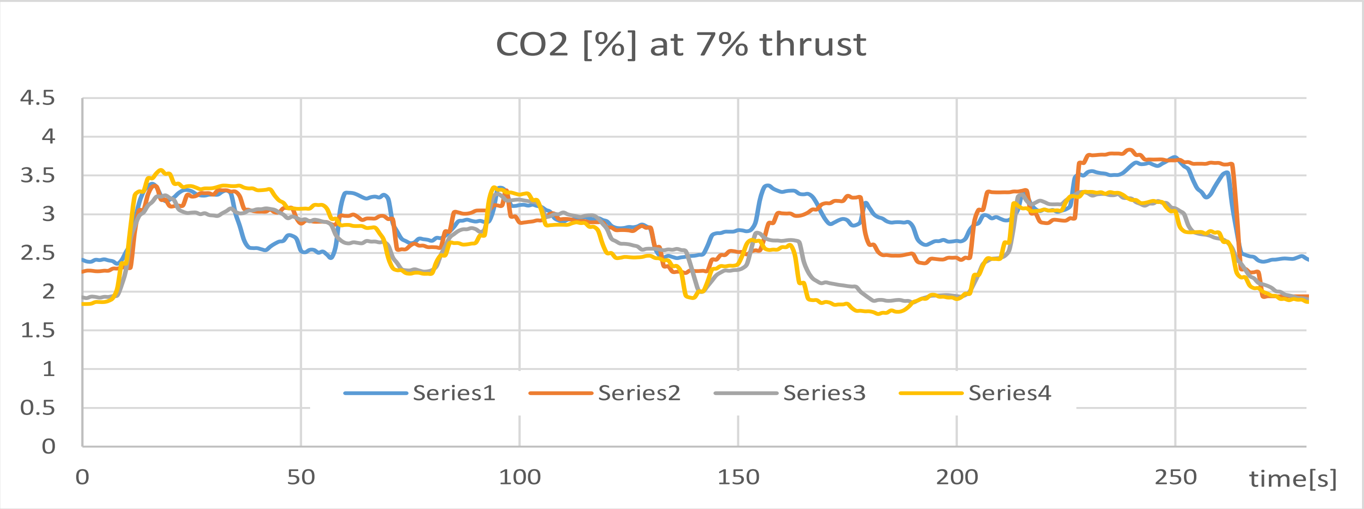
- **5 x 300 s = 1500 s + engine stabilization = approx. 30 min engine run time**
- **12:28:35 – 15:41:10 = 3¼ hours testing time once set up, warmed up, etc.**
- **2 working days on site total including setup troubleshooting (could be 1 day)**

Results - gases

CO_2 varies with position, is generally repeatable, but not always in each position.
Overall per operating point 7-14% range.
High repeatability not expected at 7 cm exit plume diameter, 14 mm between sampling points.

Dilution ratio varied with operating point (and across sampling points), average 8:1 at 7% and 5.4:1 at 100% thrust, due to variable exhaust velocity & sample line pressure

NO generally very low
NO_2, NH_3 not detected
CO and formaldehyde (HCHO) quantified
Large amount of unresolved hydrocarbons (most likely engine lubricating oil)
FTIR spectra can be analyzed ex-post for additional compounds (not done here)



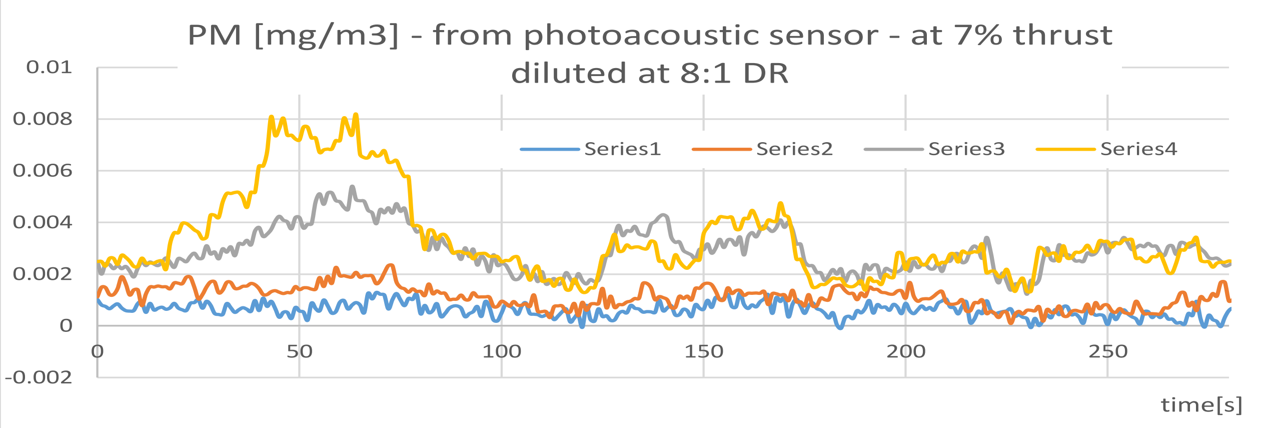
start time	end time	load [% thrust]	FTIR undiluted exhaust CO [ppm]	HCHO [ppm]	NO [ppm]	CO2 [%]	diluted CO2 NDIR [%]	avg. dilution ratio
12:23:35	12:28:35	7%	2603	50.9	2.1	2.92	0.37	8.91
12:29:10	12:34:10	30%	3201	68.9	2.6	2.84	0.42	7.54
12:43:10	12:48:10	85%	1933	43.7	5.3	3.59	0.68	5.58
13:24:20	13:29:20	100%	2204	56.1	6.5	4.30	0.85	5.29
13:52:25	13:57:25	7%	2680	57.1	2.7	2.83	0.38	8.25
14:06:40	14:11:40	30%	3616	85.0	3.5	2.81	0.45	6.85
14:13:20	14:18:20	100%	1929	56.1	5.7	3.95	0.78	5.36
14:20:00	14:25:00	85%	1742	41.3	3.7	3.50	0.62	6.08
15:01:25	15:06:25	7%	4942	151.2	7.6	2.58	0.41	6.89
15:08:00	15:13:00	85%	1799	39.4	4.6	3.37	0.62	5.84
15:23:20	15:28:20	30%	3607	84.9	4.4	2.74	0.49	6.11
15:36:10	15:41:10	100%	1812	58.8	6.8	3.92	0.76	5.43

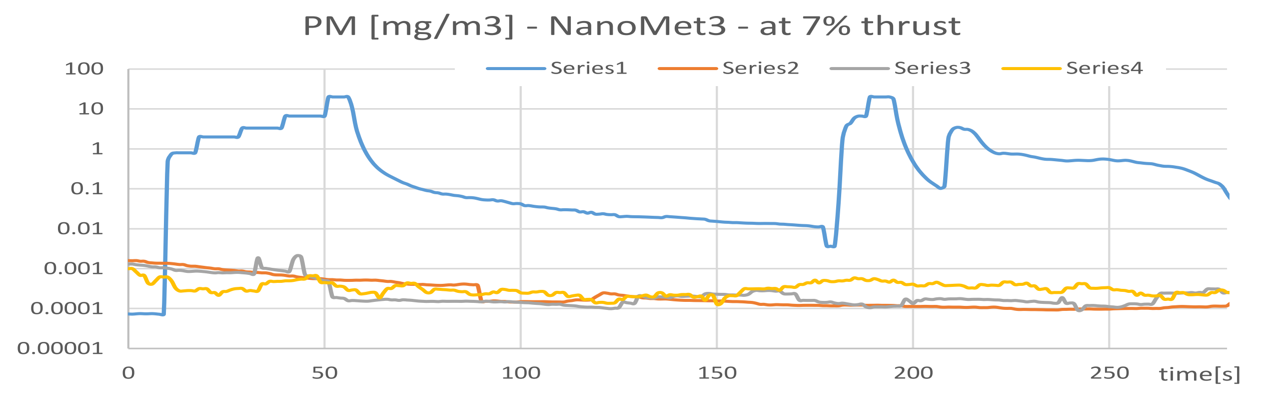
Results – particles (online)

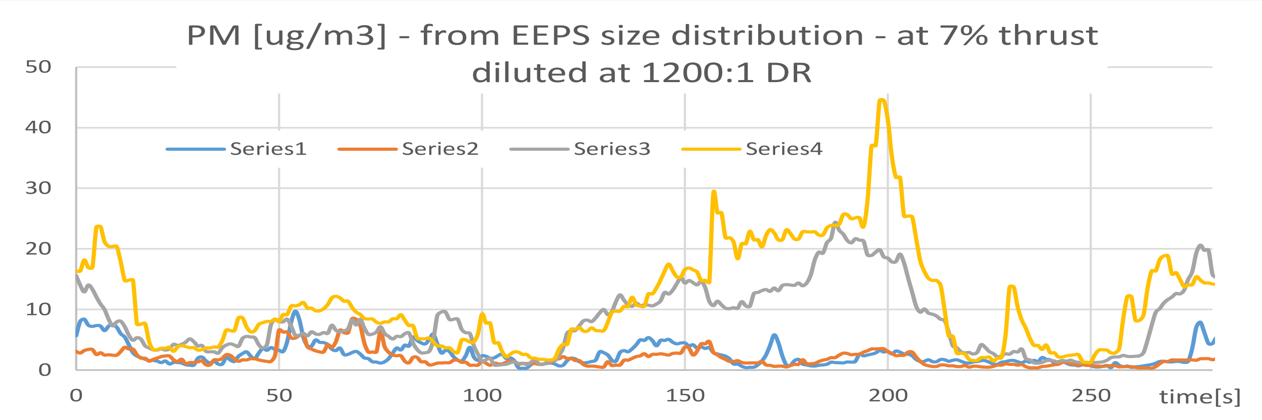
- nvPM by photoacoustic sensor very low, <10 ug/m^3
- PM from EEPS size distributions tens of ug/m^3 (ejector diluter at 350 C -> close to nvPM?)
- but nvPM by NanoMet3 (used primarily for nvPN) very high on the first run …

Probable cause: artefacts in volatile particle remover due to engine lubricating oil droplets

- Filters were yellow-ish
- Problem gone with switching NanoMet3 from raw to diluted sample







Results – particles (online - averages)

- nvPM by photoacoustic sensor very low, <1 ug/m^3
- PM from EEPS size distributions units of ug/m^3 (ejector diluter at 350 C -> close to nvPM?)
- nvPM NanoMet3 (used primarily for nvPN) very high on the first run, but low when dilution increased
- Particle number from EEPS and NanoMet3 not always consistent – semi-volatile particle artefacts

			EEPS diluted		NanoMet undiluted			MSS dil
start	end	load	PN	PM	PN	diameter	PM	diluted
time	time	[% thrust]	[#/cm3]	[ug/m3]	[#/cm3]	[nm]	[mg/m3]	[mg/m3]
12:23:35	12:28:35	7%	1.26E+05	2.50	8.55E+07	26.1	1.74	0.0006
12:29:10	12:34:10	30%	9.83E+04	1.35	4.73E+08	16.8	7.64	0.0005
12:43:10	12:48:10	85%	6.59E+04	1.47	2.96E+08	20.8	7.82	0.0004
13:24:20	13:29:20	100%	2.51E+05	2.65	6.00E+07	15.4	1.05	0.0010
13:52:25	13:57:25	7%	1.12E+05	1.98	1.25E+04	24.5	0.00	0.0011
14:06:40	14:11:40	30%	9.36E+04	1.33	8.38E+03	24.3	0.00	0.0008
14:13:20	14:18:20	100%	1.00E+05	2.35	2.79E+03	30.0	0.00	0.0004
14:20:00	14:25:00	85%	3.82E+04	1.04	1.31E+05	23.5	0.00	0.0001
15:01:25	15:06:25	7%	2.65E+05	12.16	2.60E+06	72.5	0.06	0.0033
15:08:00	15:13:00	85%	2.54E+05	7.03	1.34E+06	24.8	0.02	0.0006
15:23:20	15:28:20	30%	1.15E+05	4.08	2.81E+06	55.0	0.03	0.0003
15:36:10	15:41:10	100%	7.31E+04	4.33	1.82E+03	48.0	0.00	-0.0001

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Results – particles (offline)

- 47 mm diameter Whatman QMA quartz fiber filters
  gravimetric and EC/OC (thermogravimetry, Sunset, NIOSH protocol) analyses
- Filter loading (gravimetry) corresponds to 4-12% of the consumption of the engine lubricating oil
- About half of this was detected as "OC" (semivolatiles)
- EC (elemental carbon, nvPM) was less than 1% of OC
  - and even some of this was possibly an artefact (< 1 ug/m^3 per photoacoustic sensor)

Filter no.	mode	duration minutes	gravimetry ug	OC ug per filter	EC ug per fitler	gravimetry mg/m3	OC mg/m3	EC mg/m3
1	engine off	10	67	109	0.004	3.6	6.0	**0.000**
2	7%	4.5	310	192	1.342	37.6	23.3	**0.163**
3	30%	5	373	243	1.782	34.7	22.6	**0.166**
4	85% - incomplete, lost FTIR comm.	4.75	506	355	1.512	41.3	29.0	**0.123**
5	85%	5	1031	538	1.955	79.9	41.7	**0.152**
6	100%	5	980	294	2.256	71.5	21.4	**0.165**
7	7% & 30% & 85% & 100%	25.333	3218	1507	3.954	56.0	26.2	**0.069**
8	85%	5	828	348	1.721	64.3	27.0	**0.133**
9	2 x 7%	11.75	2045	988	4.257	94.9	45.8	**0.198**
10	85%	5	1261	521	1.881	97.8	40.4	**0.146**
11	2 x 30%	14.6	2409	1135	3.060	76.7	36.2	**0.097**
12	2 x 100%	11.6	2696	1393	3.042	126.8	65.5	**0.143**
First set 7-30-85-100% (filters 2, 3, 5, 6)			*2694*	*1267*	*7*	*59.1*	*27.8*	***0.161***
Second set 7-30-85-100% (filter 7)			*3218*	*1507*	*4*	*56.0*	*26.2*	***0.069***
Third+fourth set 7-30-85-100% (filters 8, 9, 10, 11, 12)			*9240*	*4384*	*14*	*92.4*	*43.8*	***0.140***

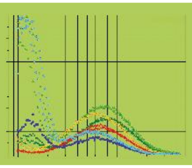
Results – particles (offline)

- 47 mm diameter Whatman QMA quartz fiber filters
  gravimetric and EC/OC (thermogravimetry, Sunset, NIOSH protocol) analyses
- Filter loading (gravimetry) corresponds to 4-12% of the consumption of the engine lubricating oil
- About half of this was detected as "OC" (semivolatiles)
- EC (elemental carbon, nvPM) was less than 1% of OC – this confirms all previously mentioned artefacts
  - and even some of this was possibly an artefact (< 1 ug/m^3 per photoacoustic sensor)

Smoke number by reflectance: not performed

- Artefact (filters yellowish)
- EC mass corresponds to smoke number SN < 2 (limit is SN=50)
- True nvPM mass probably much lower

Filter no.	mode	duration minutes	gravimetry ug	OC ug per filter	EC ug per fitler	gravimetry mg/m3	OC mg/m3	EC mg/m3
1	engine off	10	67	109	0.004	3.6	6.0	**0.000**
2	7%	4.5	310	192	1.342	37.6	23.3	**0.163**
3	30%	5	373	243	1.782	34.7	22.6	**0.166**
4	85% - incomplete, lost FTIR comm.	4.75	506	355	1.512	41.3	29.0	**0.123**
5	85%	5	1031	538	1.955	79.9	41.7	**0.152**
6	100%	5	980	294	2.256	71.5	21.4	**0.165**
7	7% & 30% & 85% & 100%	25.333	3218	1507	3.954	56.0	26.2	**0.069**
8	85%	5	828	348	1.721	64.3	27.0	**0.133**
9	2 x 7%	11.75	2045	988	4.257	94.9	45.8	**0.198**
10	85%	5	1261	521	1.881	97.8	40.4	**0.146**
11	2 x 30%	14.6	2409	1135	3.060	76.7	36.2	**0.097**
12	2 x 100%	11.6	2696	1393	3.042	126.8	65.5	**0.143**
First set 7-30-85-100% (filters 2, 3, 5, 6)			*2694*	*1267*	*7*	*59.1*	*27.8*	***0.161***
Second set 7-30-85-100% (filter 7)			*3218*	*1507*	*4*	*56.0*	*26.2*	***0.069***
Third+fourth set 7-30-85-100% (filters 8, 9, 10, 11, 12)			*9240*	*4384*	*14*	*92.4*	*43.8*	***0.140***



Conclusions

Small jet engine testing done in the field, while on the aircraft (held stationary)

- **Testing at 7%, 30%, 85%, 100% load, all three times, various order**
- **At each point, traversing 21 positions across the exhaust plume exit plane**
- **Both online measurements (at each position and average per point) and filter sampling**
- **Gravimetry and EC/OC analysis performed on filters for added check and calibration**

All testing done during a single visit

- **5 x 300 s = 1500 s + engine stabilization = approx. 30 min engine run time**
- **12:28:35 – 15:41:10 = 3¼ hours testing time once set up, warmed up, etc.**
- **2 working days on site total including setup troubleshooting (could be 1 day)**

Results were accepted by EASA for engine approval (type approval? Individual?)

- **Visual check of data continuously and at the end of each point – helpful**
- **Gravimetric analysis – helpful (not required by the legislation)**
- **Bringing additional instruments – helpful**
- **FTIR used as a single instrument for all gases (no gas bottles, only liquid nitrogen)**
- **nvPN and nvPM measurements and smoke number (by filter reflectance)
may suffer from artefacts in low-soot, high-oil combustion in very small engines**