Aircraft OPERATIONS Lab uc3m

Comunidad de Madrid | CONSEJERÍA DE CIENCIA, UNIVERSIDADES E INNOVACIÓN

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

PhD Student: **Raúl Quibén Figueroa**
Supervisors: **Manuel Soler, Rauno Cavallaro**

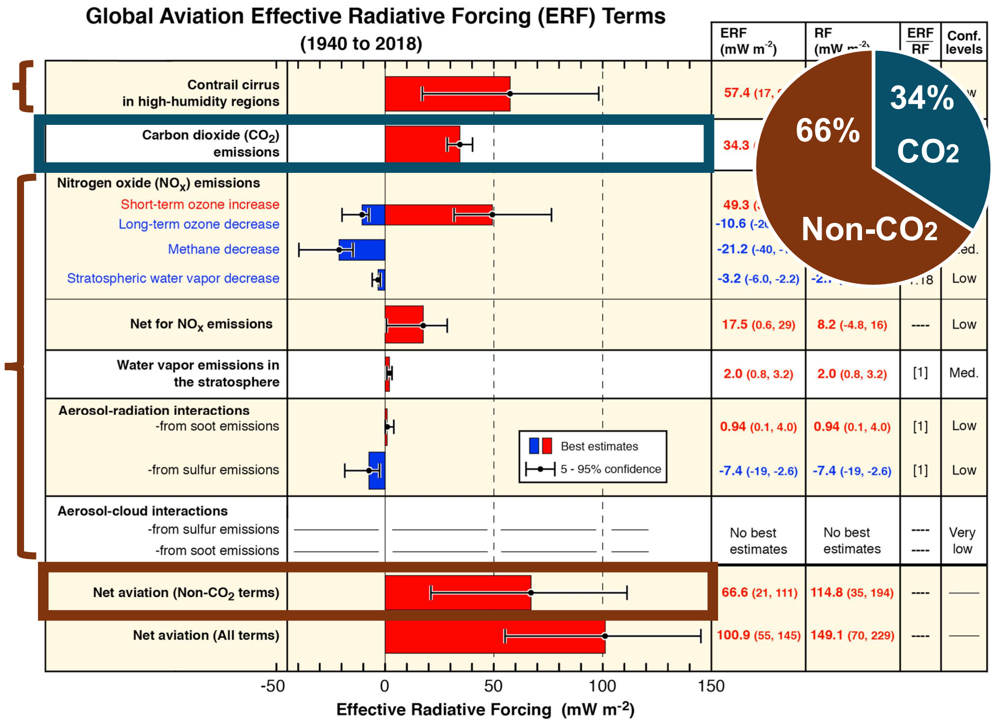
PhD Aerospace Engineering UC3M
Doctoral Meetings 2026
2nd and 3rd June 2026

MOTIVATION

uc3m PHD

Flightradar24.com

- Temperature change
- Precipitation change
- Rise of sea level



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

- 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:**

Operational:

- Flight planning
- Non-CO2 oriented

CORSIA EU ETS

Policy-based

Technological:

- Alternative forms of propulsion: electrification/hybridization
- Alternative fuels: SAF, **H2**
- Advancements in drag/consumption reduction

MOTIVATION

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

$$2H_2 + O_2 \rightarrow 2H_2O + Energy$$

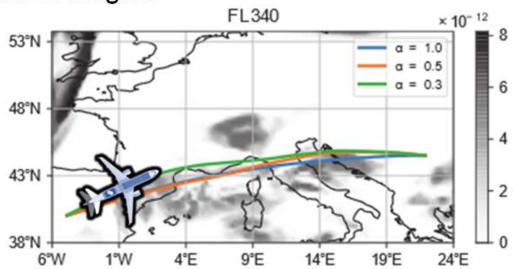
Direct **CO2 emissions** are **eliminated**

Produced by **renewable sources**

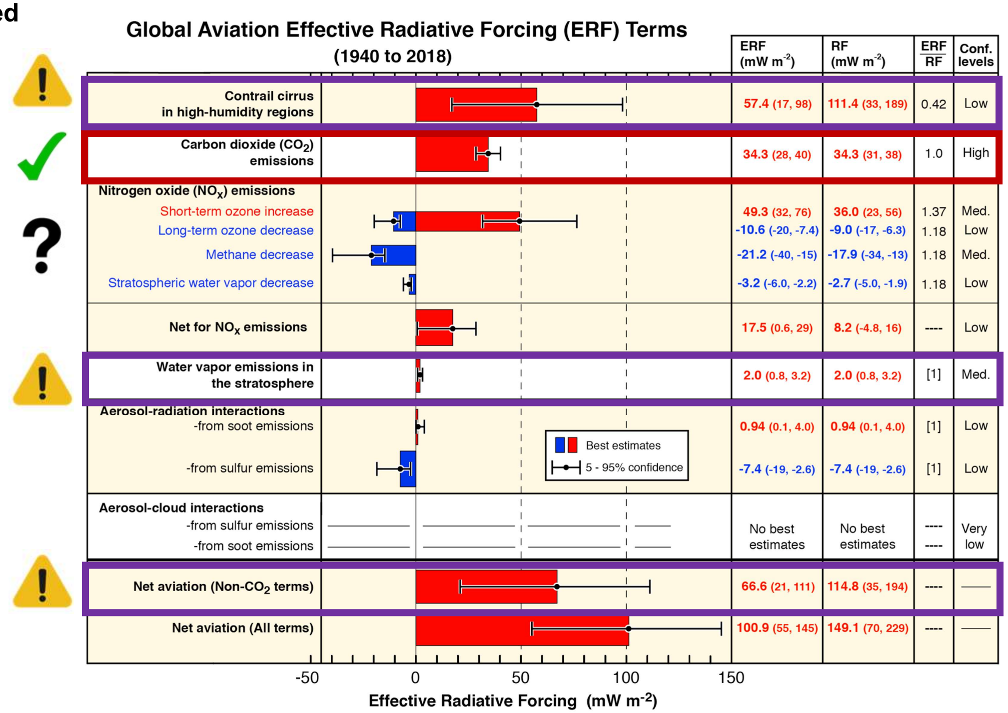
Non-CO2 emissions: **water vapour + contrails**, can play an equally or even larger noxious role to the environment.

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

Research and **design** of H2 aircraft conceptual models

+

Operational and **trajectory** study of H2 aircraft

Round off the problem

Tackling both CO2 and non-CO2 emissions impact

Maximizing the benefits

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

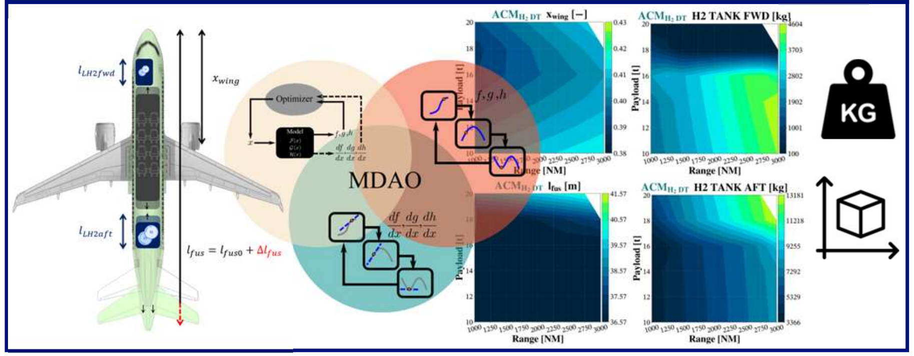
Objective 1: H2 aircraft design analysis and optimization models.

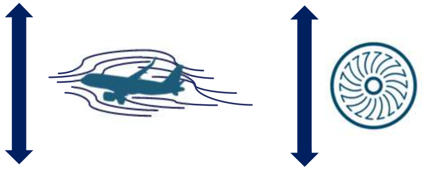
- **RQ:** What are the conceptual design H2 aircraft models?
- **RQ:** Feasibility and maximum capabilities?
- **RQ:** Design and performance drivers?
- **RQ:** Most beneficial configurations?

Objective 2: Climate optimal trajectory planning algorithms for H2 aircraft.

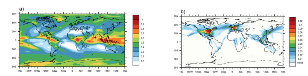
- **RQ:** Which are optimal operational and flight conditions?
- **RQ:** Climate optimal routes?
- **RQ:** Network implications?

H2 AIRCRAFT DESIGN AND OPTIMIZATION

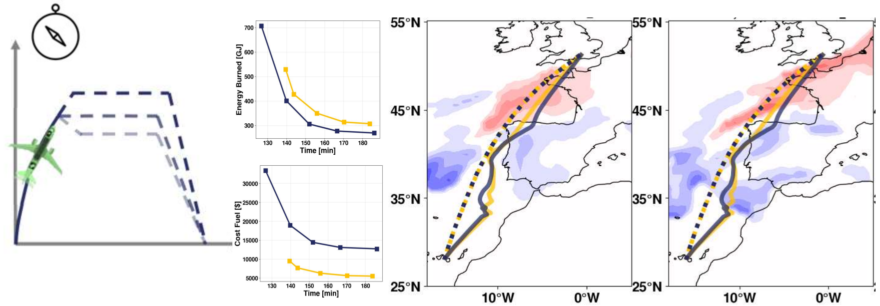




Emissions and impact



OPTIMAL TRAJECTORY PLANNING



AIRCRAFT MDO

uc3m PHD

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

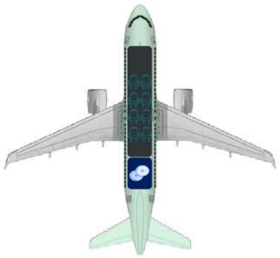
Design analysis and optimization

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{by varying} & \underline{x}_i \leq x_i \leq \overline{x}_i \\ \text{subject to} & g_j(x) \leq 0 \\ & h_l(x) = 0 \end{array}$$

Cost, emissions, impact, weight…

Geometry, size, power rating…

Mission, airworthiness, physical feasibilities



State of Art on H2 MDO

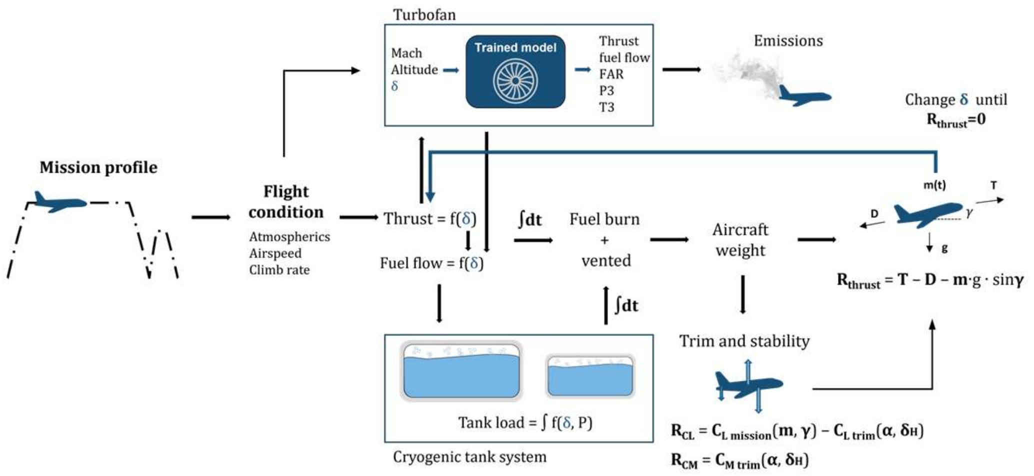
	MDO	Tank Thermo - dynamics	Stability	Mission Airworthiness	Emissions
Adler and Martins (2024)	Yes	No	No	No	No
Proesmans and Vos (2024)	Yes	Yes (?)	Yes	No	Yes
Barton et al (2023)	No	No	No	No	Yes
Palaia et al (2024)	Yes	Yes	No	No	No
Silberhorn et al (2022)	Yes	No	No	No	Yes

- Need to understand the **impact** of different mission objectives (range, payload…) and technological predictions on **design.**
- Explore maximum capabilities of H2 aircraft under **different configurations**

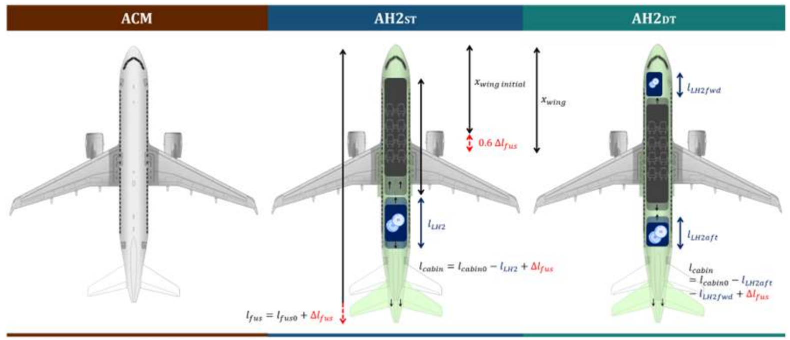
RQ: What are the conceptual design H2 aircraft models?
RQ: Feasibility and maximum capabilities?
RQ: Design and performance drivers?
RQ: Most beneficial configurations?

Quibén Figueroa, R., Cavallaro, R. & Soler, M. (2026). *Multidisciplinary design optimization of hydrogen-powered transport aircraft*. Sent to Journal of Aircraft.

Complete H2 aircraft MDO



Comparison against conventional kerosene reference

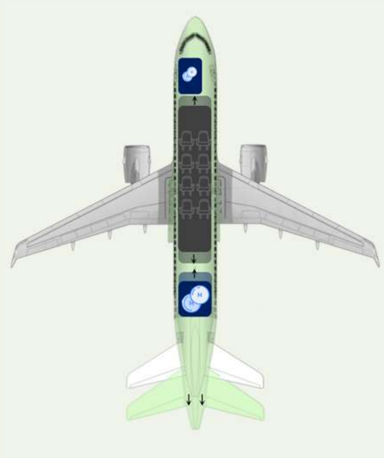


- ✓ Feasibility and capabilities
- ✓ Main design and performance drivers
- ✓ Impact and costs quantification

FROM DESIGN TO TRAJECTORY

The optimized aircraft is compressed into a differentiable dynamical model — that model is what the trajectory optimizer sees.

1 · DESIGN



Optimized H_2 configuration

geometry · mass · tanks · propulsion (MDO)

OEW: 52 [t]
Fuselage length: 40.5 [m]
Max Fuel: 6500 kg
…

2 · DYNAMICAL MODEL

$$f(M,h,\delta) = f_0 + \sum_{i=1}^{20} k_i M^{p_{i1}} h^{p_{i2}} \delta^{p_{i3}}$$

Response-surface surrogate of the MDO model.

Forces, thrust and H_2 flow become **smooth, cheap, differentiable** functions of mass M, altitude h and throttle δ.

Analogous aerodynamical model, fitted to the geometrical changes applied

3 · TRAJECTORY

Embedded in the point-mass dynamics:

$$\dot{x} = f(t, p, x, u)$$

typical states x : position, altitude, mass, speed
typical controls u : throttle δ, flight-path angle

H2 AIRCRAFT TRAJECTORY OPTIMIZATION

uc3m PHD

Problem formulation

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

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

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

$$\mathbf{g}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{p}, t) \leq \mathbf{0}$$

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*
Niklaß et al. (2019)	CO_2 and non-CO_2	aCCFs	Direct OC	Case-specific	–	Unconstrained
Yamashita et al. (2020)	CO_2 and non-CO_2	aCCFs	GA	Case-specific	–	Unconstrained
Matthes et al. (2020)	CO_2 and non-CO_2	aCCFs	Direct OC	Case-specific	–	Unconstrained
Lührs et al. (2021)	CO_2 and non-CO_2	aCCFs	Direct OC	Case-specific	–	Unconstrained
Yamashita et al. (2021)	CO_2 and non-CO_2	aCCFs	GA	Case-specific	–	Unconstrained
Yin et al. (2023)	CO_2 and non-CO_2	aCCFs	GA	Case-specific	–	Unconstrained
Simorgh et al. (2023*a*)	CO_2 and non-CO_2	aCCFs	ARS	Case-specific	MET	Structured airspace
Simorgh et al. (2024)	CO_2 and non-CO_2	aCCFs	Robust OC	Case-specific	MET	Unconstrained
Castino et al. (2024)	CO_2 and non-CO_2	aCCFs	GA	Case-specific	–	Unconstrained

H_2 is completely missing.

No study optimizes trajectories for a hydrogen aircraft

Proposed studies

1. **Indirect solution via PMP**
   - Theoretical approach
   - Solve canonical problem: 1D cruise at constant altitude
   - Understand optimal operating conditions
   - Focus on the influences on performance (qualitative not quantitative)

2. **Direct solution via ROC library**
   - Implications of the introduction into a realistic scenario
   - Climate impact minimization
   - Limited variations

RQ: Which are optimal operational and flight conditions?

RQ: Climate optimal routes?

PROBLEM FORMULATION: OPTIMAL CRUISE

uc3m PHD

Fuel/cost-optimal cruise of a transport aircraft — indirect optimal control (PMP → BVP)

- Cruise phase: 2D (1D) flight at constant altitude
- Quasi-steady flight
- Single regular control, no singular-arc classification

$$\frac{dx}{dt} = v, \qquad \frac{dv}{dt} = \frac{T(\Pi, v, \bar{h}) - D(\Pi, v, \bar{h})}{m}, \qquad \frac{dm}{dt} = -f_m(\Pi, v, \bar{h}),$$

$$\rightarrow \quad \frac{dv}{dt} = \frac{T(\Pi, v, \bar{h}) - D(\Pi, v, \bar{h})}{m} = 0, \quad \forall t \in [t_0, t_0 + \Delta t]$$

1. Optimal control problem

$$\min_{v,\, t_f} \quad \mathcal{J} = \int_{t_0}^{t_f} (1-\alpha)\dot{m}_{fuel}(v, \Pi, h)\ \mathrm{d}t + \alpha\, \mathrm{d}t, \qquad \alpha \in [0, 1],$$

$$\begin{aligned}
\text{s.t.} \quad & \dot{x} = v(t), \\
& \dot{m} = -\dot{m}_{fuel}(v(t), \zeta(v, m, h), h), \\
& x(t_0) = 0, \quad m(t_0) = m_0, \quad \boxed{x(t_f) = x_f} \\
& u(t) = v(t) \in \mathcal{U} := [v_{\min}, v_{\max}], \\
& v_{\min} = 150\ \mathrm{m/s}, \qquad v_{\max} = 280\ \mathrm{m/s}.
\end{aligned}$$

Formulating the Hamiltonian,

$$\mathcal{H} = \lambda_x v - \lambda_m \dot{m}_{fuel}(v, \Pi, h),$$

2. Pontryagin's Max Principle → 2BVP

being the costates,

$$\dot{\lambda}_x = -\frac{\partial \mathcal{H}}{\partial x} = 0 \implies \lambda_x = \text{const},$$

$$\dot{\lambda}_m = -\frac{\partial \mathcal{H}}{\partial m} = \lambda_m \frac{\partial \dot{m}_{fuel}}{\partial m}.$$

and solving the optimality residual,

$$\frac{\partial \mathcal{H}}{\partial v} := \lambda_x + \frac{-\alpha - \lambda_x v}{\dot{m}_{fuel}} \left[\frac{\partial \dot{m}_{fuel}}{\partial M} \frac{1}{a} + \frac{\partial \dot{m}_{fuel}}{\partial \Pi} \frac{\frac{\partial D}{\partial v} - \frac{1}{a}\frac{\partial T}{\partial M}}{\frac{\partial T}{\partial \Pi}} \right] = 0.$$

with the transversality conditions:

$$\mathcal{H}(t_f) = -\frac{\partial \Phi}{\partial t_f} = -\alpha \quad \text{(free final time)},$$

$$\boxed{\lambda_m(t_f) = \frac{\partial \Phi}{\partial m(t_f)} = -(1-\alpha)} \quad \text{(free final mass)}.$$

3. BILEVEL: Altitude optimization + Mass consistency

Introducing altitude ***h*** as a static design variable,

$$\frac{\partial \mathcal{J}^*}{\partial h} = 0,$$

and mass consistency constraint,

$$\boxed{m_0 = m_{\mathrm{OEW}} + m_{\mathrm{pay}} + m_{H_2},}$$

the problem to solve results in:

$$\boldsymbol{\xi} = \left[t_f,\ \lambda_x,\ h,\ m_{H_2}\right]^T$$

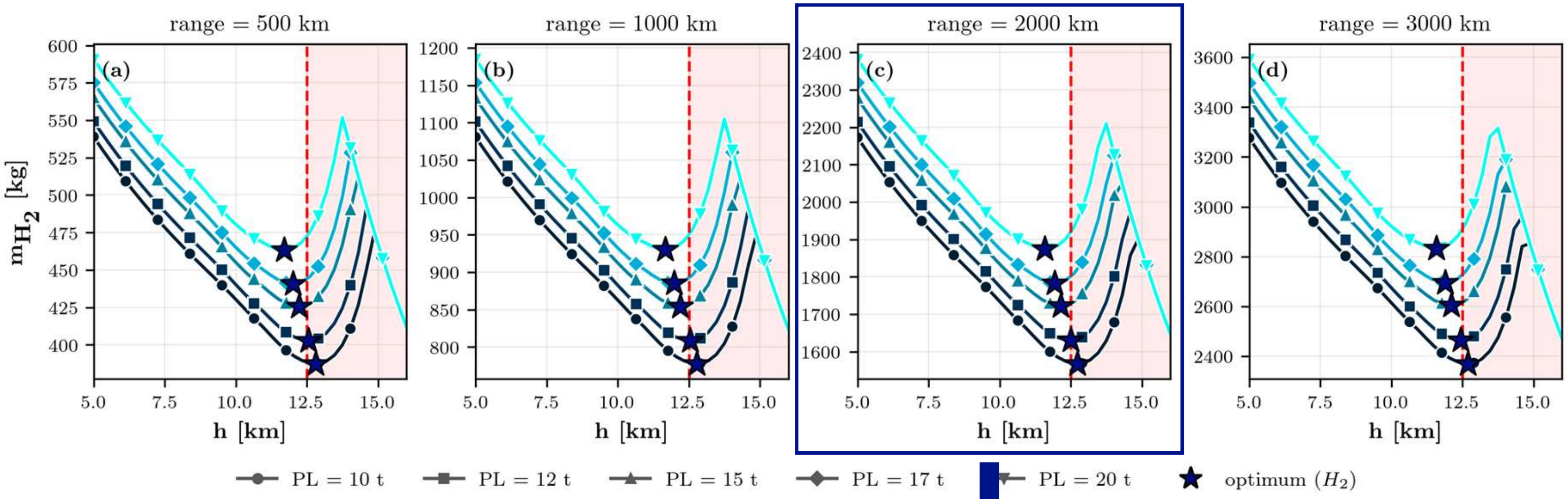
$$\boldsymbol{F}(\boldsymbol{\xi}) = \begin{bmatrix} x(t_f; \boldsymbol{\xi}) - x_f \\ \dfrac{\alpha + \lambda_x v(t_f; \boldsymbol{\xi})}{(1-\alpha)\, \dot{m}_f(t_f; \boldsymbol{\xi})} + 1 \\ [m_0(\boldsymbol{\xi}) - m(t_f, \boldsymbol{\xi})] - m_{fuel} \end{bmatrix} = \mathbf{0},$$

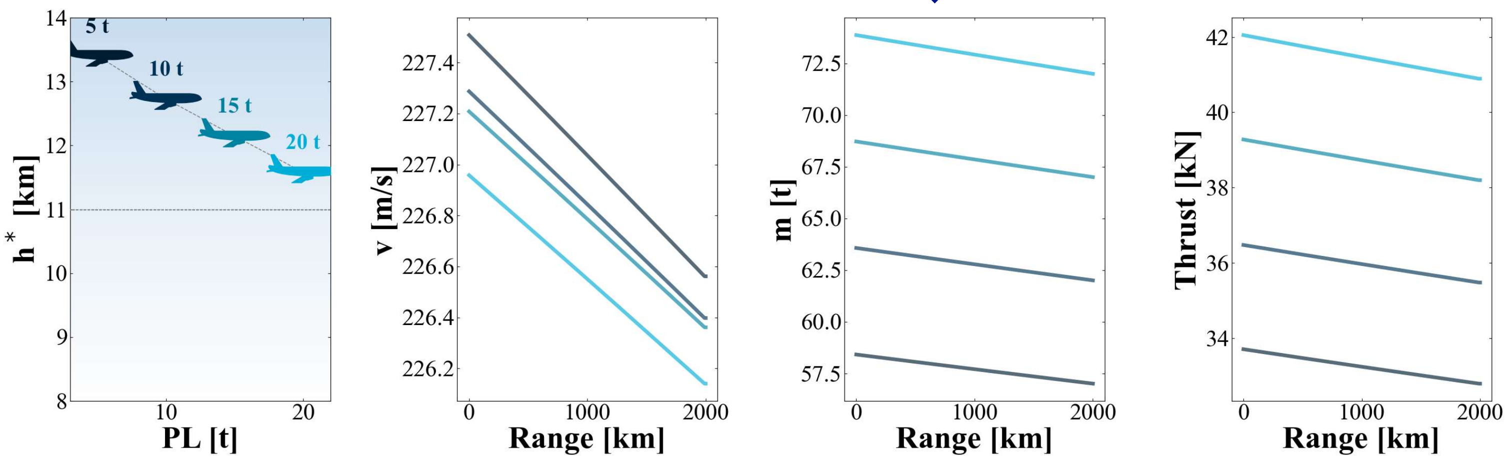
RESULTS I: OPTIMAL CRUISE

uc3m PHD

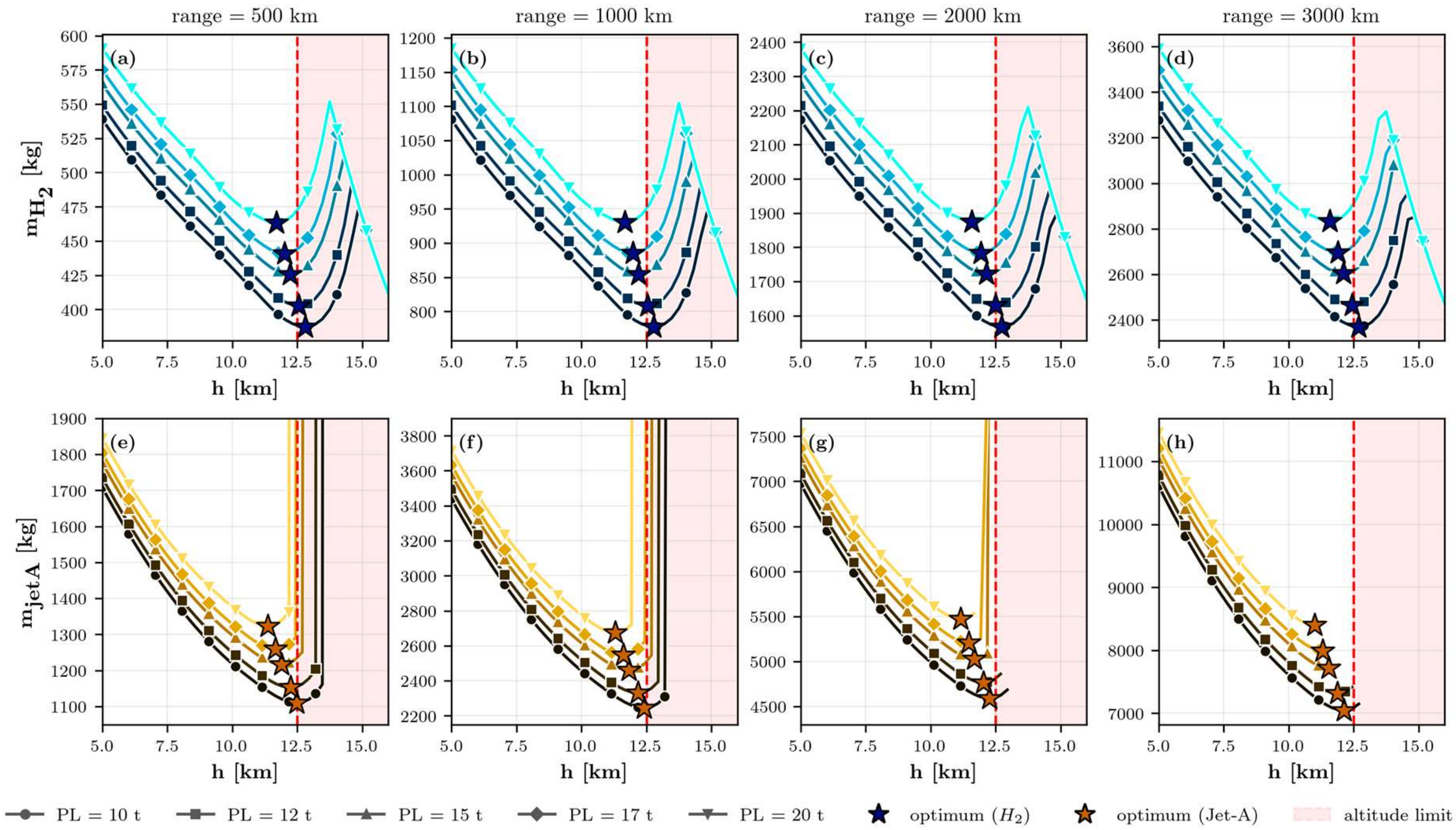
fuel-optimal cruise

$\alpha = 0$



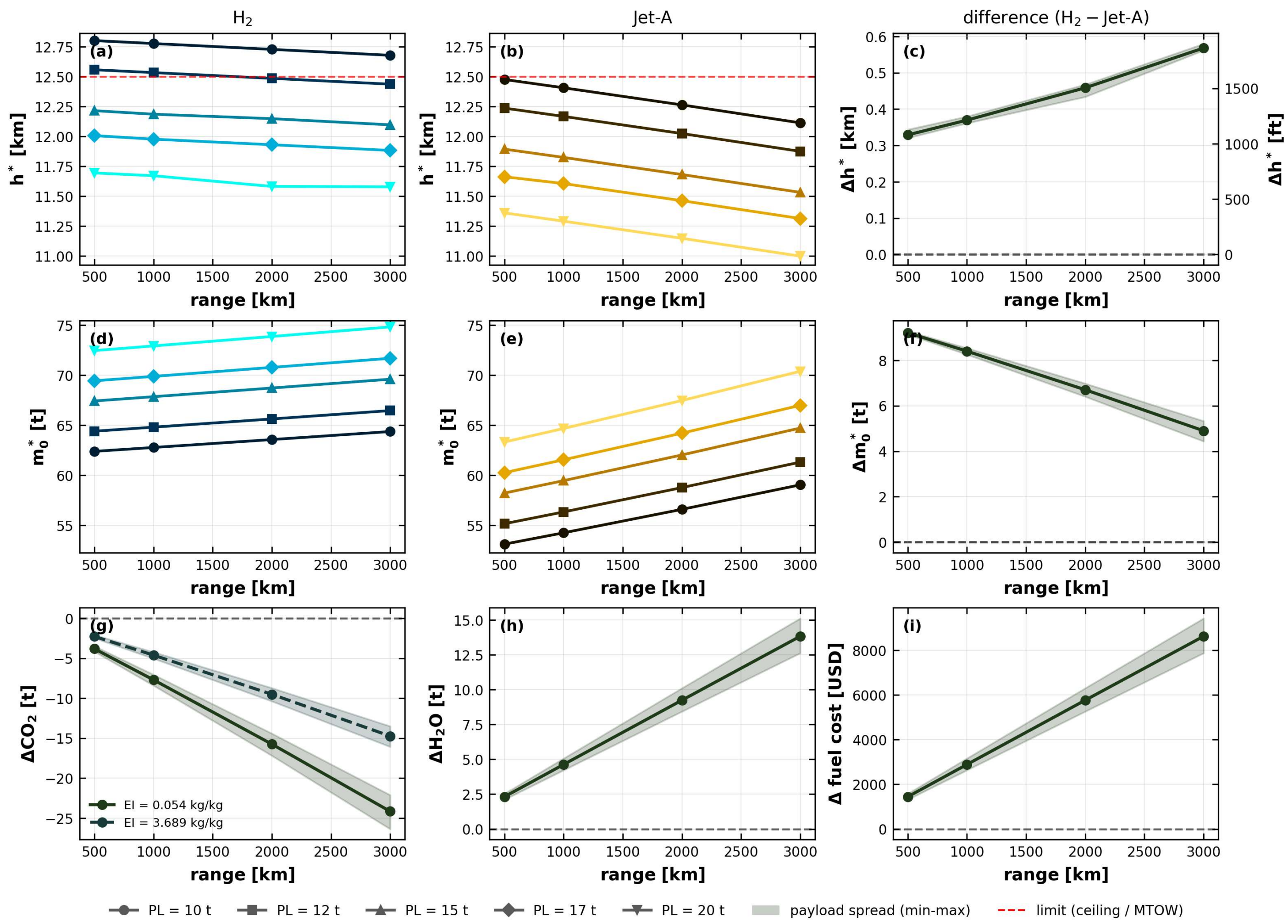


RESULTS I: OPTIMAL CRUISE



RESULTS I: OPTIMAL CRUISE

uc3m PHD



Potential natural segregation of FL, easing traffic organization!

RESULTS II: Climate optimal flight path

uc3m PHD

ROC library for trajectory optimization in free-routing airspace is augmented with H2 aircraft models

Simorgh, A., Soler, M., Dietmuller, S., Matthes, S., Yamashita, H., Castino, F., Yin, F. (2024). *Robust 4D climate-optimal aircraft trajectory planning under weather-induced uncertainties: free-routing airspace*. Transportation Research Part D, 131.

\+

COCiP gridded model is used for estimating contrail energy forcing (EF)

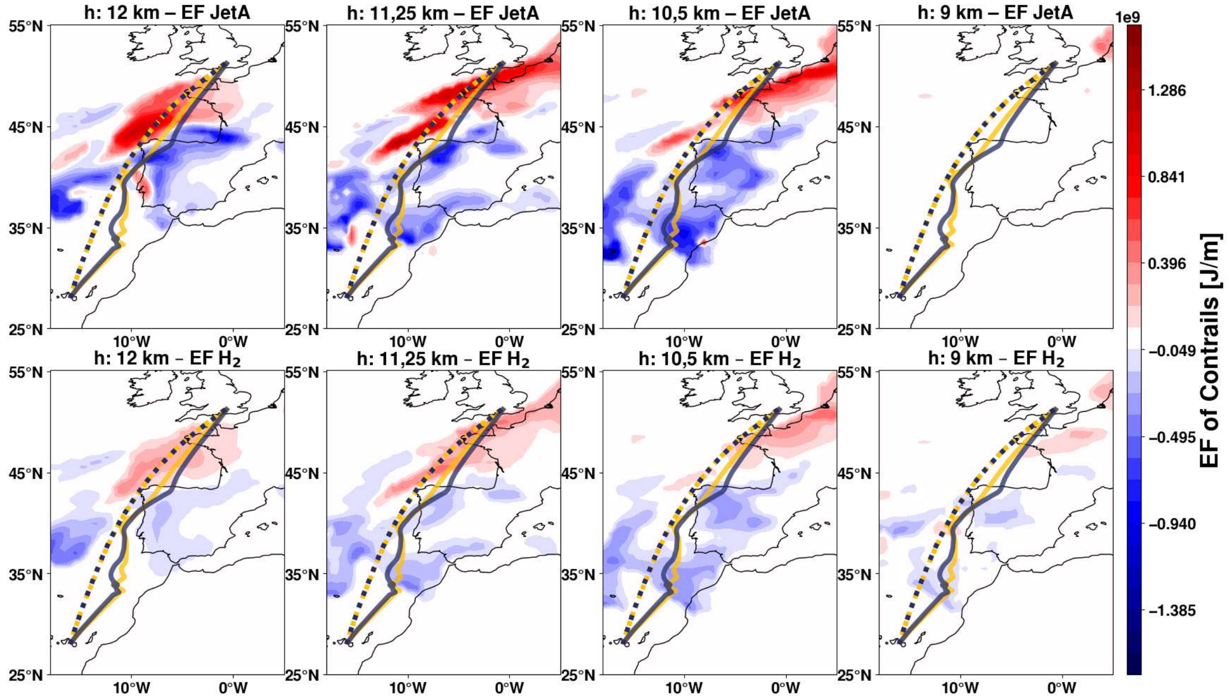
STUDY CASE

Fuel, time and climate impact (contrail energy forcing) optimization

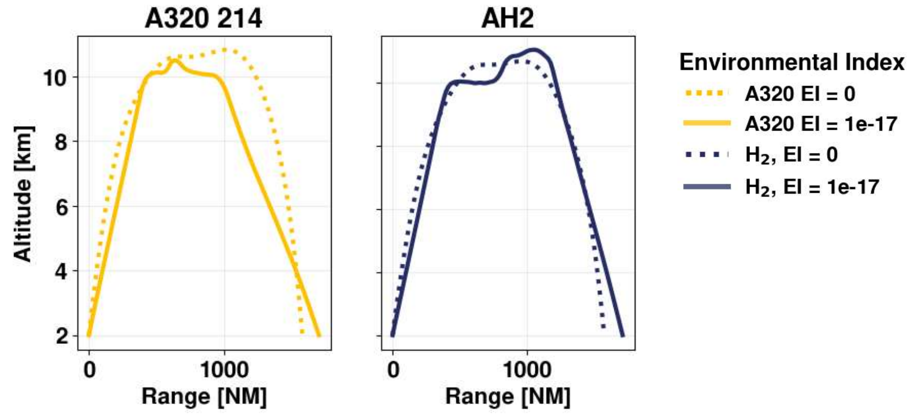
$$f(x) = C_i \cdot (C_m \cdot m_{fuel}(x) + C_t \cdot t_f(x)) + E_I \cdot EF(x)$$

$$C_i = 1.0, \quad C_M = 0.5, \quad C_T = 0.5$$

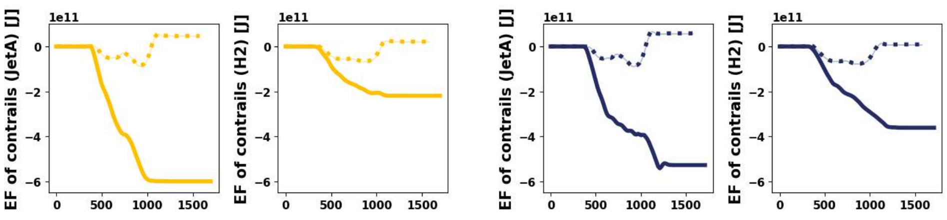
Real-case application comparing 4D trajectory optimization performance for a flight between Tenerife and London.



t_0: 26/01/2024 06:00 UTC
Tenerife to London



Accumulated EF



FUTURE WORK

NEXT STEPS

- Finish and submit the paper on **hydrogen aircraft trajectory optimization**
  - 1D optimal altitude cruise
- Prepare new test cases for 4D optimization
- **Write the thesis!**

Lines of research:

- Hydrogen aircraft **Non-CO2 emissions** estimation + impact
  - NOx
  - Contrails
- Higher fidelity hydrogen subsystems
  - Engine
  - Cryogenic tank

ACHIEVEMENTS

uc3m PHD

Raúl Quibén Figueroa: PhD student at Universidad Carlos III de Madrid (UC3M).
- rquiben@ing.uc3m.es
- https://www.linkedin.com/in/raul-quiben/

Research stay

Stanford University

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 Tecnology, DOI: https://doi.org/10.1016/j.ast.2024.109246

Fundación ENAIRE – Aeronautical Innovation Luis Azcárraga Award 2025

[Under review at Journal of Aircraft] **R. Quiben,** R. Cavallaro, M. Soler**:** *Multidisciplinary design optimization of hydrogen-powered transport aircraft*

[Under preparation] **R. Quiben,** R. Cavallaro, M. Soler**:** *H2-powered aircraft trajectory optimization*

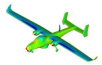
Scholarships:

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

Beca Movilidad 2024

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)



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).

EGU 25 Quibén Figueroa, R., Ferreira, T., Gorlé, 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,.

5th ECATS Conference Brussels 2023. *Multidisciplinary optimization of H2-powered aircraft to reduce emissions and costs*

Thank you!
Questions?

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

PhD Student: **Raúl Quibén Figueroa**
Supervisors: **Manuel Soler, Rauno Cavallaro**

Research was supported by funding from Comunidad de Madrid under the grant: *Ayudas para la contratación de personal investigador predoctoral en formación* with reference PIPF-2022/ECO-26345.