aircraft Trajectory analysis for Reduced EnVirOnmentaL impact -TREVOL-

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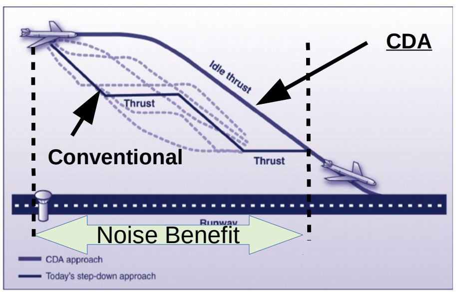
MOTIVATION

Originally: *Minimization of operational costs = minimizing fuel consumption.

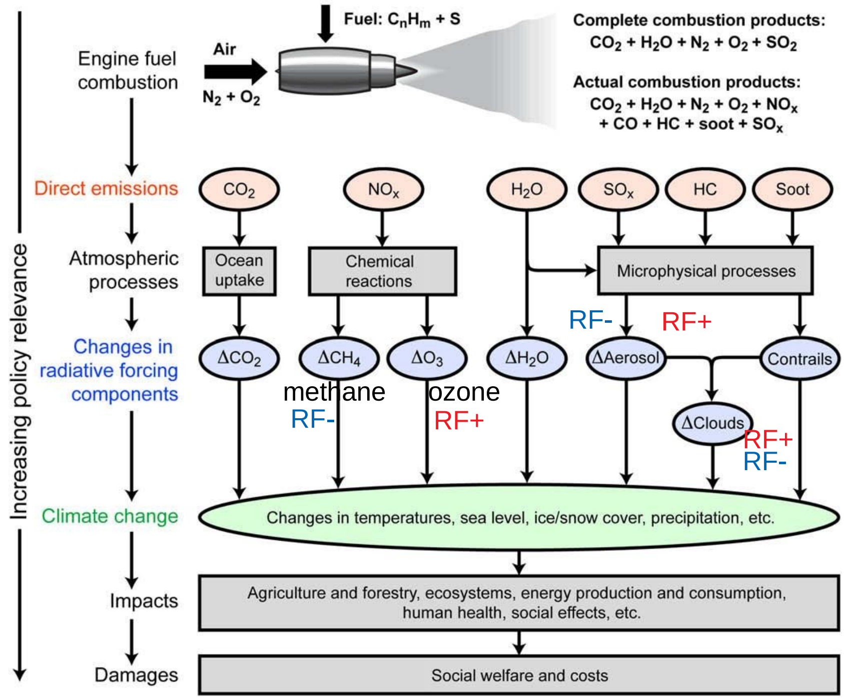
Later: CO2 emissions directly linked to burned fuel → practice* environmentally friendly.



Sources: Naverus and AVTECH.

<u>Next problem</u>:
Non-CO2 emissions??

Aircraft emissions and climate change

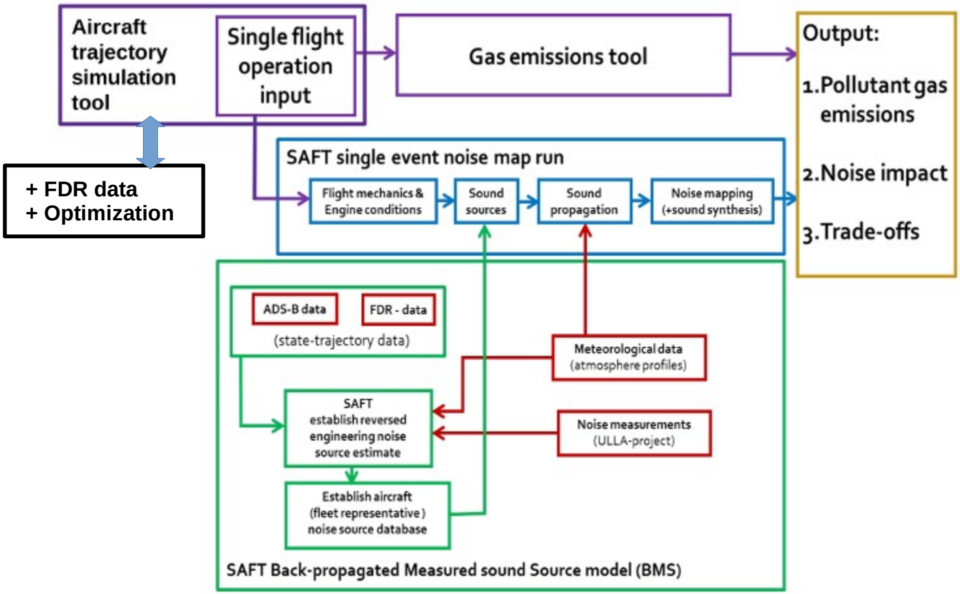


D. J. Wuebbles et al., Issues and Uncertainties Affecting Metrics For Aviation Impacts on Climate, 2010

CONCEPT, STRATEGY & GOAL

- The project consists in reducing the environmental impact in terms of gas emissions and noise through flight procedures analysis.

- <u>Goal</u>: to define the most suitable trade-off strategies for a combined reduction in **noise**, **CO_2, and non-CO_2 emissions**.



MODELING: Emissions

- Emissions (fossil fuel, Jet A-1) related to aircraft operation (including emissions from taxi, startup, and APU (auxiliary power unit)):
  - Carbon Monoxide (CO),
  - Total Hydrocarbons (HC),
  - Non-Methane Hydrocarbons (NMHC),
  - Volatile Organic Compounds (VOC),
  - Total Organic Gases (TOG),
  - Oxides of Nitrogen (NOx),
  - Sulfur Oxides (SOx),
  - Particulate Matter (PM) / soot,
  - Carbon Dioxide (CO2),
  - Water vapour (H2O), and
  - Speciated Organic Gases (SOG), including hazardous air pollutants (HAPs).

MODELING: Emissions

- Based on emission index (EI): emission in grams per kilogram of fuel consumed.

Fuel composition-based factors

Proportional to the fuel burned

$$\mathrm{EICO_2} = 3155\ \mathrm{g/(kg\ fuel)}$$
$$\mathrm{EIH_2O} = 1237\ \mathrm{g/(kg\ fuel)}$$
$$\mathrm{EISOx} = 0.8\ \mathrm{g/(kg\ fuel)}$$

Boeing Fuel Flow Method 2 (BFFM2)

Atmosphere dependent

$$\mathrm{EICO_{alt}} = \mathrm{EICO_{sl}}(f_{sl})\frac{\theta^{3.3}}{\delta^{1.02}}$$
$$\mathrm{EIHC_{alt}} = \mathrm{EIHC_{sl}}(f_{sl})\frac{\theta^{3.3}}{\delta^{1.02}}$$
$$\mathrm{EINOx_{alt}} = \mathrm{EINOx_{sl}}(f_{sl})\sqrt{\frac{\delta^{1.02}}{\theta^{3.3}}}e^{H}$$

Atmosphere

$$\theta = T/T0$$
$$\delta = P/P0$$

ICAO emissions databank (AEED)

BADA database or FDR

$$f_{sl} = f_{alt}\frac{\theta^{3.8}}{\delta}e^{0.2M^2}$$

MODELING: Emissions

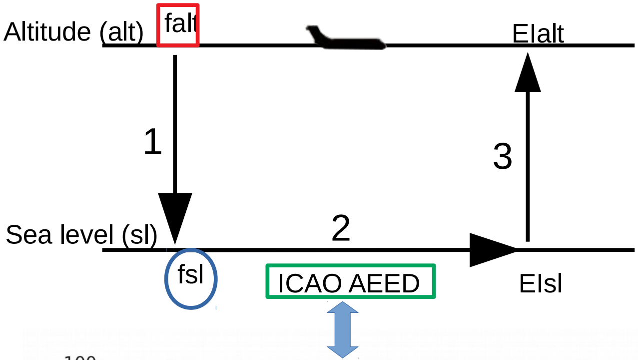
- Boeing Fuel Flow Method 2 (BFFM2)

$$EICO_{alt} = EICO_{sl}(f_{sl})\frac{\theta^{3.3}}{\delta^{1.02}}$$

$$EIHC_{alt} = EIHC_{sl}(f_{sl})\frac{\theta^{3.3}}{\delta^{1.02}}$$

$$EINOx_{alt} = EINOx_{sl}(f_{sl})\sqrt{\frac{\delta^{1.02}}{\theta^{3.3}}}e^{H}$$

$$f_{sl} = f_{alt}\frac{\theta^{3.8}}{\delta}e^{0.2M^2}$$

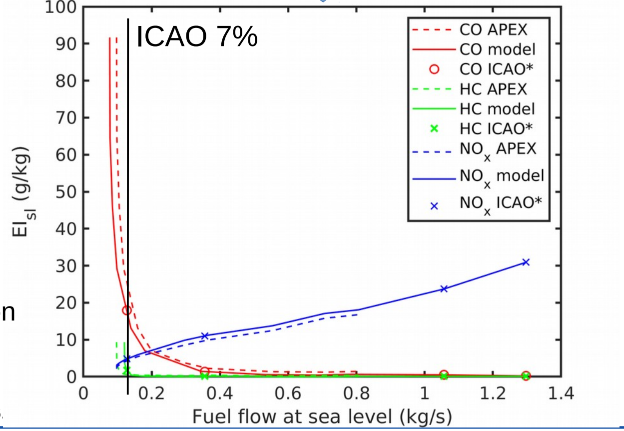


Total emissions in kilograms

$$HC = \frac{1}{1000}\int_{t=0}^{t_f}(EIHC_{alt}\cdot f_{alt})dt$$

ICAO emission indices only for power settings >=7%!

Engine: CFM56-7B27 (ICAO adjusted for installation effects *)
APEX data for a similar engine (CFM56-2-C1).



*C. C. Wey et al., Aircraft Particle Emissions eXperiment (APEX). NASA/TM—2006-214382, 2006.

MODELING: Noise

- Ground noise footprints estimated with software SAFT developed within CSA.
- SAFT covers several methods for aircraft noise mapping → here ECAC Doc 29 implementation used.
- ECAC Doc 29: Standard Method of Computing Noise Contours around Civil Airports
  - *Widely used and linked to an international aircraft noise and performance (ANP) database.*
  - *Flight configurations are not directly included, but indirectly partly accounted for through thrust dependency.*

MODELING: Trajectory

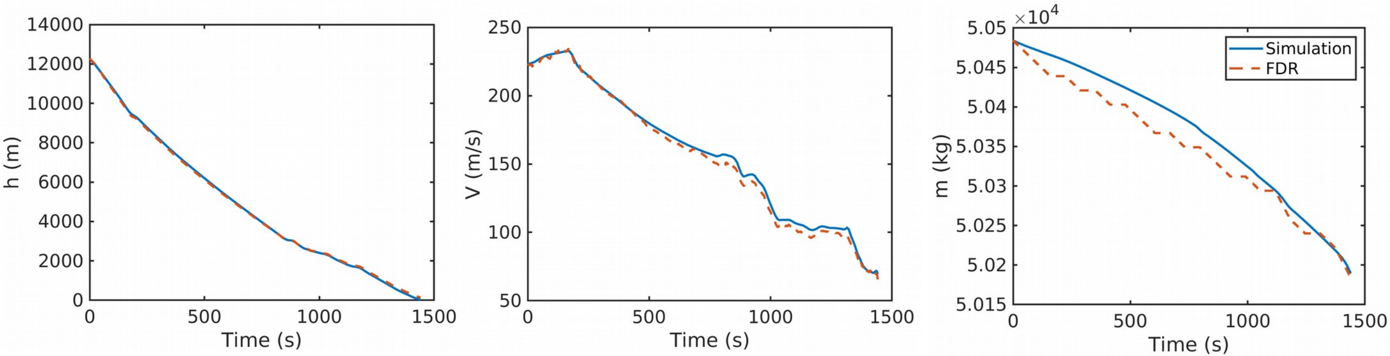
- Aircraft type: Boeing 737-800
- Point mass approximation → Time integration of the equations of motion (non linear ODE)
- Assumption $\dot{\gamma}$ small
- Control variables, c : flight path angle, N1 (fan rotor speed), flaps, landing gear.

$$\dot{V} = (T cos(\alpha + \epsilon) - D)/m - g sin\gamma$$

$$\dot{h} = V sin\gamma$$

$$\dot{m} = -b$$

$$\dot{y} = f(y, c), \qquad y = \begin{pmatrix} V \\ h \\ m \end{pmatrix}, \qquad c = \begin{pmatrix} \gamma \\ \delta_T \\ \nu_f \\ \mu_g \end{pmatrix}$$

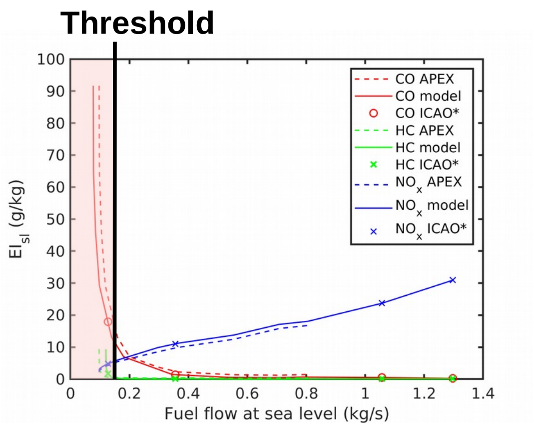


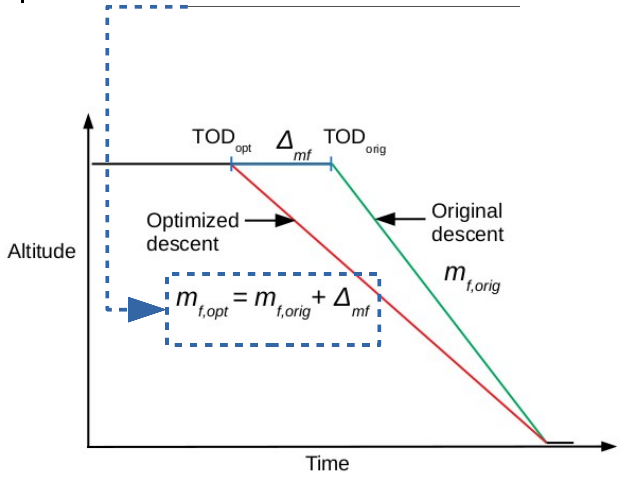
MODELING: Optimization

- Input Trajectory: CO_2 and noise optimized.
- **Goal**: Optimize also for CO and HC by avoiding critical exponential growth.

➡ Strategy: Set a **threshold** at sea level at 0.17 kg/s and increase to that value, converted fuel flows at sea level below 0.17 kg/s.

➡ Requirements: Similar vertical profile and total fuel consumed.



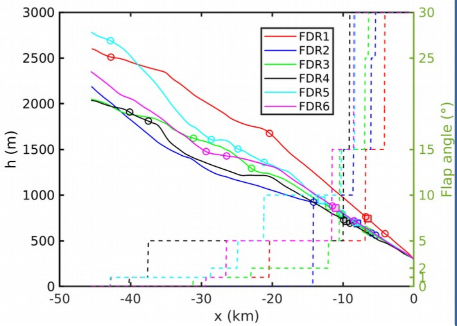


RESULTS: Emissions

- Flight trajectories of reference (FDR1-6)

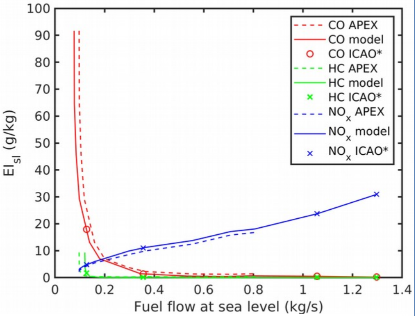
Flight data recorder (FDR) data provided by Scandinavian Airlines System (SAS)

Trajectories

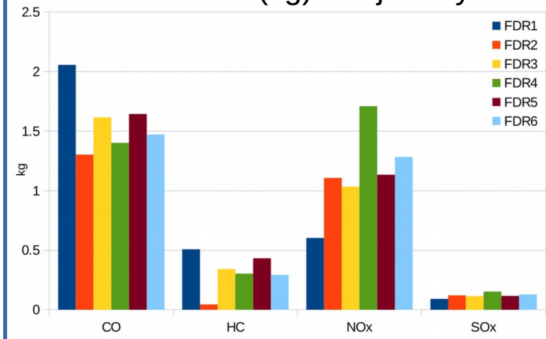


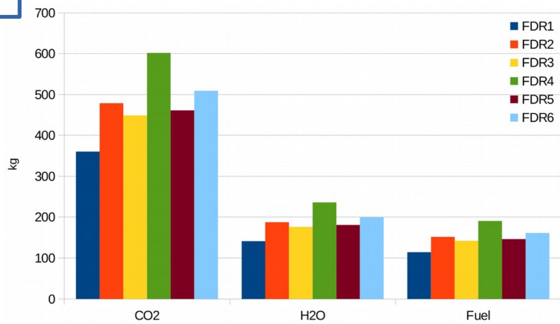
Recall

Emissions indices



Emissions (kg) / trajectory



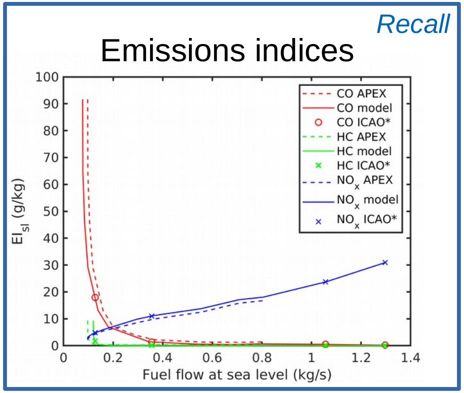


Ordering: 1 (the lowest) to 6 (the highest)

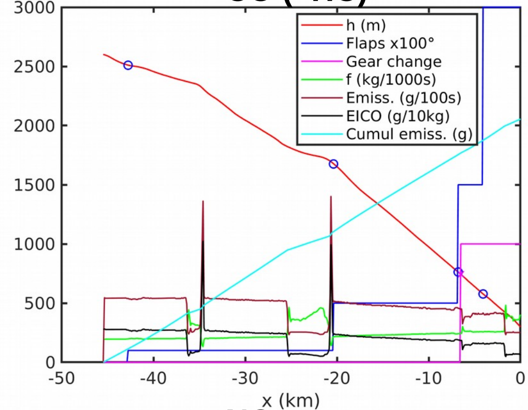
FDR#	CO	HC	NO_x	CO_2	H_2O	SO_x	Fuel
1	6	6	1	1	1	1	1
2	1	1	3	4	4	4	4
3	4	4	2	2	2	2	2
4	2	3	6	6	6	6	6
5	5	5	4	3	3	3	3
6	3	2	5	5	5	5	5

RESULTS: Emissions

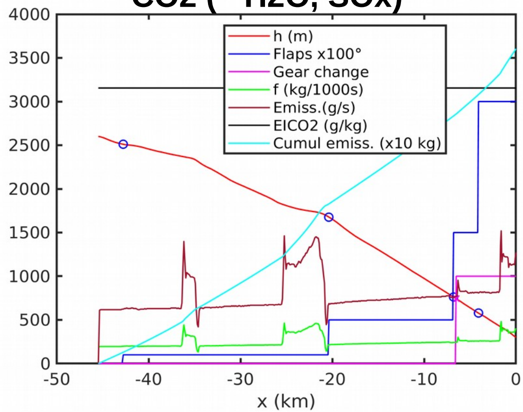
- Emissions analysis for a single trajectory (FDR1)



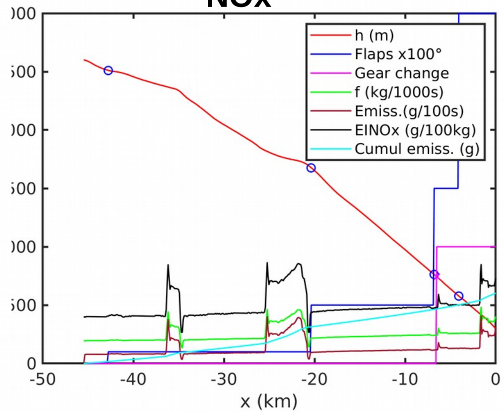
CO (~HC)



CO2 (~ H2O, SOx)



NOx

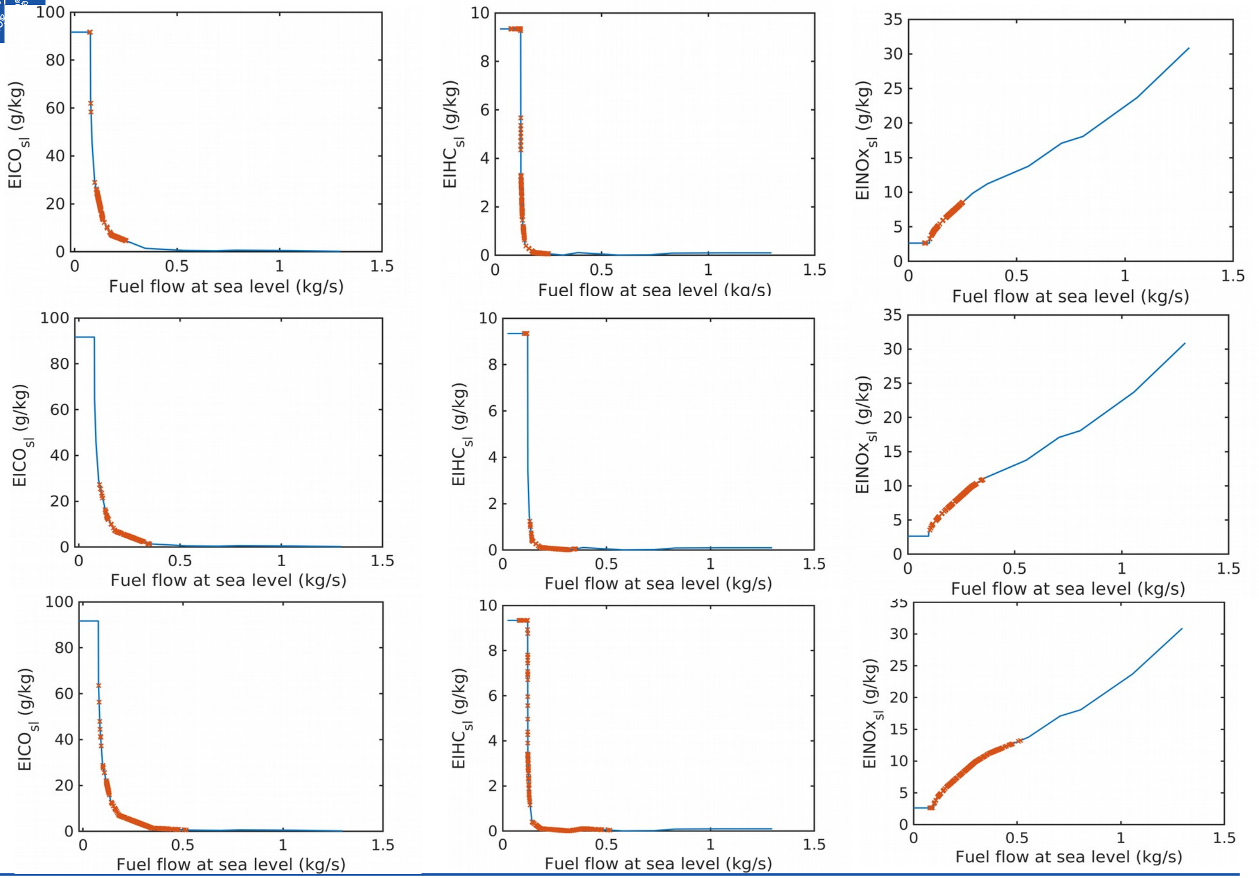


RESULTS: Emissions

FDR1

FDR2

FDR4



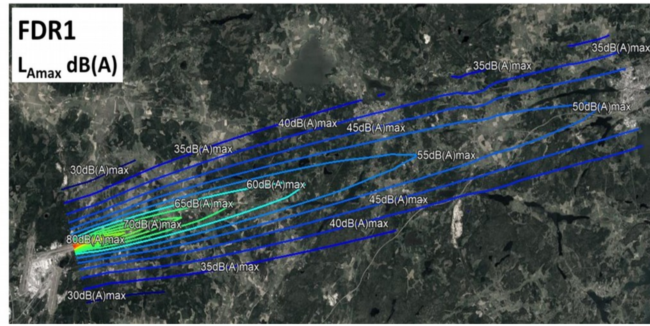
RESULTS: Noise

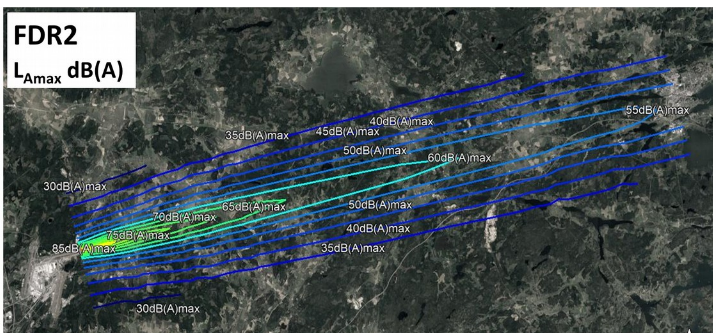
- Noise prediction

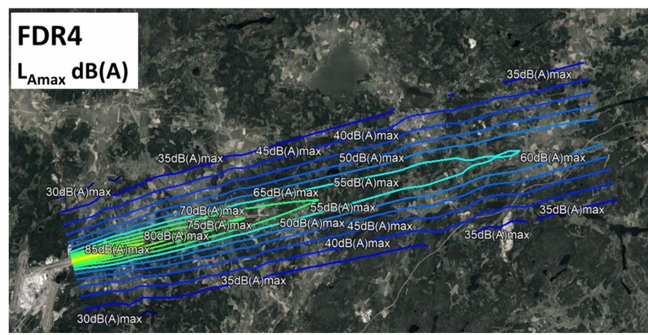
Flights assumed to be straight, and positioned in the approach phase at Arlanda Airport runway 26, in Stockholm (Sweden).

FDR1: highest altitude and lowest thrust → lowest noise levels:
~ 17 km extension of the 60 dBA contour out from the runway, vs ~ 26 km for FDR2 and 30 km for FDR4.

<u>In agreement with</u> fuel flow levels and trajectory ordering with respect to the fuel burned and proportional emissions such as CO_2.



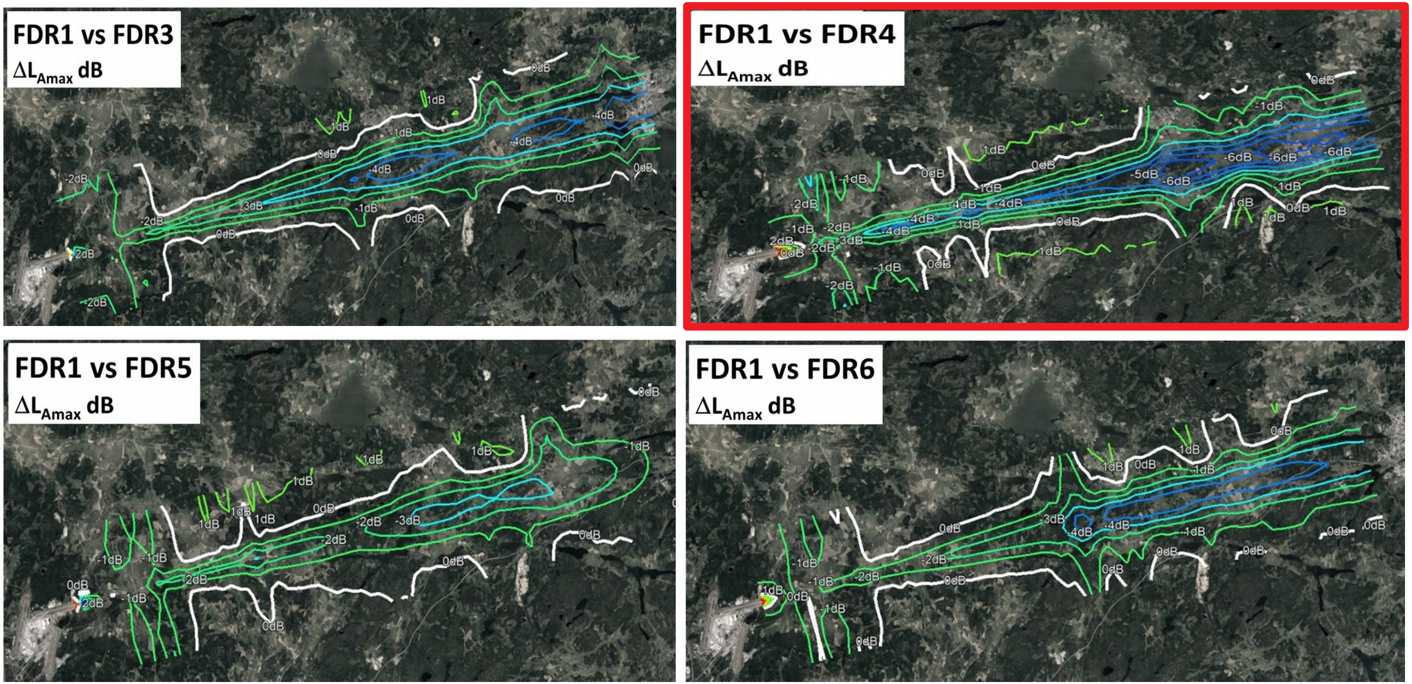




Noise contour maps of the maximum A-weighted sound level (LAmax)

RESULTS: Noise

$$\Delta L_{\mathrm{Amax,FDR1},i} = L_{\mathrm{Amax,FDR1}} - L_{\mathrm{Amax,FDR}i}, \text{ for } i \in \{2 : 6\}$$



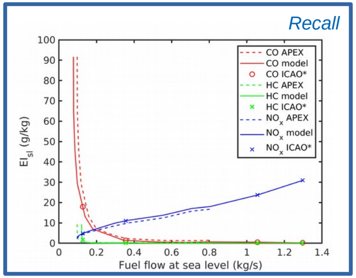
Noise prediction difference of FDR1 with respect to FDRi using SAFT ECAC Doc 29 implementation.

RESULTS: Noise & Emissions

- Observations made for noise prediction are aligned with the fuel burned proportional emissions (CO2, H2O, SOx) and NOx:
  - Flight trajectories with highest fuel burned proportional emissions (and NOx) result in highest noise impact.
  - FDR1: most favorable in terms of noise and fuel burned proportional emissions (and NOx), contrary to FDR4.

➡ A decrease in thrust will lead to lower noise and burned fuel, thereby reducing emissions proportional to the burned fuel (and NOx).

➡ **Challenge**: to define a trade-off strategy considering as well the fuel-flow inversely dependent emissions, HC and CO.



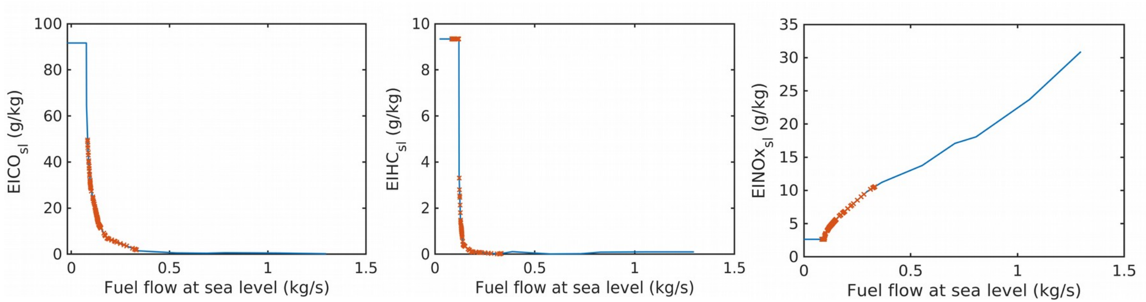
RESULTS: Optimization

- CO and HC minimization (without considering fuel burned)

FDR1	CO (kg)	HC (kg)	NO_x (kg)	CO_2 (kg)	H_2O (kg)	SO_x (kg)	Fuel (kg)
Original	7.24	1.57	1.42	928.61	364.09	0.24	294.33
CO/HC-optimized	4.20	0.10	2.72	1324.03	519.12	0.34	419.66
Reduction factor	1.72	15.7	-	-	-	-	-
Increase factor	-	-	1.92	1.43	1.43	1.42	1.43

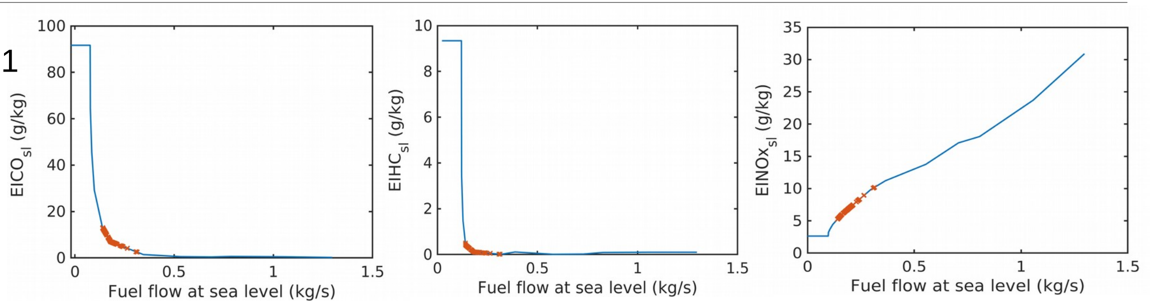
Original FDR1 descent[1] (simulated)

[1]Descent trajectory from 12km down (see validation)



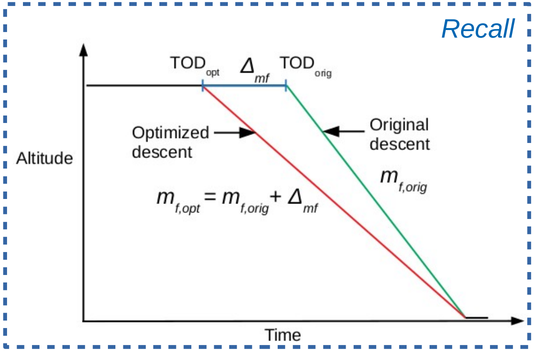
Optimized FDR1 descent[1] (simulated):

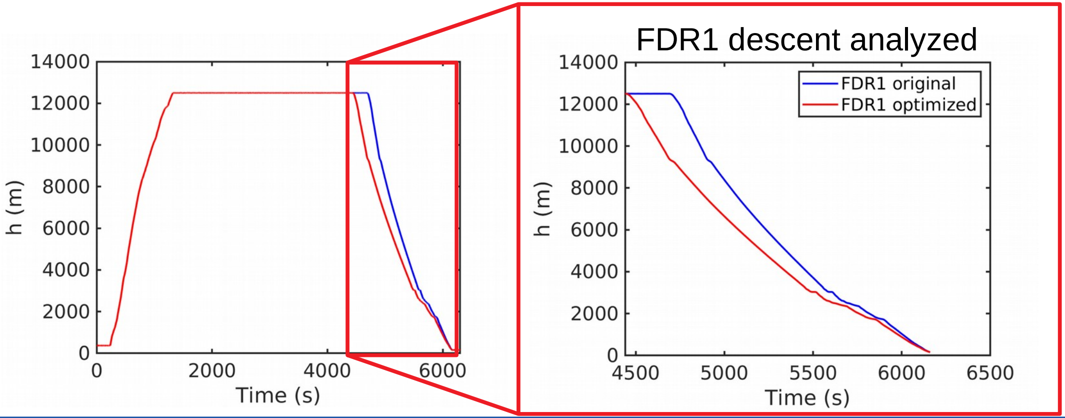
N1+12% for fsl<0.17 kg/s



RESULTS: Optimization

- Environmentally optimal trajectory
  - *Optimization including CO and HC emissions → CO and HC minimization considering fuel burned.*
  - *Same strategy: Minimum threshold at sea level of 0.17 kg/s.*
  - **New**: *Definition of an appropriate earlier TODopt , to compensate for the additional fuel flow required for optimization of the descent phase.*



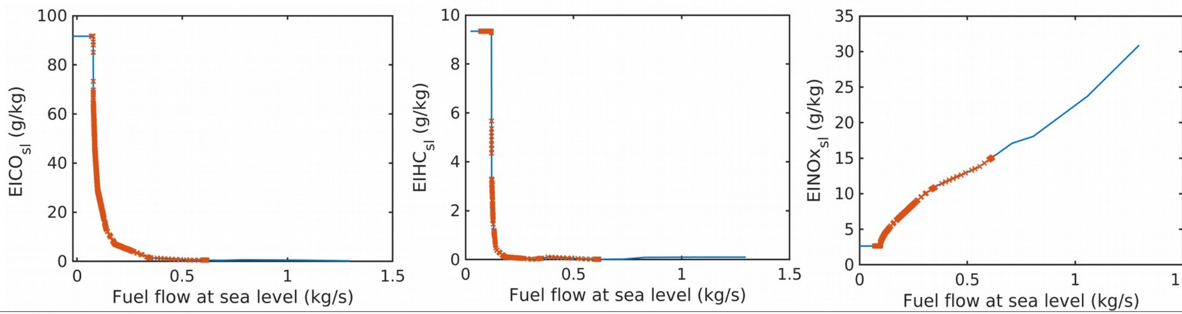


RESULTS: Optimization

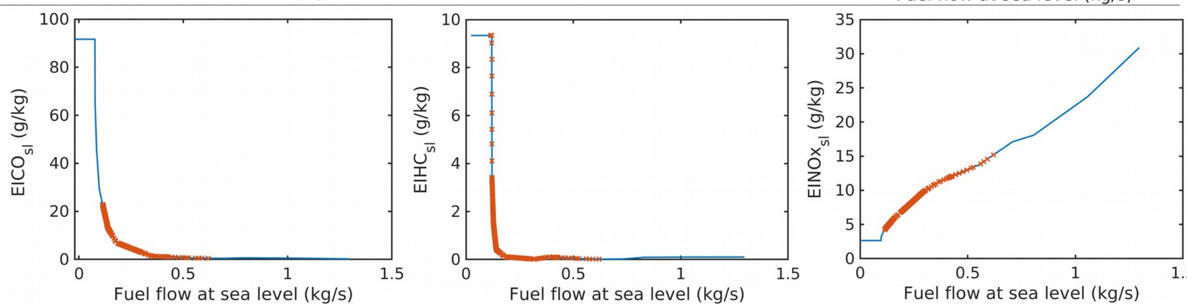
CO and HC minimization (considering fuel burned)

FDR1	CO (kg)	HC (kg)	NO_x (kg)	CO_2 (kg)	H_2O (kg)	SO_x (kg)	Fuel (kg)
Original	9.41	2.19	2.80	1306.56	512.27	0.33	414.12
Optimized	6.61	0.52	2.40	1307.33	512.57	0.33	414.37
Reduction factor	1.42	4.21	1.17	~1	~1	1	~1

Original
FDR1



Optimized
FDR1 descent



RESULTS: Optimization

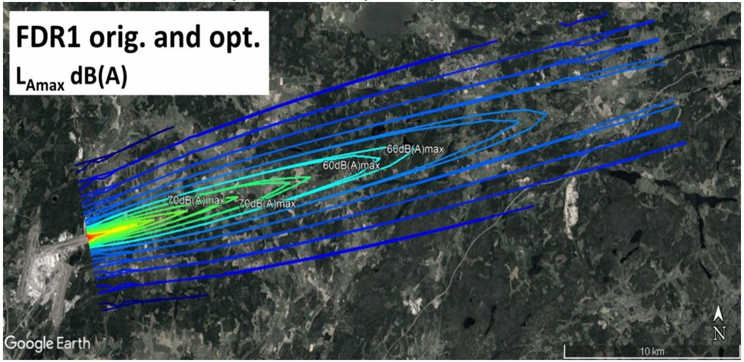
- New noise impact

FDR1 opt. increases thrust and decreases altitude:

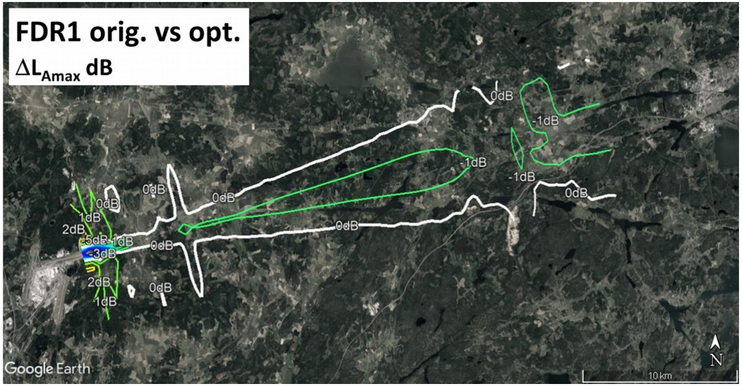
➡ *Slight increase in noise level of 1 dB close to the ground track.*

➡ *~2 km between the two 60 dB(A) contours, and smaller shift for the other contour levels along the ground track.*

Noise contour patterns superimposed absolute levels



Level differences



CONCLUSIONS

- Flight Trajectories are generally favorable to either [fuel burned proportional emissions(&NOx) and noise] **OR** [HC and CO].
- **Opposite trend in emissions** indices with respect to fuel flow reflects the **complexity** for a common environmental strategy.
- **Exponential growth of HC and CO emissions indices at low idle thrust and no ICAO emissions data for power settings <7% → poor modeling**
- **Need for**
  - *More measurements for engine certification for thrust levels below 7% .*
  - *A minimum threshold for idle thrust during the descent phase.*
- **An optimal environmental solution**: Higher idle thrust above a minimum threshold (7%?) and earlier TOD to compensate the increased fuel burn.
- **Results:** HC and CO emissions reduction by a factor of:
  - *4.2 and 1.4, respectively, for similar noise level and fuel burned.*
  - *~16 and ~2, respectively, for 1.4 times more fuel burned.*

CONCLUSIONS

- **Application**
  - *<u>Pre-tactical phase</u>: operational flight plans optimization.*
  - *<u>Tactical phase</u>: minimum N1 during descent.*

- <u>Future work</u>
  - *Meteorology data integration for noise and emissions computation.*
  - *Lateral profile included in the optimization.*
  - *More aircraft types and engines → definition of threshold?*

<u>Educational platform for a new master's level course :</u>
Aircraft Performance and Air Traffic Management (SD2830) with strong focus on sustainability.
https://www.kth.se/student/kurser/kurs/SD2830?l=en

<u>Publications</u>*:*

Otero, E.; Tengzelius, U.; Moberg, B. **Flight Procedure Analysis for a Combined Environmental Impact Reduction: An Optimal Trade-Off Strategy**. *Aerospace 2022, 9, 683, https://doi.org/10.3390/aerospace9110683*

Otero, E., Ringertz, U. Case Study on the Environmental Impact and Efficiency of Travel. CEAS Aeronaut J 13, 163–180 (2021). https://doi.org/10.1007/s13272-021-00547-1

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TRAFIKVERKET

THANK YOU
FOR YOUR ATTENTION