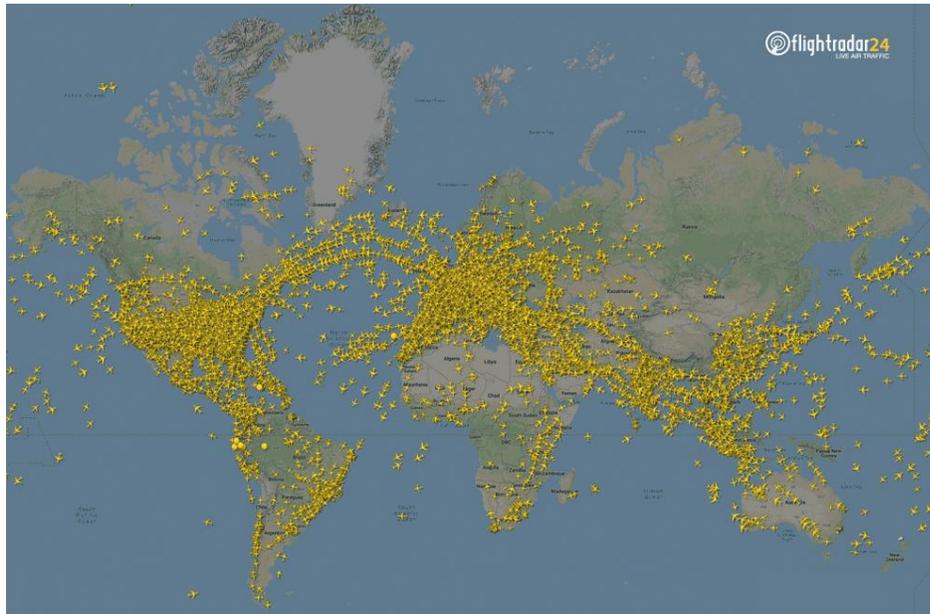




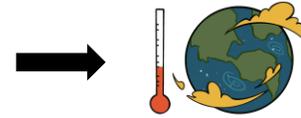
H2-fuelled aircraft configuration and trajectory optimisation to reduce aeronautic environmental impact

Author: Raúl Quibén Figueroa
Supervisor: Manuel Soler, Rauno Cavallaro

MOTIVATION



Flightradar24.com



- Temperature change
- Precipitation change
- Rise of sea level

Aviation is a **contributor to climate change** (~3.5%, Lee et al. 2021)

Increasing number of flights

Urgent need to reduce emissions to meet climate mitigation goals (Paris COP21 agreement)

Quick and disruptive measures

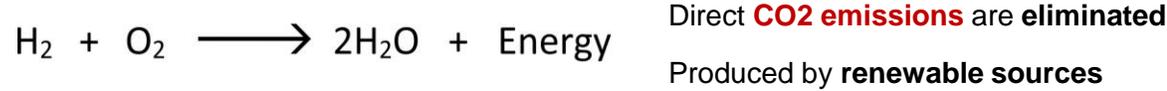
MITIGATION MEASURES



MOTIVATION



Hydrogen has emerged as a promising **long-term sustainable solution** for aviation

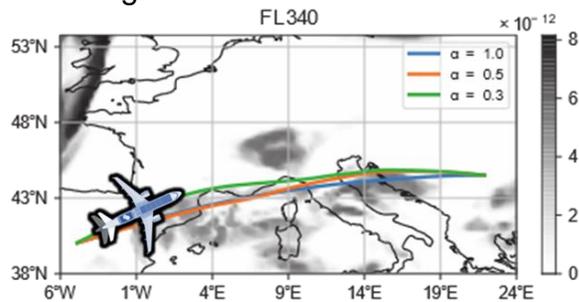


Non-CO₂ emissions: **water vapour + contrails**, can play an equally or even larger noxious role to the environment.

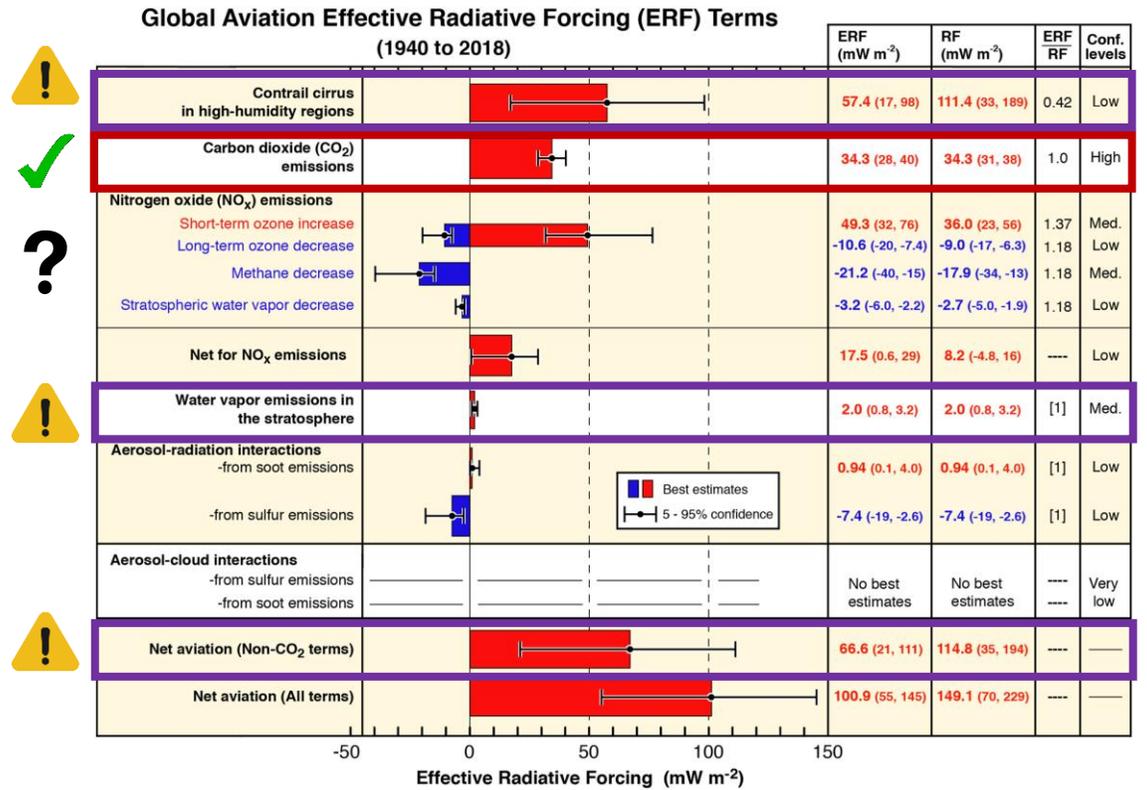


<https://rmi.org/contrail-mitigation-a-collaborative-approach-in-the-face-of-uncertainty/>

The mitigation of this non-CO₂ effect has been proved promising through operational strategies



Strong dependency on time and location

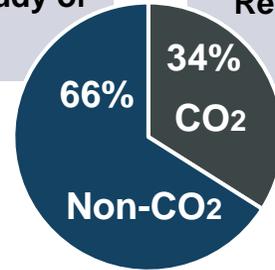


Lee et al. *The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018*, Atmospheric Environment, 2021

SCIENTIFIC OBJECTIVES

Operational and trajectory study of H2 aircraft

Research and design of H2 aircraft conceptual models



Round off the problem

Tackling both CO2 and non-CO2 emissions impact

Maximizing the benefits

General objective: analyze the introduction of H2 aircraft quantifying its climate impact reduction potential and derived costs



Objective 1: H2 aircraft design analysis and optimization models.

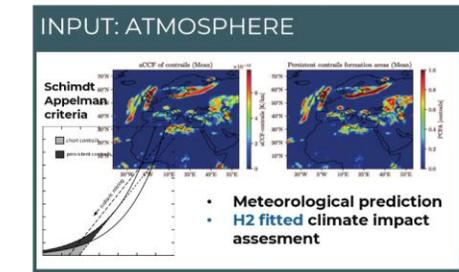
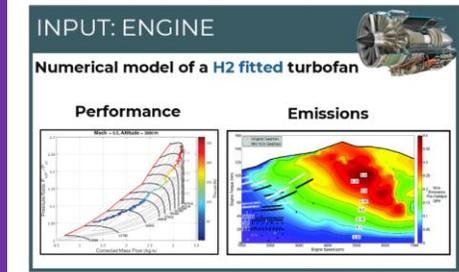
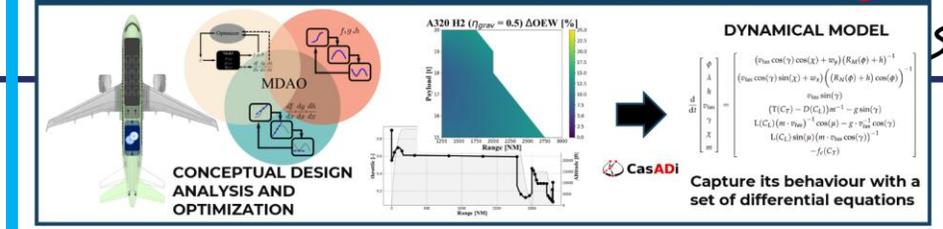


Objective 2: H2 aircraft emissions and climate impact modelling.

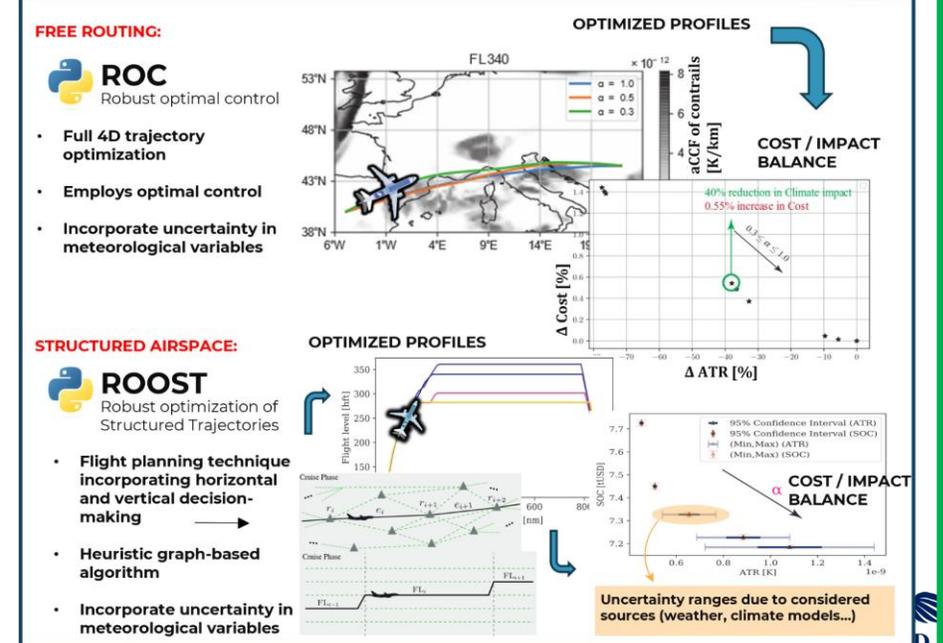


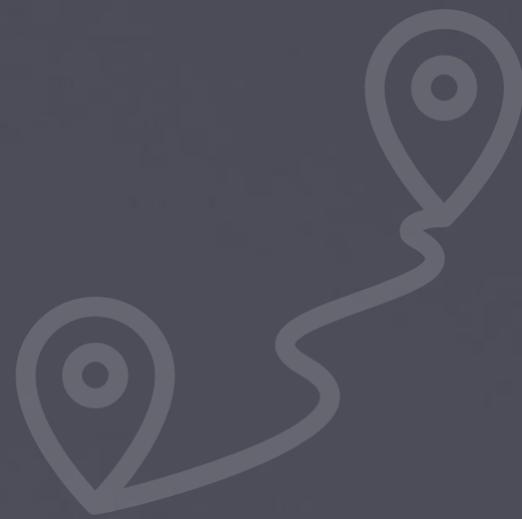
Objective 3: Climate optimal trajectory planning algorithms for H2 aircraft.

H2 AIRCRAFT DESIGN AND OPTIMIZATION



CLIMATE OPTIMAL TRAJECTORY PLANNING





AIRCRAFT DESIGN



Digital tools that predict the potentials of the technology are of paramount importance

Design analysis and optimization

minimize $f(x)$
 by varying $\underline{x}_i \leq x_i \leq \bar{x}_i$
 subject to $g_j(x) \leq 0$
 $h_l(x) = 0$

Cost, emissions, impact, weight...
 Geometry, size, power rating...
 Mission, airworthiness, physical feasibilities



Quibén Figueroa, R., Cavallaro, R., Cini, A., & Soler Arnedo, M. (2023). MOTIVATION (Mdao fOr susTainable aViATION)-Framework development for the design and optimization of H2 powered aircraft. In AIAA AVIATION 2023 Forum (p. 4151).

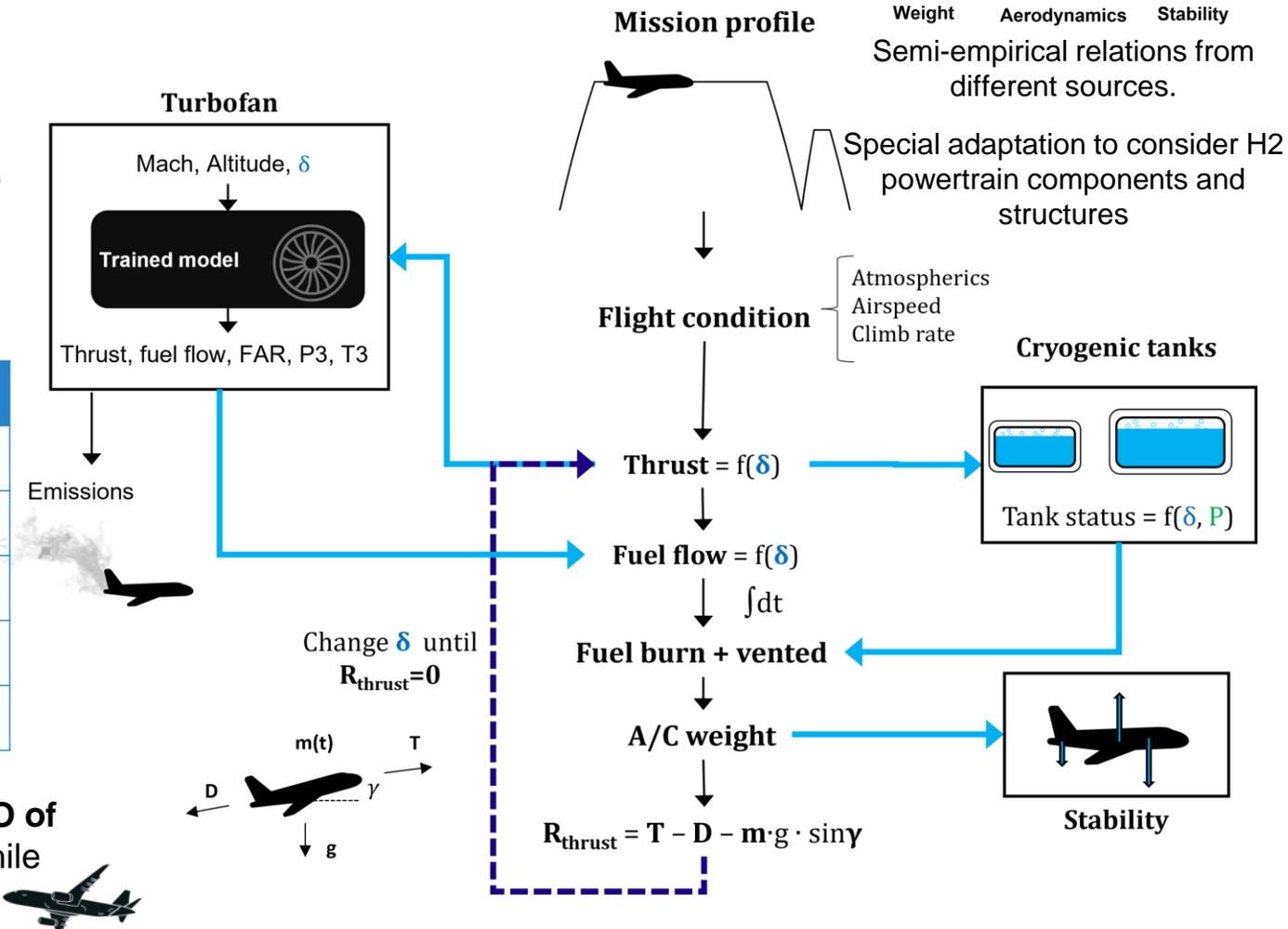


Weight Aerodynamics Stability
 Semi-empirical relations from different sources.

Conceptual design H2 aircraft SoA

	MDO	Tank Thermodynamics	Stability	Mission Airworthiness	Emissions
Adler and Martins (2024)	Yes	No	No	No	No
Proesmans and Vos (2024)	Yes	No	Yes	No	Yes
Barton et al (2023)	No	No	No	No	Yes
Palaia et al (2024)	Yes	Yes	No	No	No
Silberhorn et al (2022)	Yes	No	No	No	Yes

Objective 1: need for a platform to assess the **conceptual MDO** of a H2 tube-wing aircraft fulfilling all its **specific requirements** while computing its **impact** and compliant with current airworthiness



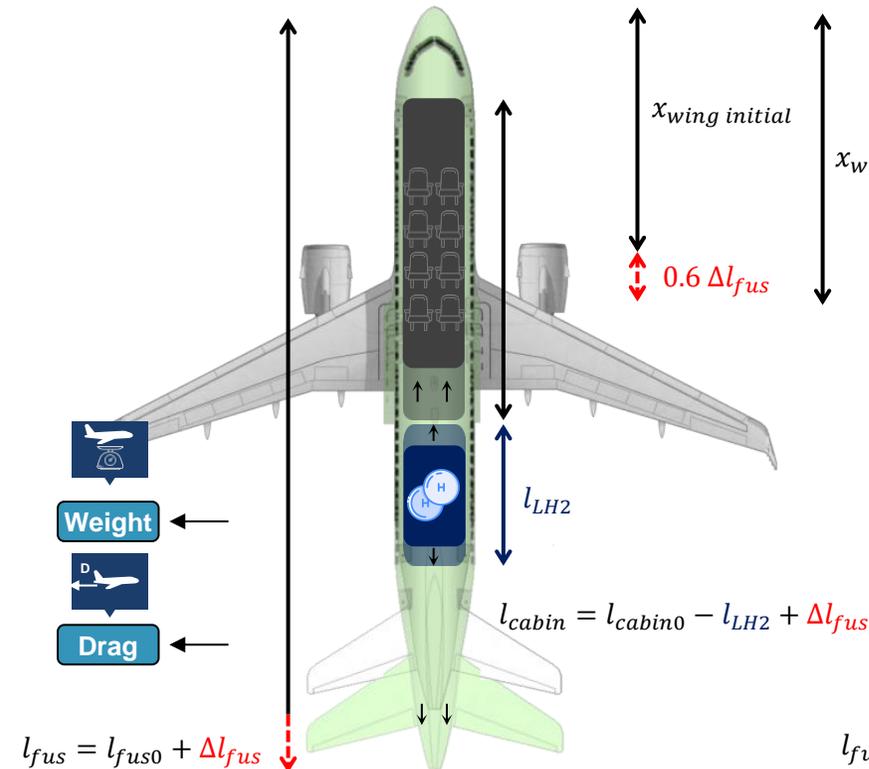
AIRCRAFT DESIGN: TEST CASE



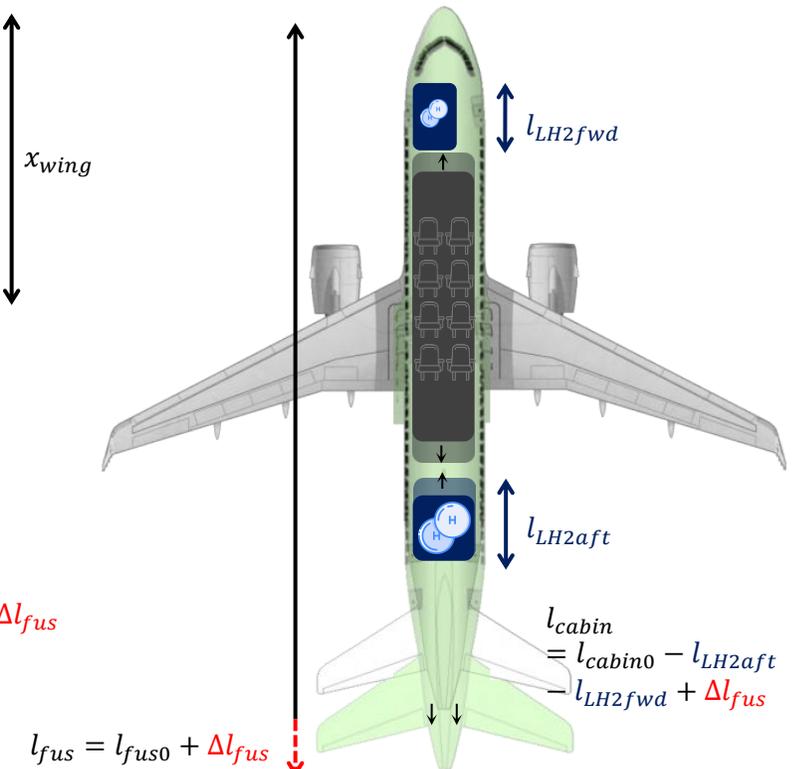
A320neo H2-modified aircraft:

- Equivalent to CFM56 turbofan model optimized in **pyCycle**.
- LH2 tank introduction: **stretch the fuselage**
- Double tank configuration: stability and certification concerns

SINGLE REAR TANK



DOUBLE TANK

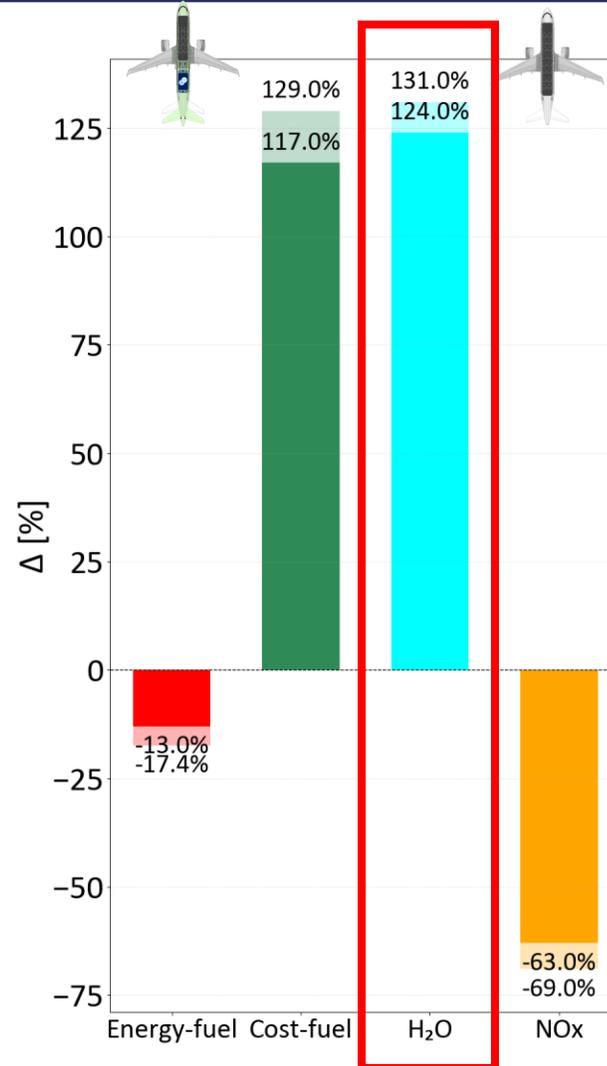


AIRCRAFT DESIGN



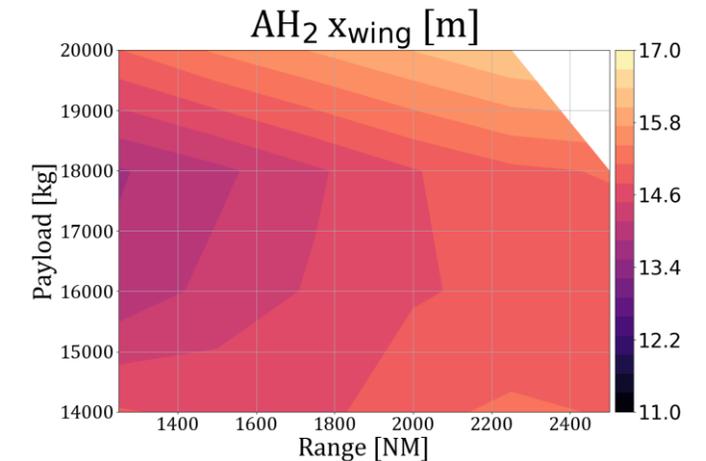
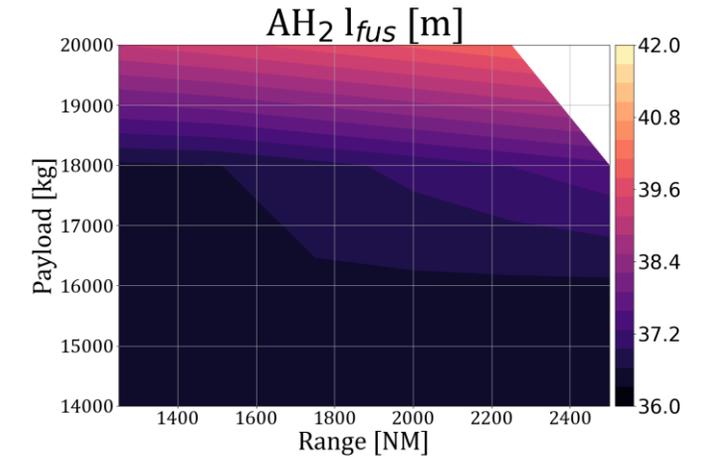
Optimization campaign:

- Altitude = 34,000 [ft]
- Ranges: 1,000 to 2,500 [NM]
- Payloads: 14 to 20[t].
- $\eta_{grav} = 0.5$



l_{fus} proportionally shifts the wing position. x_{wing} adjusts to satisfy stability constraints.

Shift of the wing position resulting from the increased weight of the hydrogen tanks.



Differences w.r.t. to DT configurations not relevant under selected optimization problem

Total CO₂:

- **Green H2:** reductions of up to 99% can be achieved.
- **Blue H2:** reduction is limited to 70%.

		JET A-1	Blue H2	Green H2
Density	kg/m ³	814.7	70.2	70.2
LHV	MJ/kg	43.1	118,35	118,35
2035 Price	\$/kg	0.776	5.95	5,60

For $EINO_{x_{SL}}$ three kerosene generic correlation models have been used, the trend is $\rightarrow EINO_{x_{SL}} = \alpha * P_3^{m \in [0.4, 0.5]} * e^{\{\beta * T_3\}}$



CONTRAIL ANALYSIS



How to handle all this excess in H2O? Flying this aircraft in a climate optimal way: contrail analysis

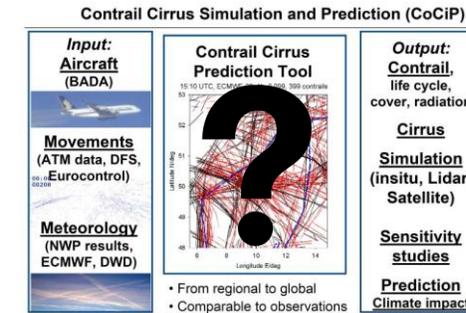
Contrail formation and effect is still subject to **huge uncertainties**

H2 aviation particular case has nearly **not been addressed**: new particle and environment scenario, no experimental evidence (available)



Current/accessible models for aircraft trajectory simulation:

	H2	Adaptability	Concerns
SAC	Yes	-	Only formation, too simplistic
CoCiP	Yes (?)	Yes (?)	Needs particle emissions input, huge number of assumptions
APCEMM	No	?	Too complex to modify from user point of view
aCCFs	No	No	Simulation-based on kerosene aircraft, restricted to specific regions and weather patterns
Advection-diffusion (in-house)	No	Yes	Needs already an ice particle distribution from another model

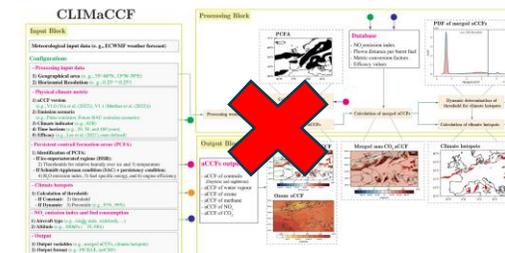


MAIN CONCERNS

- **Model/data for particle emission is missing**
- Lack of reliability in existing models
- Lack of applicability in the new approaches
- Impossible to have date-driven models

New higher fidelity approaches for H2:

	Method	Phase focus	Validation
Lottermoser and Unterstrasser (2025)	EULAG-LCM LES	Vortex	No
Ferreira et al (2024)	E-L LES	Jet and vortex	No
Bier et al (2024)	LCM box model	Jet and vortex	No



Objective 2: H2 aircraft emissions and climate impact modelling: adapt current models or build a useful one for ATO from Hi-Fi



CONTRAIL ANALYSIS



Objective 2: H2 aircraft emissions and climate impact modelling: adapt current models or **build a useful one for ATO from Hi-Fi**



- Project with Stanford University
- Compare under-construction solver against benchmark models, results and data
- **Eventual goal of augment the platform to H2 contrails**

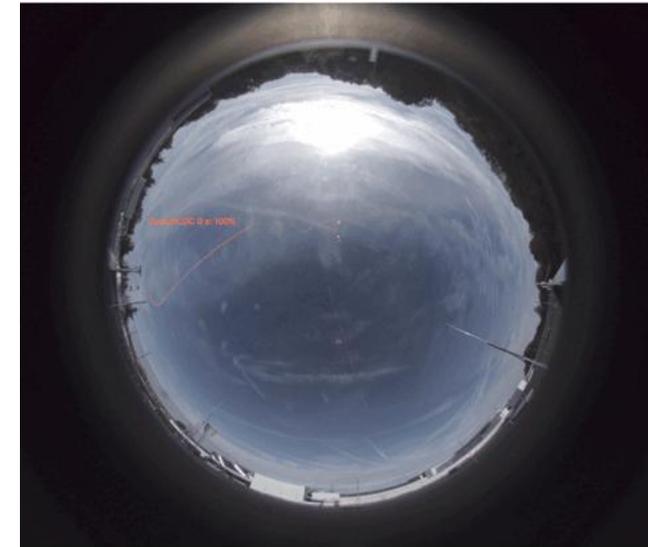
3D LES simulation



Eulerian–Lagrangian approach for **two-phase compressible** flow

Contrail's **jet & early vortex regimes** over short timescales (<5s) — only formation

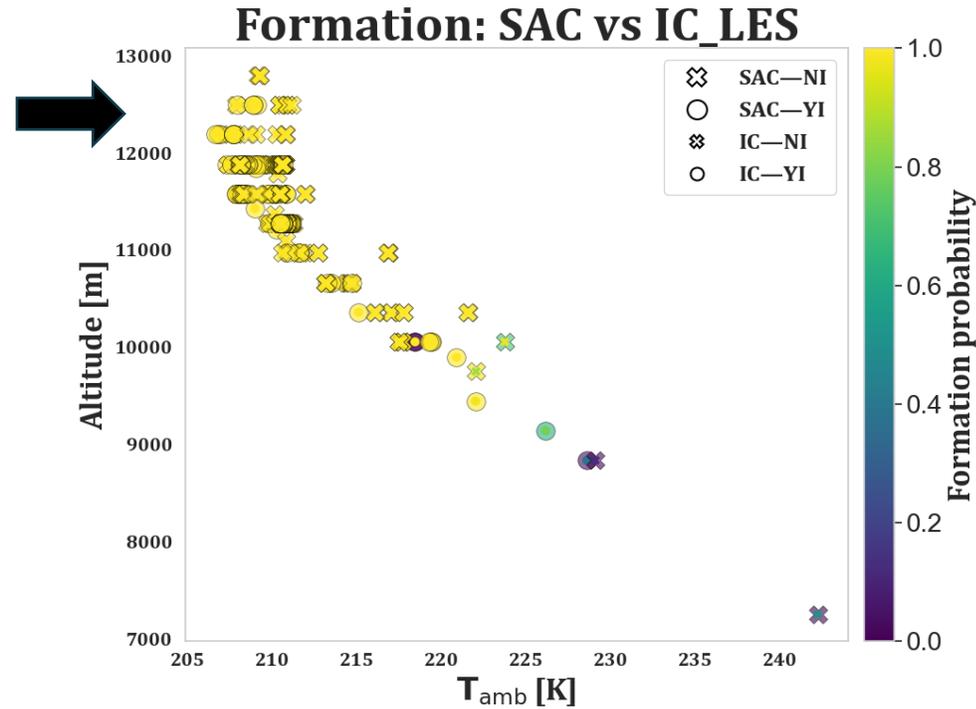
Ground-based camera imagery:



Understand predictability and limitations of models

- Focus on contrail formation
- Using images as **benchmark**
- Comparison against **COCiP/SAC** and **LES**
- **Dependence on reliable data** (atmospheric and aircraft)

CONTRAIL FORMATION



	Yes Image (YI)	No Image (NI)
Yes SAC (> 0.5)	98%	99%
No SAC (< 0.5)	2%	1%

	Yes Image (YI)	No Image (NI)
Yes SAC (> 0.5)	78%	47%
No SAC (< 0.5)	22%	52%

Not much difference found between SAC and IC for LES probability analysis → **most contrails forms, half persist**

Small set of cases: limitations on the variability of conditions

- **Similar limitations and problems** at first glance
- Implications for operational contrail avoidance – **importance of accurate, real-time atmospheric data** (also for isolating the effect of aircraft/engine parameters)

LES simulations can be a helpful tool to understand **contrail formation**. Ground cameras show potential to support the **enhancement** of contrail modelling: **fine tuning parameters and understanding their limitations**.

Work still needed for H2

Reuniwatt



Quibén Figueroa, R., Ferreira, T., Gorté, C., and Soler Arnedo, M.: Comparing high-fidelity LES of early contrail formation with ground-based images, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-17191, <https://doi.org/10.5194/egusphere-egu25-17191>, 2025.





TRAJECTORY OPTIMIZATION



Trajectory optimization: approaches

Problem formulation

$$\min_{u \in \mathcal{U}} J_i(t_0, t_f, \mathbf{x}, \mathbf{u}) = \mathcal{M}(t_0, t_f, \mathbf{x}(t_0), \mathbf{x}(t_f)) + \int_{t_0}^{t_f} \mathcal{L}(t, \mathbf{x}(t), \mathbf{u}(t), \mathbf{p}) dt$$

Cost, time, emissions, climate impact...

with respect to: $\dot{\mathbf{x}}(t) = \mathbf{f}(t, \mathbf{p}, \mathbf{x}(t), \mathbf{u}(t))$ H2 aircraft dynamical model

$$\mathbf{h}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{p}, t) = \mathbf{0}$$

$$\mathbf{g}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{p}, t) \leq \mathbf{0} \quad \text{Path and state constraints}$$

$$\Psi(t_0, t_f, \mathbf{x}(t_0), \mathbf{x}(t_f)) = \mathbf{0}$$

Optimal control

Direct: discretize the trajectory and solve as an NLP problem

Indirect: solve problem via PMP, complex to derive analytical solutions

Non-optimal control

Meta-heuristics

Gradient-based NLP

Mathematical programming

Climate optimal trajectory optimization SoA

Study	Forcing agents	Model	Opt. algorithm	Opt. type	Uncertainty	Routing	Aircraft/Fuel
Niklaß et al. (2019)	CO ₂ and non-CO ₂	aCCFs	Direct OC	Case-specific	-	Unconstrained	Conventional
Yamashita et al. (2020)	CO ₂ and non-CO ₂	aCCFs	GA	Case-specific	-	Unconstrained	Unconstrained
Matthes et al. (2020)	CO ₂ and non-CO ₂	aCCFs	Direct OC	Case-specific	-	Unconstrained	Conventional
Lührs et al. (2021)	CO ₂ and non-CO ₂	aCCFs	Direct OC	Case-specific	-	Unconstrained	Conventional
Yamashita et al. (2021)	CO ₂ and non-CO ₂	aCCFs	GA	Case-specific	-	Unconstrained	Conventional
Yin et al. (2023)	CO ₂ and non-CO ₂	aCCFs	GA	Case-specific	-	Unconstrained	Conventional
Simorgh et al. (2023a)	CO ₂ and non-CO ₂	aCCFs	ARS	Case-specific	MET	Structured airspace	Conventional
Simorgh et al. (2024)	CO ₂ and non-CO ₂	aCCFs	Robust OC	Case-specific	MET	Unconstrained	Conventional
Castino et al. (2024)	CO ₂ and non-CO ₂	aCCFs	GA	Case-specific	-	Unconstrained	Conventional

H2 is completely missing!



Objective 3: Climate optimal trajectory planning algorithms for H2 aircraft, adapt and augment current libraries: performance (O1), emissions and impact modelling (O2).

In-house libraries



- Full 4D trajectory optimization
- Optimal control
- Incorporate uncertainty in meteorological variables
- **Free routing**

<https://github.com/Aircraft-Operations-Lab/roc>



- Flight planning technique incorporating horizontal and vertical decision-making
- Heuristic graph-based algorithm
- Incorporate uncertainty in meteorological variables
- **Structured airspace**

<https://github.com/Aircraft-Operations-Lab/roost>

TRAJECTORY OPTIMIZATION



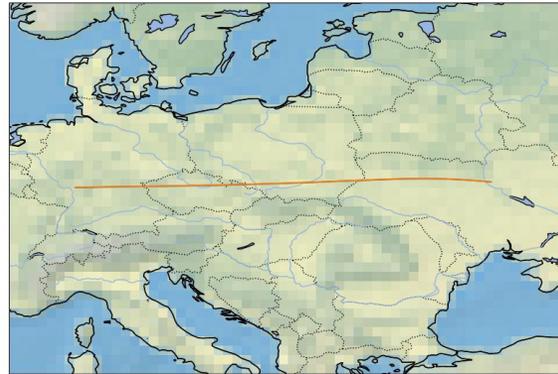
Optimal Control Problem



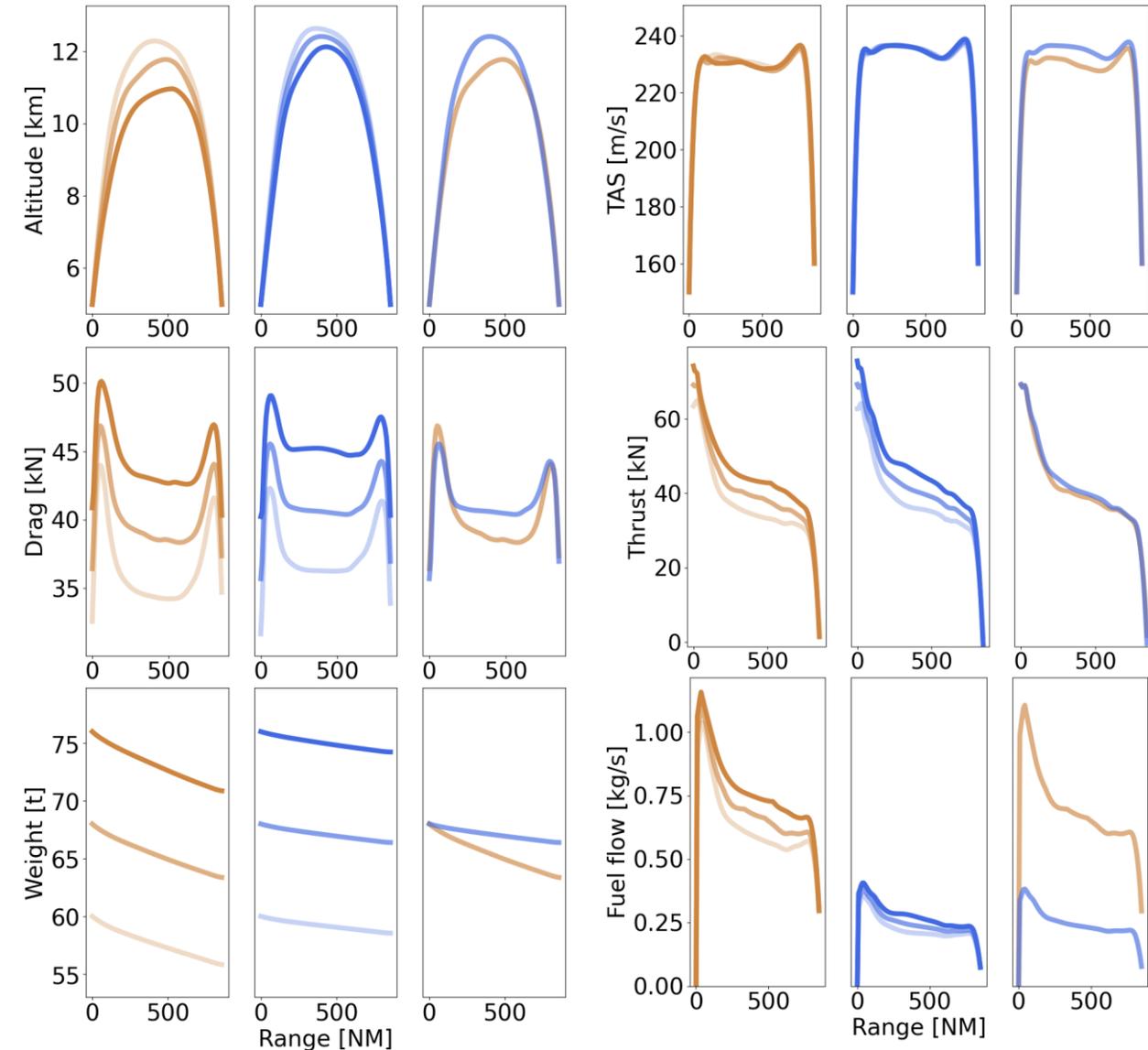
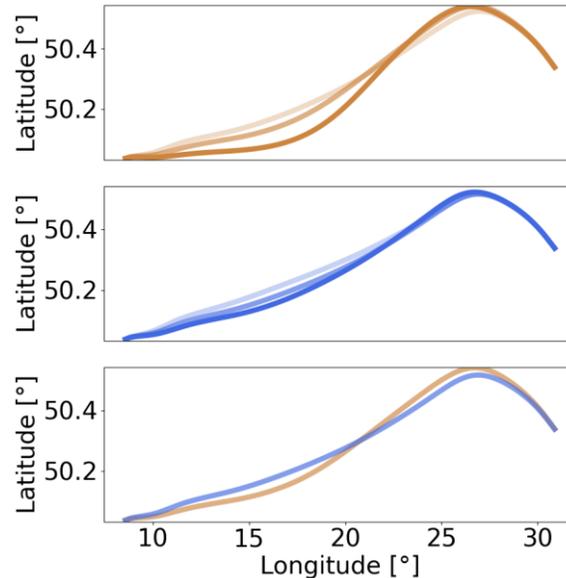
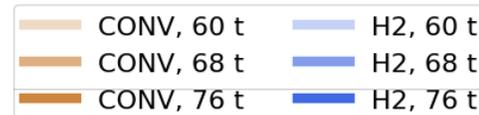
$$f(x) = \alpha \cdot Fuel(x) + B \cdot Time(x)$$

KYIV – FRANKFURT

- **CONV:** A320-214
- **H2:** Design and engine from optimization (payload = 18t, range=2000nm)



Three different TOWs



TRAJECTORY OPTIMIZATION



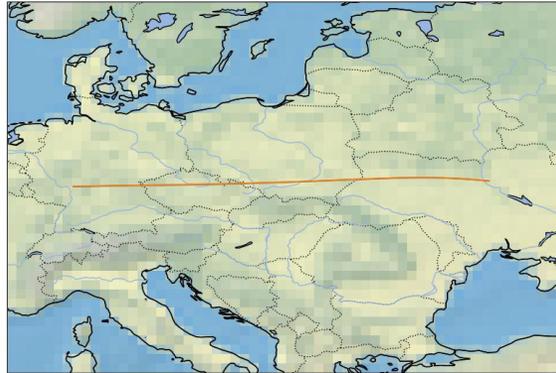
Optimal Control Problem



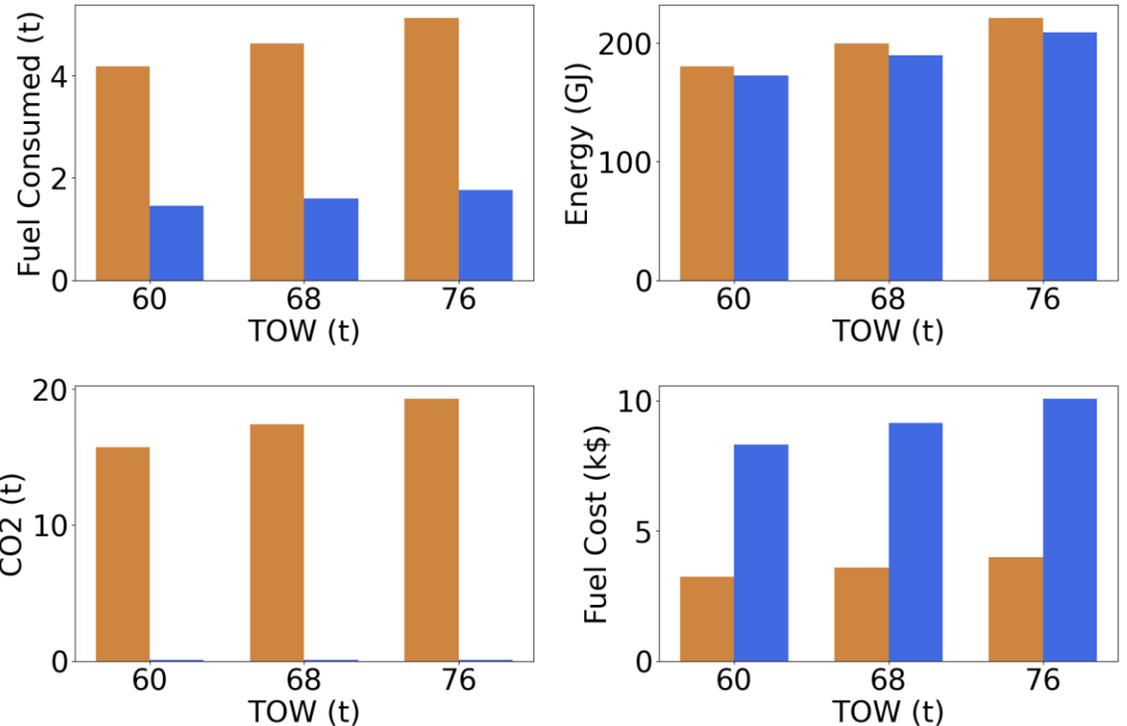
$$f(x) = \alpha \cdot \text{Fuel}(x) + B \cdot \text{Time}(x)$$

KYIV – FRANKFURT

- **CONV:** A320-214
- **H2:** Design and engine from optimization (payload = 18t, range=2000nm)



Three different TOWs



NEXT STEPS

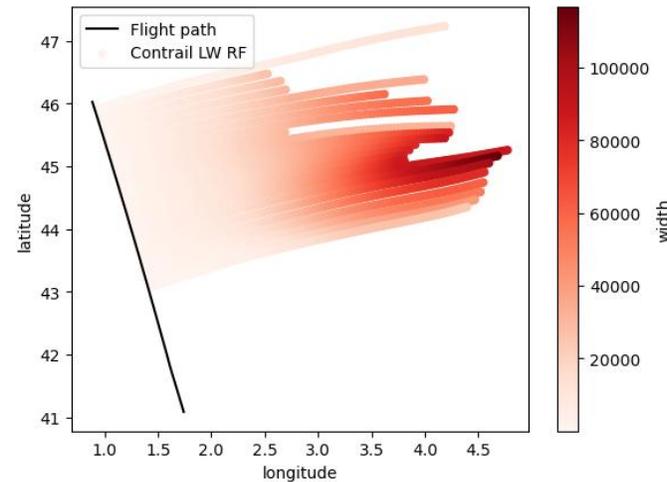
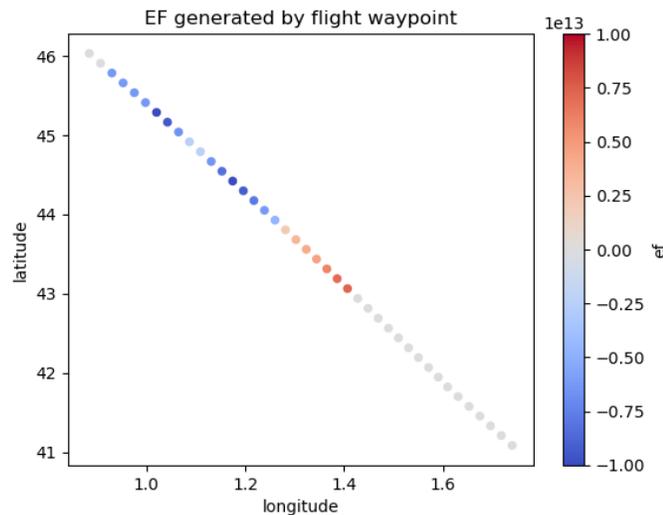


Finish the journal paper about **MDO of H2 aircraft**

- New parametric analysis on weights, ranges and technological values

Improve the work presented in EGU with more results and analysis: potential publication

Include the impact of the H2 aircraft into flying the trajectory: climate impact **assessment** and climate **optimal planning**



- Test **CoCiP module for H2**
- Compare against conventional aircraft **formation and impact** under different conditions
- **Climate and cost-optimal optimizations**

Ideally having particle emissions estimations

CONTACT AND ACHIEVEMENTS



- **Raúl Quibén Figueroa:** PhD student at Universidad Carlos III de Madrid (UC3M).
 - rquiben@ing.uc3m.es
 - <https://www.linkedin.com/in/raul-quiben/>
 - [@raulquiben](https://twitter.com/raulquiben) 
- **Rauno Cavallaro:** Associate Professor at UC3M. rauno.cavallaro@uc3m.es
- **Manuel Soler:** Associate Professor at UC3M. msolera@ing.uc3m.es



Conference Papers:



R. Quiben, R. Cavallaro, A. Cini, M. Soler: *Motivation (Mdao) for sustainable aviation* - Framework development for the design and optimization mid-range H2 powered aircraft. En AIAA AVIATION 2023 Forum. 2023. p. 4151. (DOI:[10.2514/6.2023-4151](https://doi.org/10.2514/6.2023-4151))



R. Quiben, R. Cavallaro, A. Cini, M. Soler: *Hydrogen-powered aircraft design: A multidisciplinary approach to minimize emissions and cost.* En AEROBEST 25. 2025.

Conference presentations:



4th ECATS Conference Delft 2023. *Multidisciplinary optimization of H2-powered aircraft to reduce emissions and costs* (DOI: [10.13140/RG.2.2.23549.95207](https://doi.org/10.13140/RG.2.2.23549.95207)).



EGU 25 Quibén Figueroa, R., Ferreira, T., Górlé, C., and Soler Arnedo, M.: *Comparing high-fidelity LES of early contrail formation with ground-based images*, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-17191,.



Research stay: Stanford University (May 24 – July 24)
Wind Engineering Laboratory, Civil and Environmental Engineering Department

Journal Papers:



R. Quiben, R. Cavallaro, A. Cini: *Feasibility Studies on Regional Aircraft Retrofitted with Hybrid-Electric Powertrains* Aerospace Science and Technology, DOI: [10.2139/ssrn.4720849](https://doi.org/10.2139/ssrn.4720849)

[IN PREPARATION] R. Quiben, R. Cavallaro, A. Cini, M. Soler: *Multidisciplinary optimization of H2-powered aircraft from a climate perspective*

Scholarships:

Beca CAM | Contratación para Investigadores predoctorales en formación 2023 (2023/00536/001).

Beca Movilidad 2024

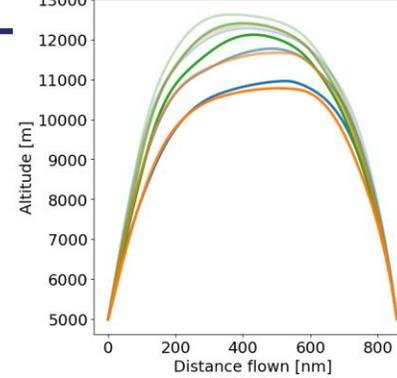


THANKS!

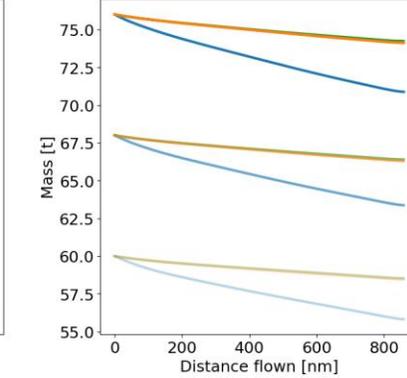
Author: Raúl Quibén Figueroa
Supervisor: Manuel Soler, Rauno Cavallaro

SOME MORE RESULTS

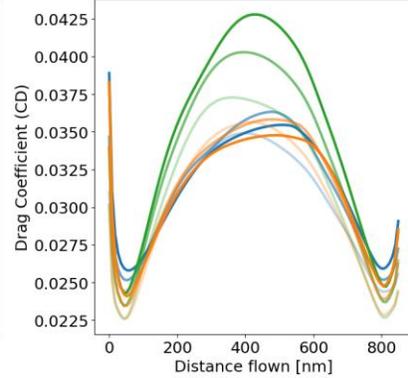
Altitude vs Distance flown



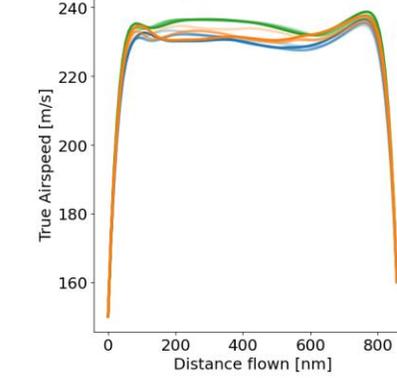
Mass vs Distance flown



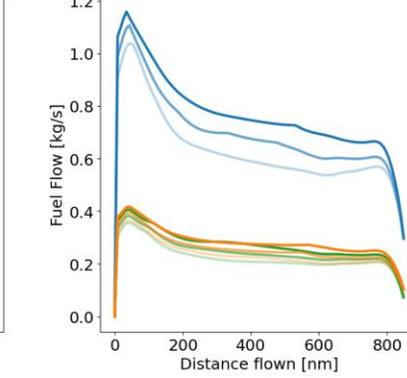
CD vs Distance flown



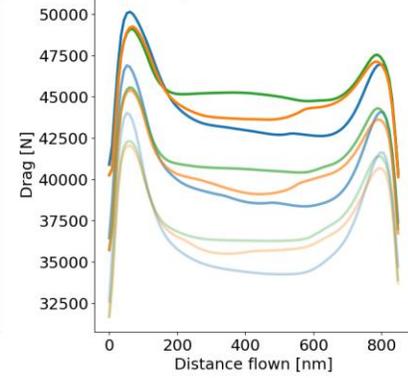
True Airspeed vs Distance flown



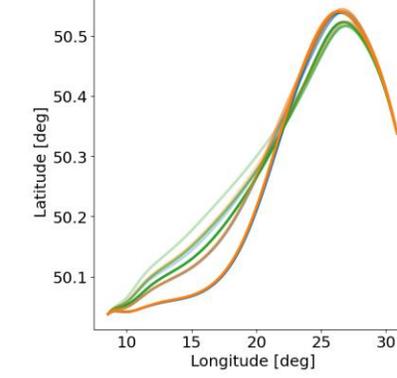
Fuel Flow vs Distance flown



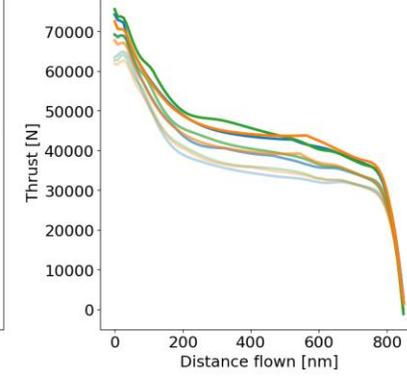
Drag vs Distance flown



Flight Path (Longitude vs Latitude)



Thrust vs Distance flown



CT_0 vs Distance flown

