[Airbus Amber]

Future Aviation:

Aircraft with reduced Climate Impact

LH2 chapter is based on “Aircraft LH2 architecture” lecture by Mickael Lallemand in the frame of “Certificat en Ingénierie Environnemantale”

Serge BONNET
Airbus - Senior Expert in Overall Aircraft Preliminary Design

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Agenda

- Purpose - Introduction
- Historical trend on Fuel reduction
- Air Traffic evolution & CO_2 emissions
- Status on Aircraft Requirements & Fuel efficiency
- How to further reduce Fuel consumption in the Future?
- Other considerations on Climate Impact
- Alternative fuels & energies
- Conclusion

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Purpose - Introduction

- The purpose of this presentation is first to address the conceptual means to reduce Aircraft fuel consumption enabled by new technologies (at both airframe & powerplant* levels) as well as the "operational" opportunities

  * *powerplant aspect will be briefly addressed since covered by next presentation*

- On top of fuel – CO2 question, more global considerations on ways to reduce Aviation Climate Impact is introduced, on Kerosene type basis first

- It also addresses alternative energies as strong means to reduce climate impact at mid-long term

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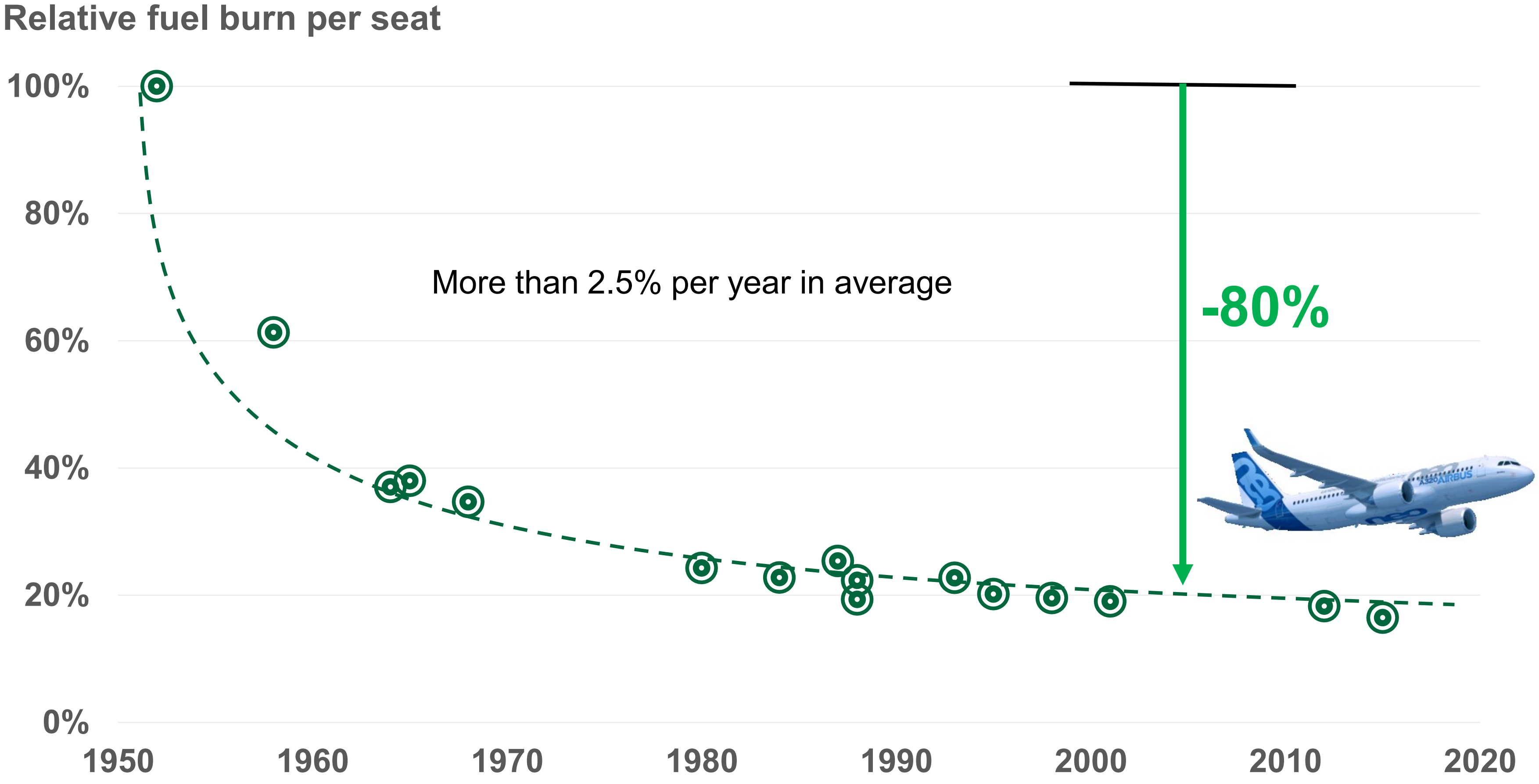
Historical trend on Fuel reduction

1 kg fuel ➔ 3.16 kg CO2



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CO_2 emissions reduction

80% reduction
in fuel burn and CO_2 since the dawn of Jet-Age

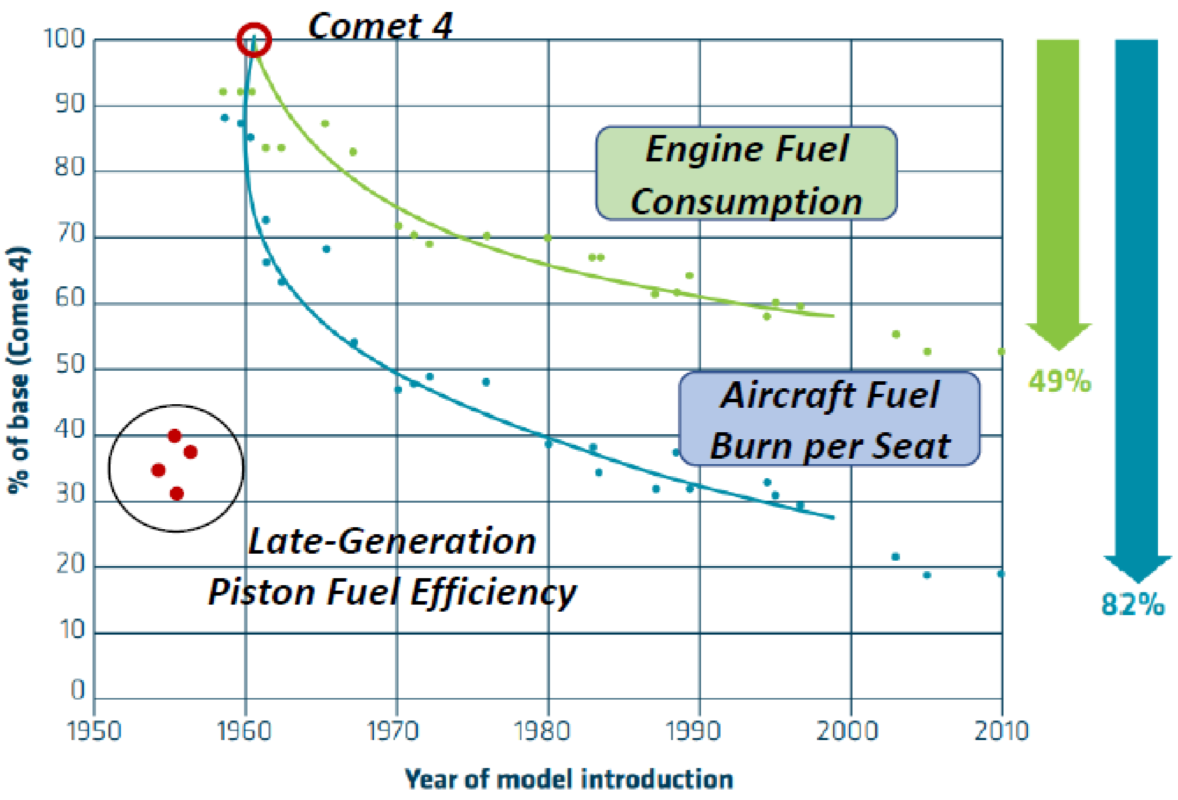
Historical trend on Fuel reduction

ICCT

The International Council on Clean Transportation is an independent nonprofit organization founded to provide first-rate, unbiased research and technical and scientific analysis to environmental regulators. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change.

ICCT chart quoted by Leeham article

https://leehamnews.com/2017/08/28/pontifications-jets-took-30-years-match-piston-efficiency/



Original source is: NLR-CR-2005-669 report
"Fuel efficiency of commercial aircraft,
An overview of historical and future trends"
Available at:
https://www.transportenvironment.org/publications/fuel-efficiency-commercial-aircraft-overview-historical-and-future-trends

More than **50%** of Aircraft Fuel efficiency gain can be attributed to **Engines** over the last 60 years

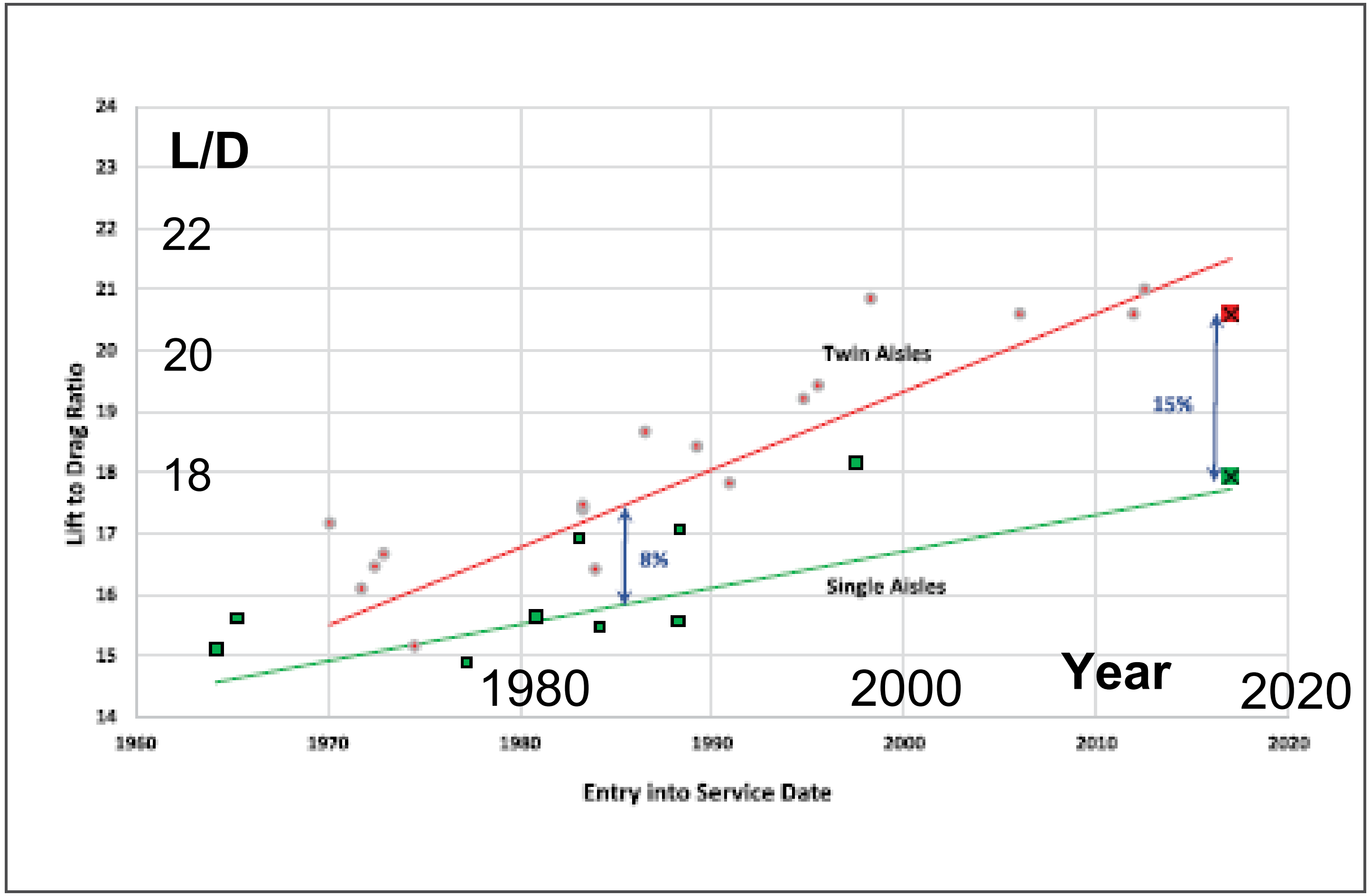
What are the other means / disciplines (than Engines) enabling to reduce Fuel Consumption ?

Historical trend on Fuel reduction

ICAO

2019 Environmental Report
AVIATION AND ENVIRONMENT

FIGURE 1: Historical Trend in Lift-to-Drag Ratio



Around **25% L/D** improvement in ~ 60 years

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Historical trend on Fuel reduction

A350 XWB

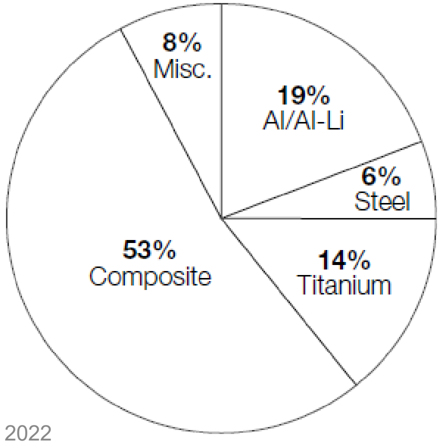
25% less

CO_2 emissions.

Over 70% of the A350 XWB's weight-efficient airframe is made from advanced materials, combining 53% of composite structures with titanium and advanced aluminum alloys. The aircraft's innovative all-new carbon fibre reinforced plastic (CFRP) fuselage results in lower fuel consumption.

Bringing together state of the art aerodynamics, advanced technologies and high performing Rolls Royce Trent XWB engines, the A350 XWB is 25% more efficient than the previous generation aircraft. By proactively supporting emissions reduction once the aircraft goes into service, the average global fleet fuel efficiency improvement per annum has been more than 2% over the last 5 years. The A350 XWB is also a quiet neighbour. It is up to 21dB below the ICAO (International Civil Aviation Organisation) Chapter 4 limit current noise standard.

A350 XWB airframe materials



CFRP

- Wings
- Centre wing box and keel beam
- Tail cone (Section 19)
- Skin panels
- Frames, stringers and doublers
- Doors (Passenger & Cargo)

Titanium

- High load frames
- Door surroundings
- Landing gear
- Pylons
- Seat tracks (wet areas)

Historical trend on Fuel reduction

A320neo

20% less CO_2
in the future.

The A320 single-aisle jetliner family is the world's best-selling single-aisle aircraft family.

It is used in a full range of services from very short-haul airline routes to intercontinental segments, on operations from challenging in-city airports to high-altitude airfields.

The A320neo (new engine option) is the latest of many product upgrades as Airbus continues to invest around 300 million euros a year in innovation for the A320 Family.

The A320neo today offers a 15% fuel burn savings compared to current single-aisle aircraft operations, and is set to increase to 20% in the future, spurred by further developments to the new engine options (CFM International's LEAP and the PW1100G PurePower from Pratt & Whitney) and sharklets as well as cabin optimisation.

Sharklets

deliver up to 4%
in fuel burn savings.

Induced drag is a consequence of the wing producing lift, which is generated by an imbalance between the pressure on upper and lower wing surfaces. Air naturally flows from high to low pressure regions, this imbalance results in a tip vortex, which is why the lift-dependent-drag is also called vortex drag.

The lift-dependent-drag is inversely proportional to the square of the span, thus an obvious way to reduce drag is to increase the span. However, this is not always possible, due to the gate sizes category at an airport.

Adding a sharklet is a way to increase the aerodynamic span and reduce the tip vortex while still fitting within these constraints.

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Air Traffic evolution & CO2 budget

Passenger traffic expected to grow at 3.6% from 2019 to 2041

Source: ICAO, Airbus GMF

Air Traffic **could** (or not) double in next 20 years
(Forecast ~ + 3.6% / year) after Covid19 crisis

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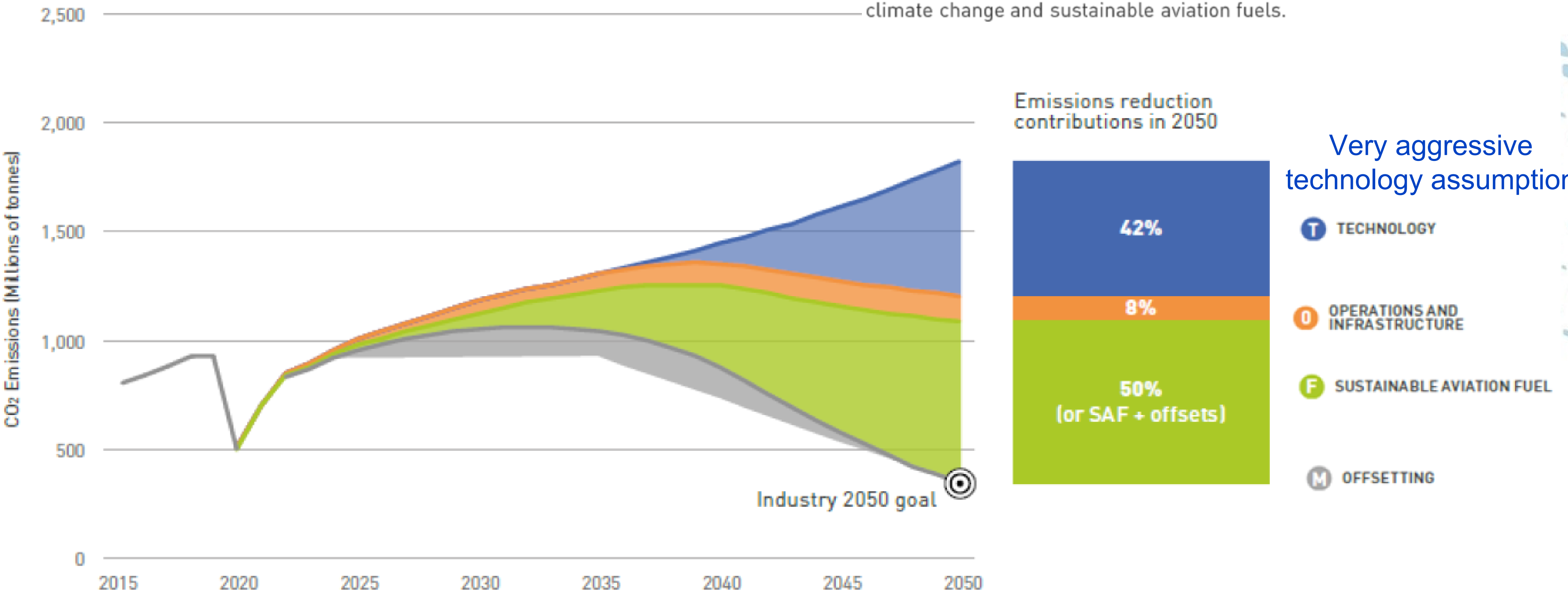
Air Traffic evolution & CO2: ATAG view

ATAG -Waypoint 2050: international aviation scenarii to achieve industry targets

The Air Transport Action Group (ATAG) is a highly respected not-for-profit association that represents all sectors of the air transport industry.

The role of ATAG is to bring together all sectors of the global aviation industry and provide a forum in which to address issues that affect us all. In recent years, much of ATAG's work has focused on the sustainable development of aviation, climate change and sustainable aviation fuels.

Example of Scenario: aspirational and aggressive technology perspective



Very aggressive technology assumption

ATAG Scenarii built to remain within the +2°C temperature rise Vs pre-industrial level

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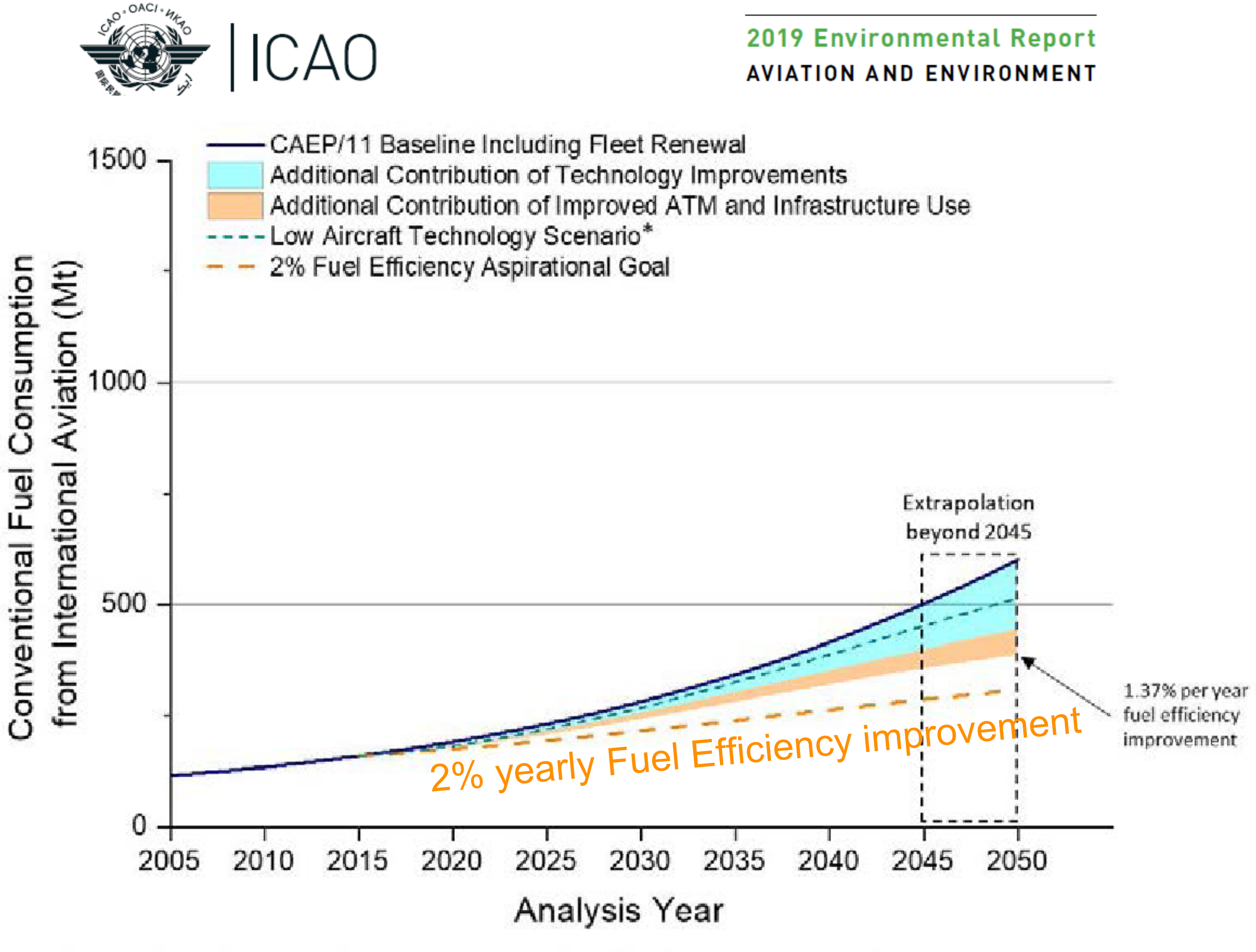
Air Traffic evolution & CO2: ICAO view

[Airbus Amber]



*Dashed line in technology contribution sliver represents the "Low Aircraft Technology Scenario."
Note: Results were modelled for 2005, 2006, 2015, 2025, 2035, and 2045 then extrapolated to 2050.

Even under the most optimistic scenario, the projected long-term fuel efficiency of 1.37% per annum falls short of ICAO's aspirational goal of 2% per annum. The long-term forecast fuel burn from international aviation is lower by about 25% compared with prior CAEP trend projections. This decrease can be attributed to a combination of more fuel efficient aircraft entering the fleet, as well as a reduction in the forecast long-term traffic demand. The computed 1.37% per annum long-term fuel efficiency includes the combined improvements associated with both technology and operations. The individual contributions from technology and operations is .98% and .39%, respectively. The .98% is slightly lower than the 1.3% cited in the latest CAEP/11 Independent Experts (IE) Review for single aisle aircraft.

Lower Technology gain assumption Vs ATAG
➔
More « non technology » effort to be done

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CO2 regulation

- Metric description:

1 / (SAR * RGF$^{\beta}$) vs. MTOW

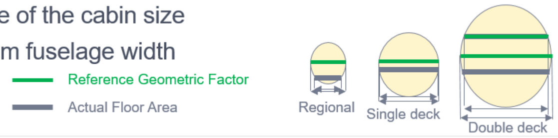
(where SAR = Specific Air Range, RGF = Reference Geometric Factor & beta =0.24)

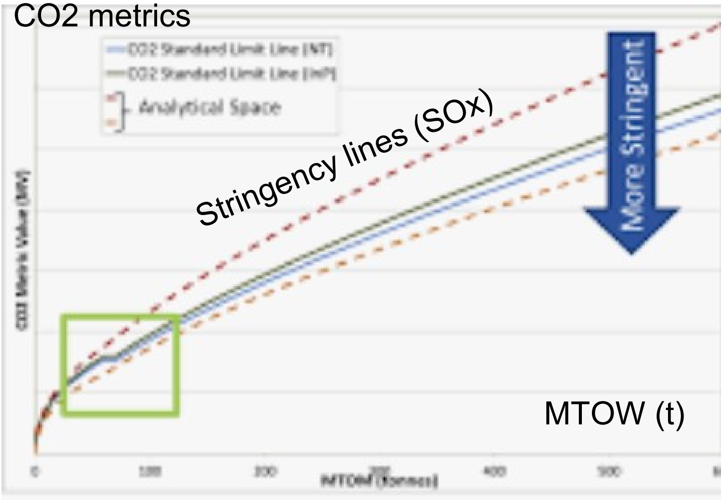
β= 0.24

- Test points: SAR evaluated at 3 test points with equal weighting measured at optimum conditions: MRC, optimum pressure altitude
  - ✓High Gross Weight: 92% MTOW
  - ✓Low Gross Weight : (0.45 MTOW +0.633 MTOW $^{0.9241}$)
  - ✓Medium Gross Weight: average weight

NOTIONAL EXAMPLES

- RGF$^{\beta}$: is a measure of the cabin size measured at maximum fuselage width





New CO2 standard- CAEP Feb 2016

New Aircraft Types

→ for MTOW> 60t SO8.5 @-36% as of 2020

In Production Aircraft Types

→ for MTOW> 60t SO7 @-33%

as of 2023 with full production cut-off in 2028.

From January 2020, regulation on CO2 applies. For A330neo:

- A330-900 certified on 21 May 2021 (251 t version in April 2022)
- A330-800 certification in S2 2022

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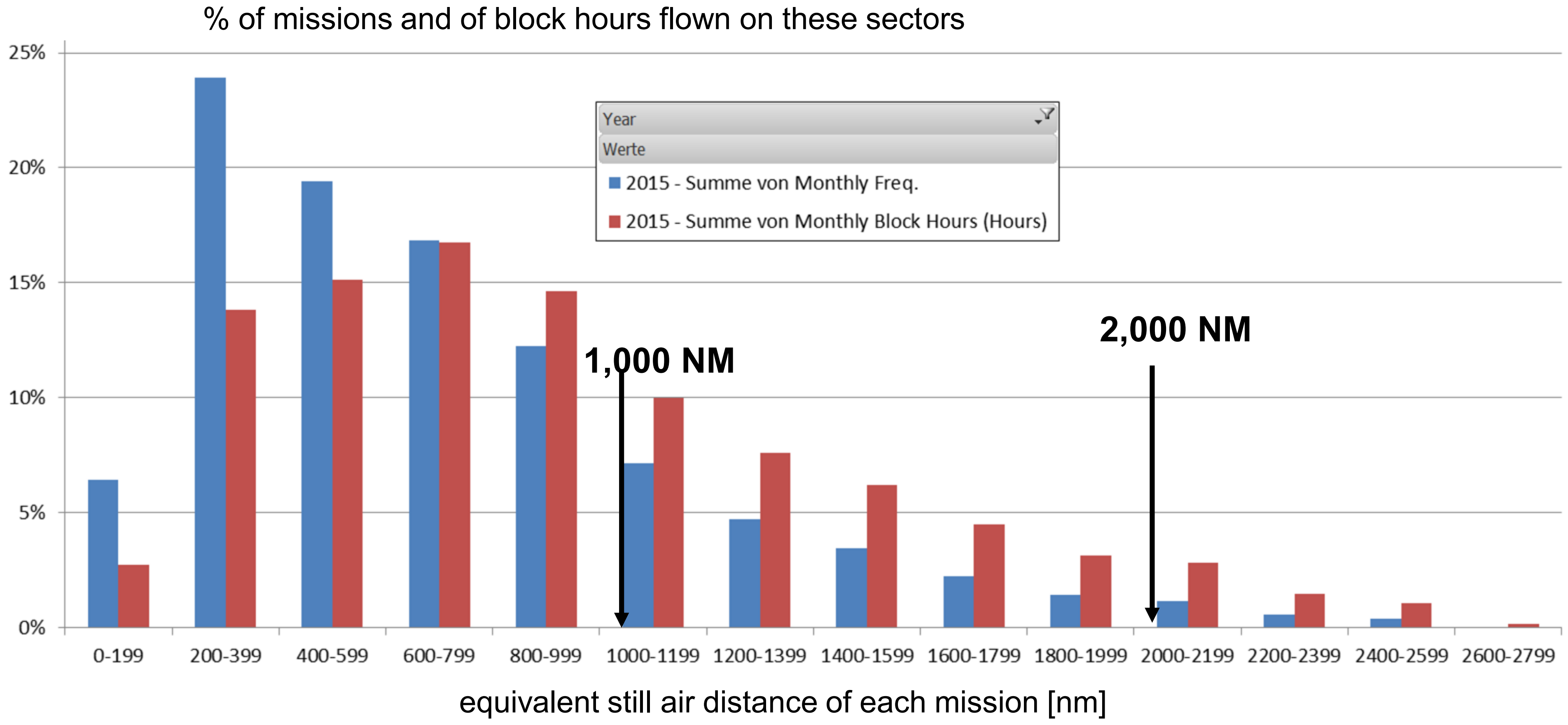
Operational Ranges of Short Range Aircraft

[Airbus Amber]



Single Range Aircraft much shorter average range than maximum range

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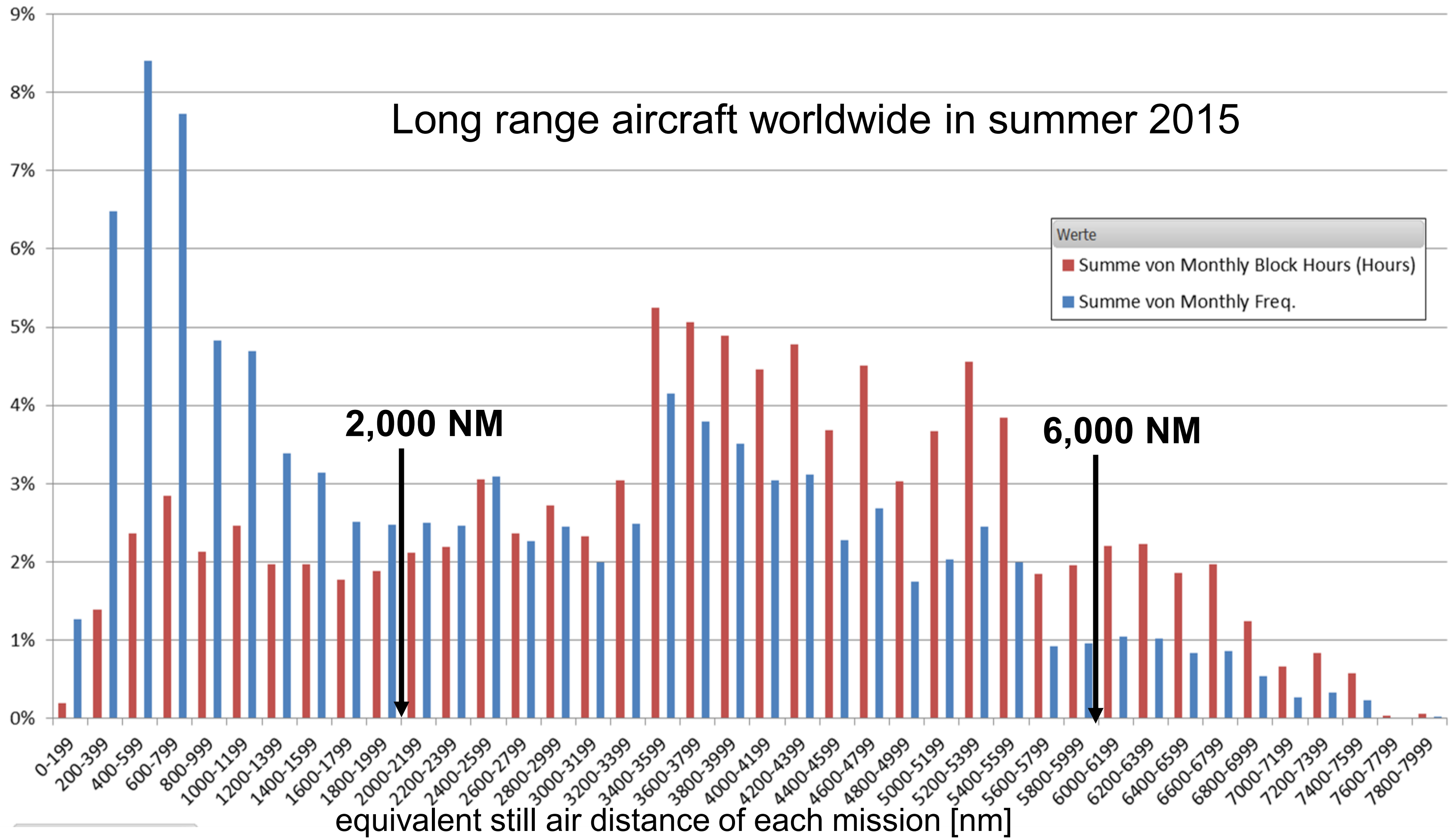
Operational ranges of Long Range Aircraft

[Airbus Amber]

% of missions and of block hours flown on these sectors



Long Range Aircraft operate on wide band range

Extract of TLARs*: Performance requirements & others

[Airbus Amber]

* Top Level Aircraft Requirements

- Capacity over range (watch the conditions)
- Initial climb altitude capability
- Take off field length (watch altitude & temperature)
- Approach speed (e.g. visibility limits change at 141kts)

- Landing distance
- Max altitude
- Max cabin altitude
- Max noise (QC level, Margin vs Chapter 4 or 14…)
- OEI ceiling…

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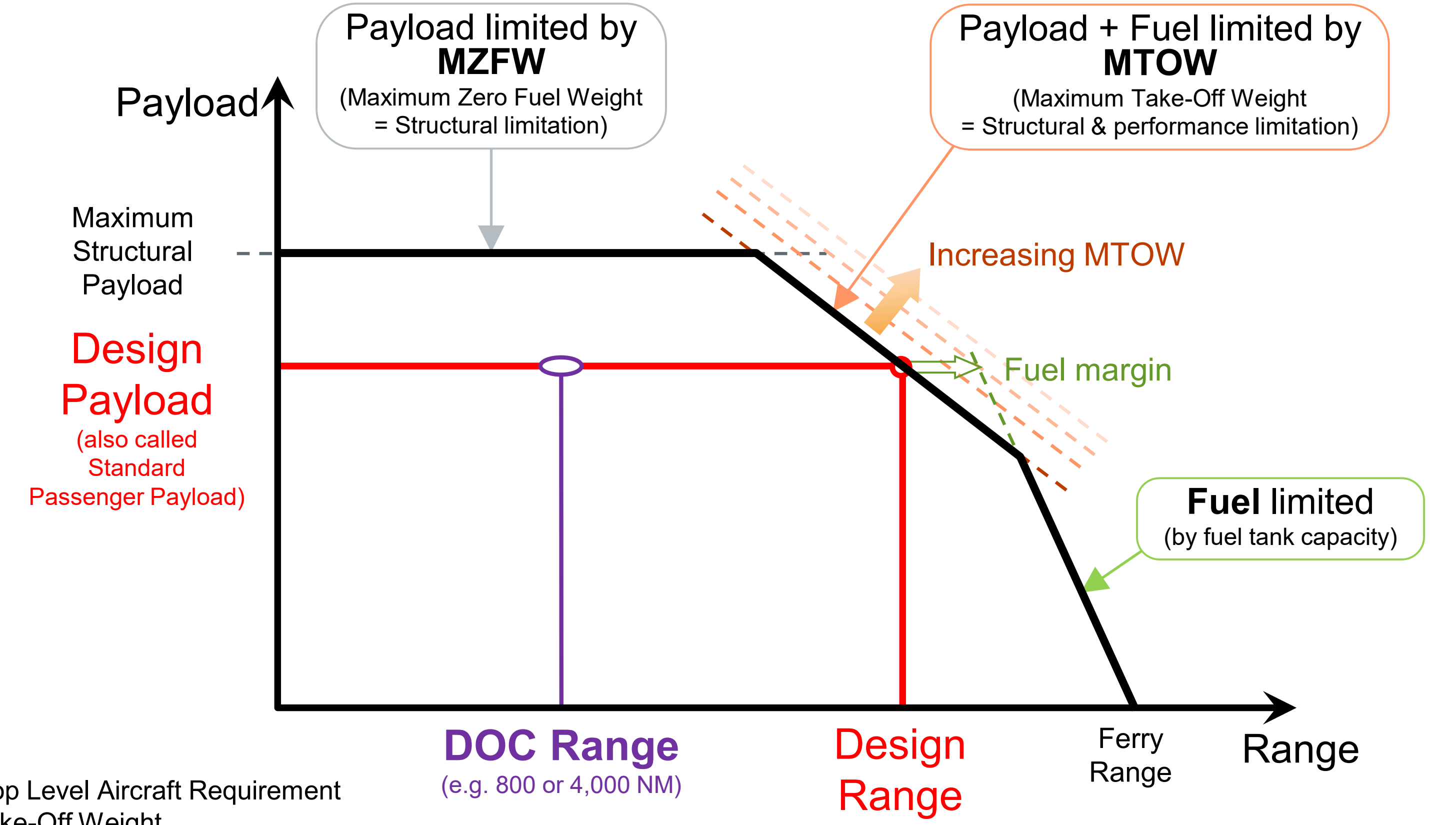
TLARs: Aircraft Capability or Payload - Range diagram

[Airbus Amber]

First Perfo TLARS:
Payload-Range at Mach target and:
✓ TOFL (Take Off Field Length)
✓ TTC (Time to Climb or ICA*)
✓ Approach Speed

* ICA= Initial Climb Altitude

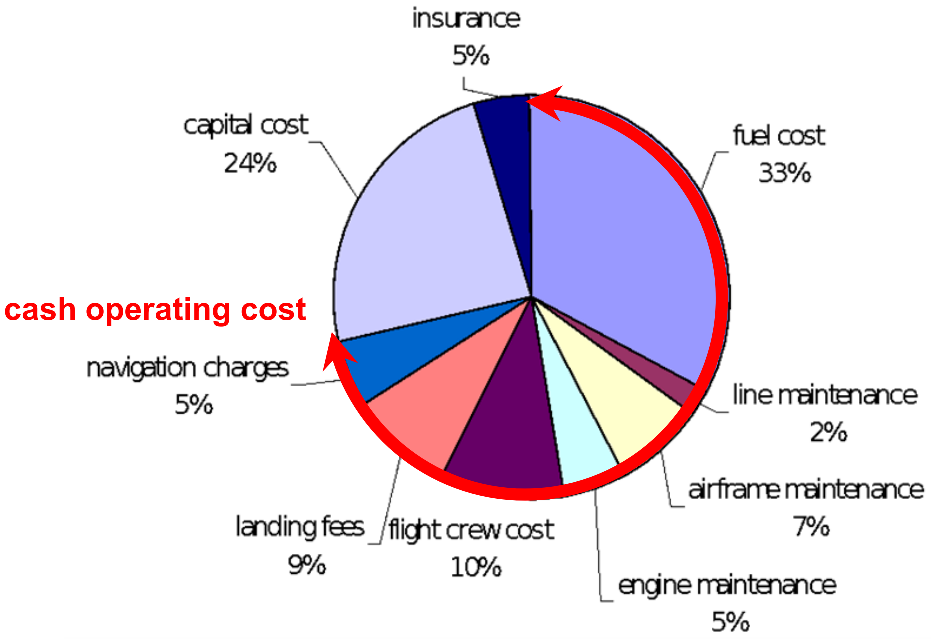


TLAR: Top Level Aircraft Requirement
TOW: Take-Off Weight
LW: Landing Weight
ZFW: Zero Fuel Weight
OWE: Operating Weight Empty
MWE: Manufacturer Weight Empty

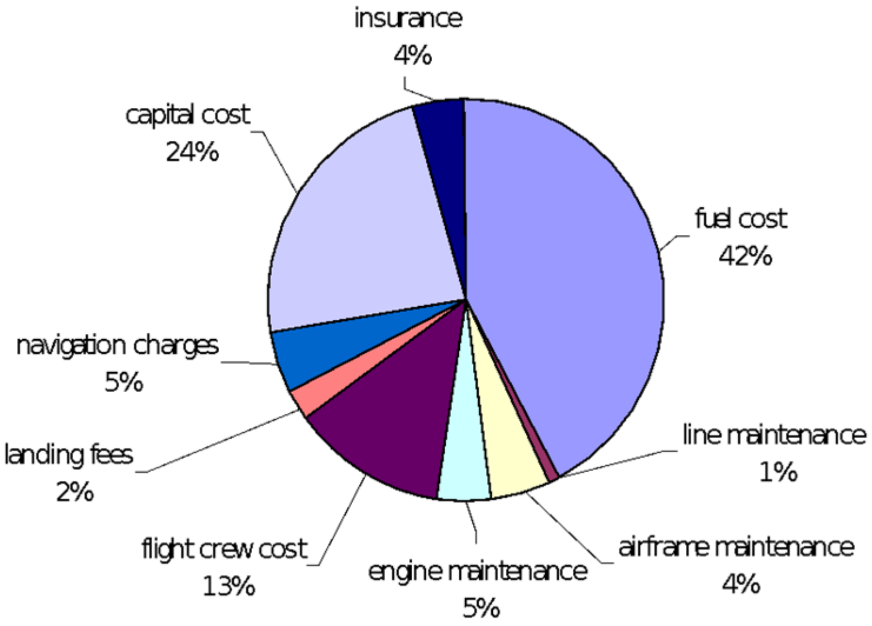
Economic Requirements or Objective: Direct Operating Costs (DOC)

[Airbus Amber]

Short range aircraft
used at 500nm
2000 trips/ year



Long range aircraft
used at 4000nm
500 trips/ year



On Operational point of view, fuel is an important factor but there are other significant costs to be accounted

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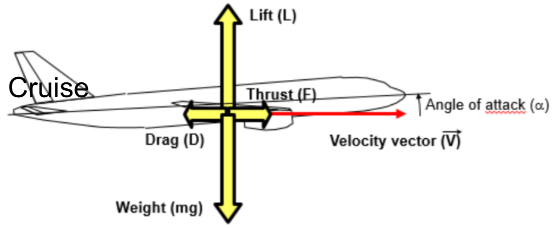
Aircraft Fuel Efficiency: Energy & Efficiency Approach

[Airbus Amber]



Lift force equation: $mg = L = \frac{1}{2}\rho V^2 S C_L$

Propulsion force equation: $F = D = \frac{1}{2}\rho V^2 S C_D$

➔ **F = mg / L/D** (where L/D = Lift over Drag ratio)

1/ **Propulsive Energy** (Ep) based on cruise values

Thrust (F) x Range travelled (R) = **mg / L/D** x R

➔ **Reduce Weight & Increase L/D**

2/ **Combustion Energy** (Ec): η is overall engine efficiency (thermodynamic x propulsive)

Ec = Ep / η ➔ **Improve engine efficiency η** (close to 40% in cruise now)

3/ Correct for the “non-cruise phases” (i.e. add ~30% on 500 NM and ~10% on 2000 NM)

4/ Calculate Fuel burnt with 43 MJ/kg, function of Range

5/ Let’s do it for m~100 t, L/D= 20, R= 1,000 NM, η= 0.4 and add 20% for non-cruise phases

Ep= 9.08 10^{10} J (90.8 GJ) - Ec= 2.27 10^{11} J (227 GJ) - Corrected Ec= 2.73 10^{11} J (273 GJ) - Fuel = 6337 kg (~6.3 t)

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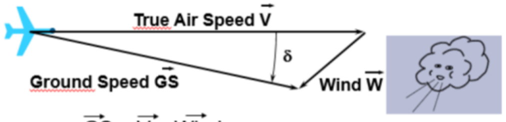
Aircraft Fuel Efficiency: Specific Range (SR) in Cruise *(or how to maximize range for a given fuel quantity)*

$$\textbf{Specific Range (SR)} = \frac{\textbf{Distance travelled}}{\textbf{Mass of fuel burned}} \quad \begin{matrix}\text{(e.g. NM)}\\ \text{(e.g. kg)}\end{matrix}$$

Note: Distance over fuel, i.e. inverse of car consumption expression in EU



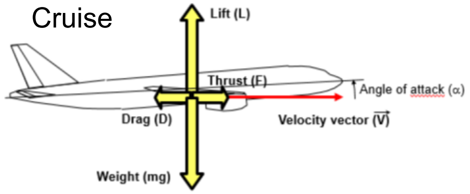
$\vec{GS} = \vec{V} + \vec{Wind}$ - δ is the drift angle

No wind ➔ GS= TAS

$$= \frac{\textbf{True Air Speed (TAS)}}{\textbf{Fuel Flow (FF)}} \quad \begin{matrix}\text{(e.g. NM/hr = kts)}\\ \text{(e.g. kg/hr)}\end{matrix}$$

$$= \frac{a\,M}{SFC\,.\,Thrust} = \frac{a\,M}{SFC\,.\,mg\,/\,L/D}$$

Cruise



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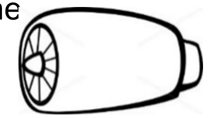
Propulsion force equation: $F = D = \frac{1}{2}\rho V^2 S\, C_D$

➔ **F = mg / L/D** (where L/D = Lift over Drag ratio)

$$\textbf{SR} = \frac{\textbf{a M L/D}}{\textbf{SFC mg}}$$

Aerodynamics

Engine



Weight

a: Sound velocity
M: Mach number
L/D: Lift over Drag
SFC: Specific Fuel Consumption
m: Aircraft mass (often called "weight")

SR needs to be maximised to minimise fuel

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How to further reduce Fuel consumption in the Future?

- Fuel Benefit values provided are **indicative** only
- Time horizon considered is **~2050**
- Overall around **25%-30%** fuel reduction at Aircraft level can be expected at iso requirements (thus on CO_2: 1kg fuel ➔ 3.16 kg CO_2).

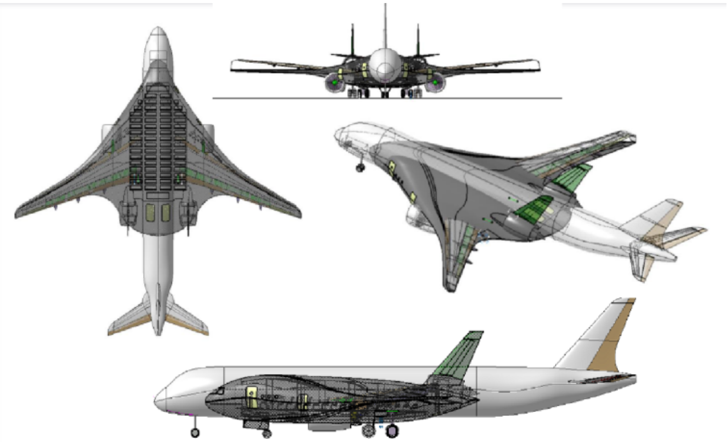
Warning: the potential benefit for each techno or from each "element" should not be simply added (not always compatible – cumulative)

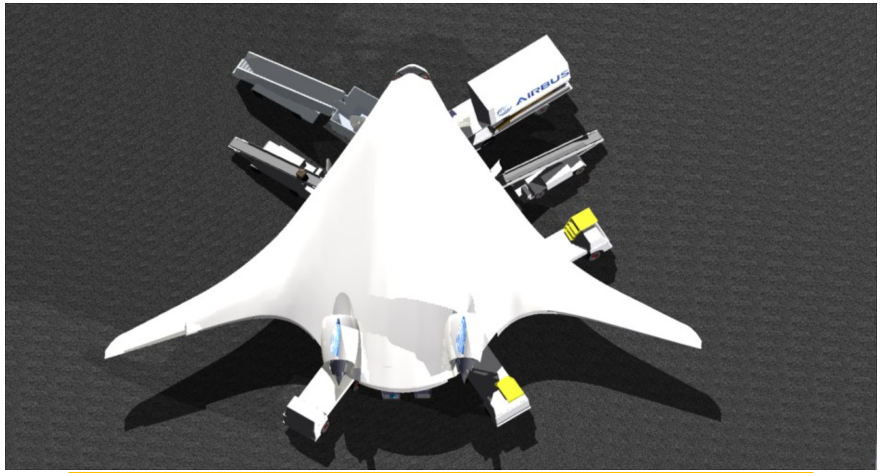
- The presentation starts by an overview of **alternative concepts**, then envisage **alternative component arrangement** for "conventional" configuration.
- A global picture on **key enablers** for fuel reduction on a conventional configuration is presented
- Then, **propulsion, aerodynamics and weight** potentials are presented
- Potential from "Reduction" of **Requirements** (TLARs) is introduced
- Finally, **Operation** improvement is mentioned

Note: Some of the previous aspects are covered briefly since more largely covered in other lectures

More unconventional: Flying wing illustration

[Airbus Amber]





Benefits

- blended surface
- lower overall empty weight
- L/D benefit (smaller wetted area)
- Fuel benefit
- engine noise shielding if on top

Penalties

- difficult ground access & emergency evacuation
- restricted CG flexibility
- difficult to stretch

Up to 10% fuel Potential?

Challenges

✓ Conventional configurations can be assessed more precisely than Unconventional configurations (more "empirism")

✓ More unconventional configuration have to highlight significant initial benefit in order to succeed (risks but also opportunities to be assessed)

Flying wing looks one of the most promising alternative concept for fuel

Conventional Configurations: Selection of Concepts

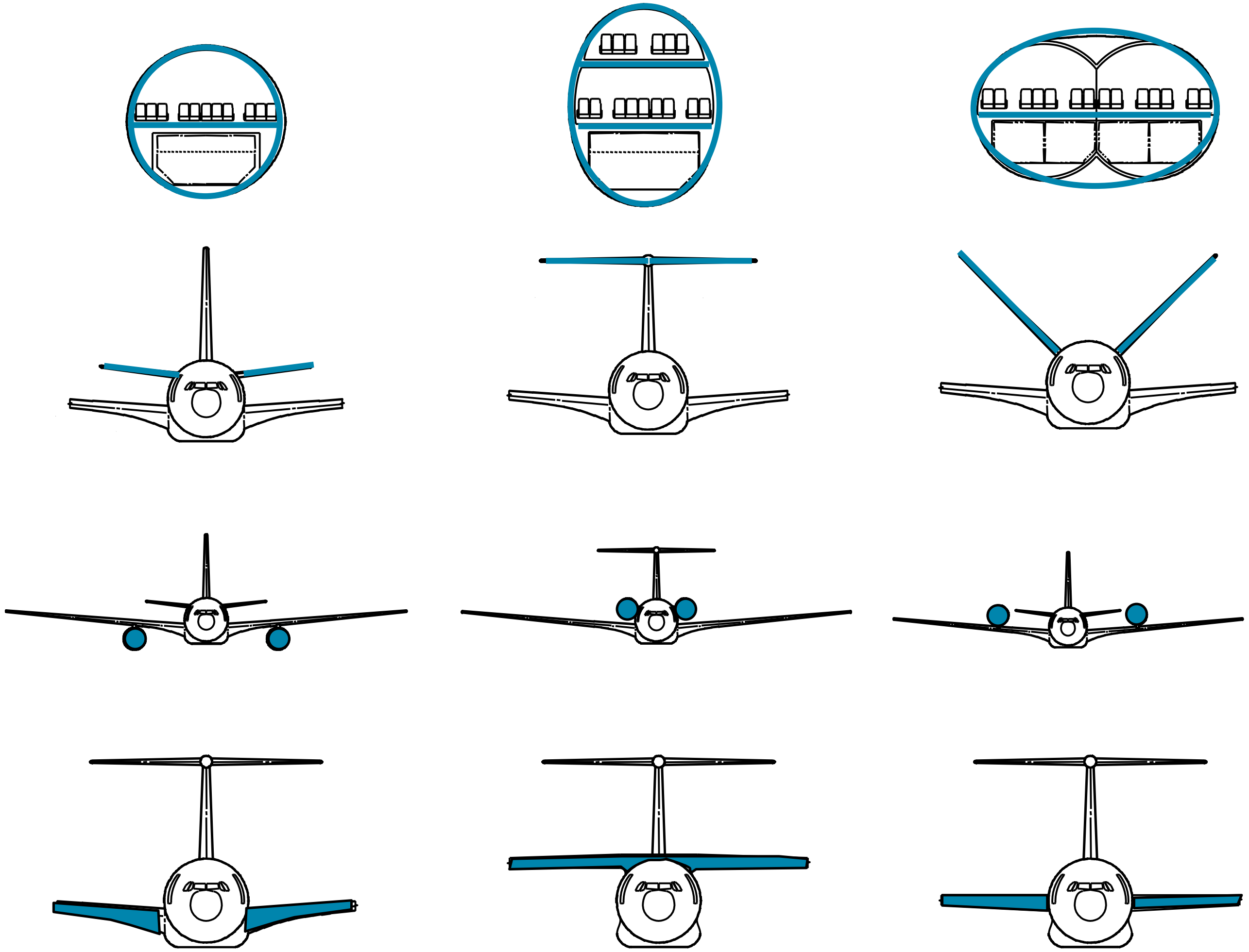
[Airbus Amber]

cross section

empennage

engine integration

wing position



For “conventional” configuration: limited fuel efficiency dispersion

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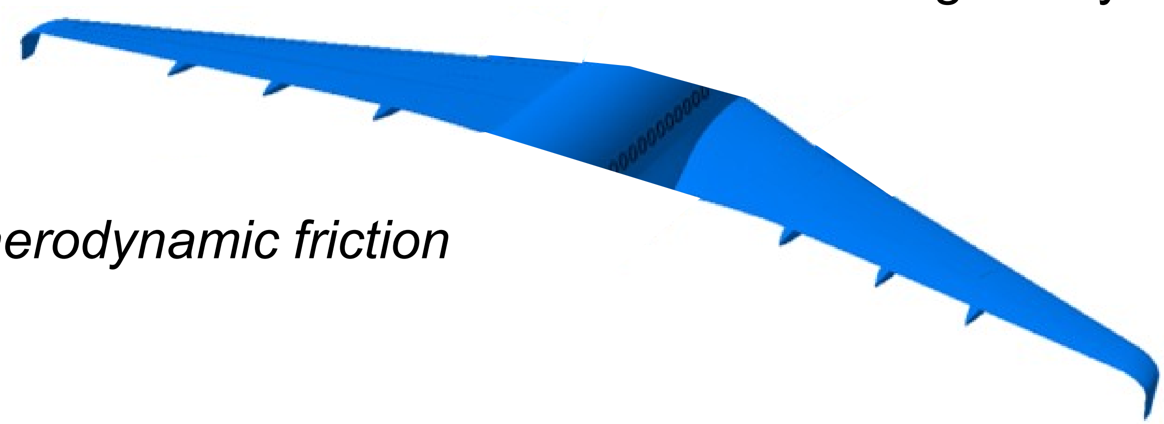
Overall Aircraft classical options for a given configuration type

[Airbus Amber]

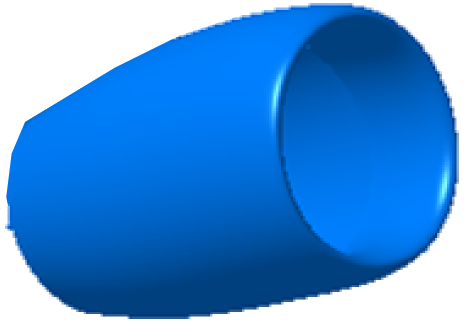
Longer wing **Span**
shorter wing chord

Lighter structure weight
lighter systems weight



Lower aerodynamic friction

More efficient Propulsion:
- Greater engine bypass flow
- Higher core compression ratio



Up to 20-25% fuel Potential?
At iso TLARs (Range, Mach…)

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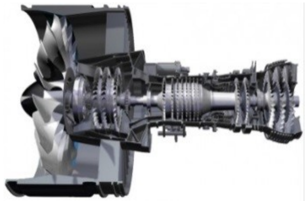
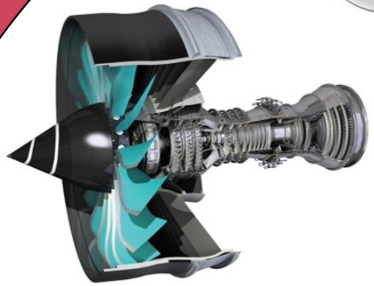
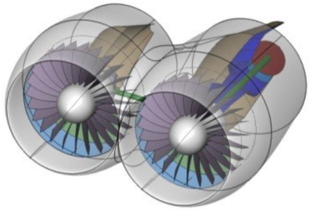
Propulsion: Perspectives & New Concepts

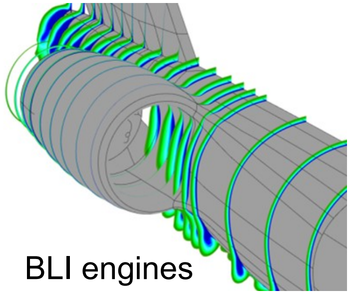
[Airbus Amber]

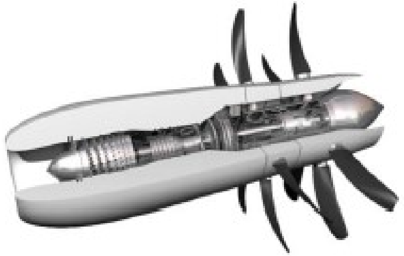
A path towards better propulsive efficiency


Advanced Turbofan
A350, NEO


UHBR Turbofans


Multi-fans


BLI engines


Open Rotor engines

Covered by Propulsion lecture


360° BLI


Distributed Propulsion


Hybrid Electric
Propulsion

Longer term radical concepts

Up to 15-20% fuel
Potential?

All options to require highly integrated airframe & powerplant design

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Aerodynamics

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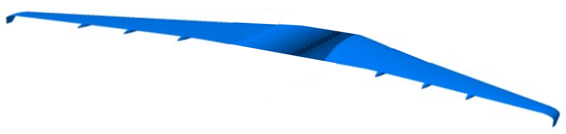
Longer wing **Span**

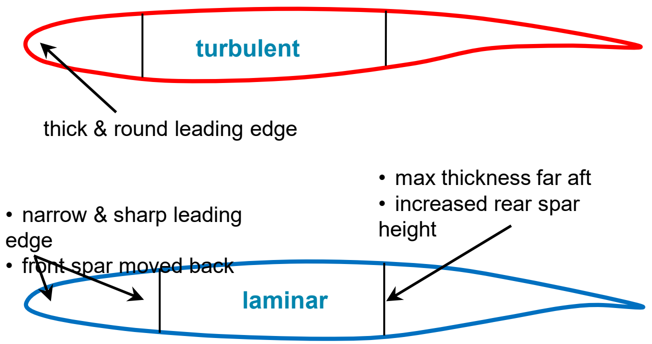
shorter wing chord

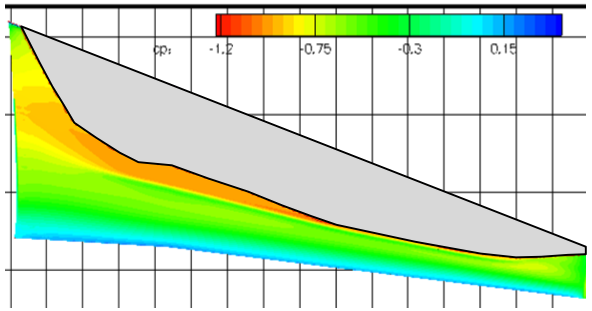


Lower **Friction:**

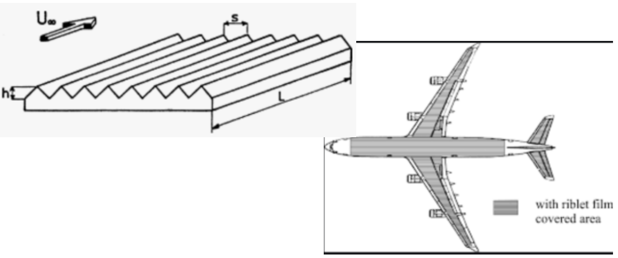
<u>**Laminar** flow on wing, tails, nacelles</u>

- <u>natural</u> laminar flow if **sweep** angle is sufficiently low
- <u>hybrid</u> (assisted by suction) laminar flow if too much sweep or too fast
- low surface imperfection (1/2 as of today) and waviness - no steps or gaps





Up to 5% fuel Potential?



Riblets

- small, sharp “mountain chains” in flow direction like on a Vinyl record
- wear needs rework after some time

Up to 2% fuel Potential?

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Weights

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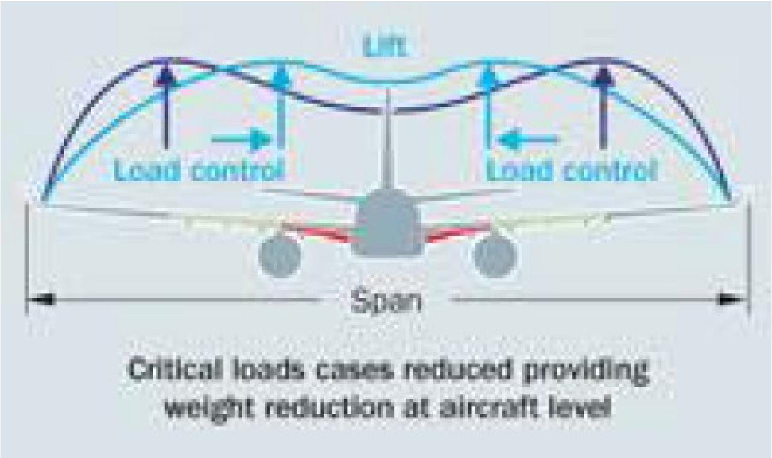
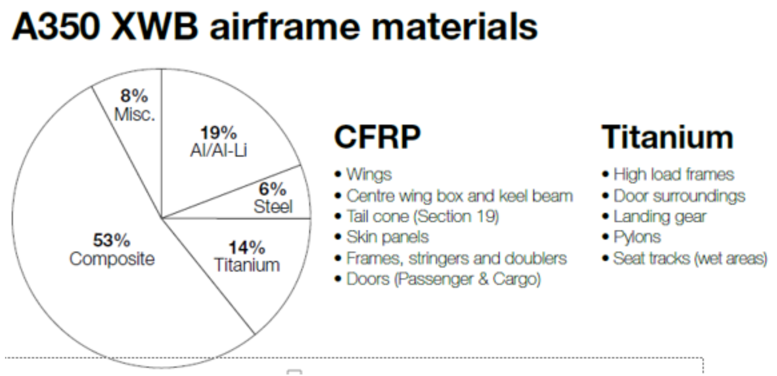
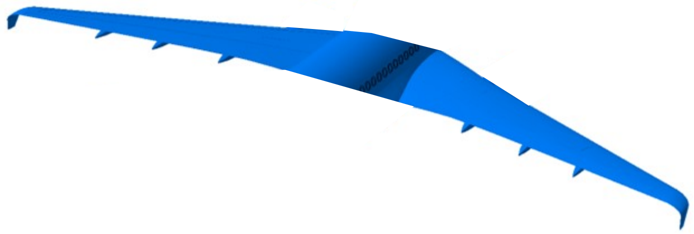
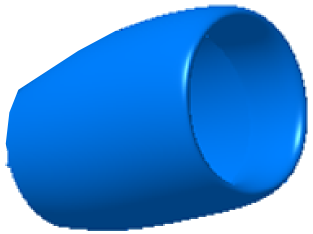


Loads Reduction



Materials: CFRP…





Up to 5% fuel Potential?

Configuration aspects: high span, high BPR engines, More safety & Comfort…

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Requirements (TLARs) reduction: Value & Cost

[Airbus Amber]

PROCESS

TLAR „sensitivities“

- constant concept
- constant technology level
- change TLARs, e.g.:
  - Longer range
  - Slower approach speed
  - Faster climb
- resize configuration:
  - larger wing
  - larger empenage
  - larger engine
  - longer gear
  - heavier structure
- estimate efficiency effects:

  4snowballed weight
  - Fuel burn
  - COC (Cash Operating Cost)

Lower Design Range

Range -30%, e.g.:

- 2,000 NM instead of 3,000 NM
- 5,000 NM instead of 7,000 NM

-5% fuel

Lower Mach number

Mach -0.05, e.g.:

- M0.75 instead of M0.8
- M0.8 instead of M0.85

-5% to -10% fuel

with indirect effects (e.g. propeller)

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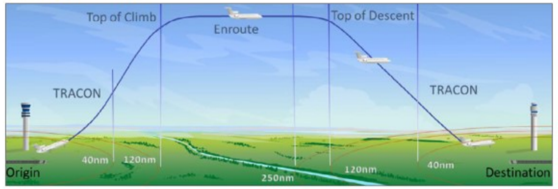
Operations

[Airbus Amber]

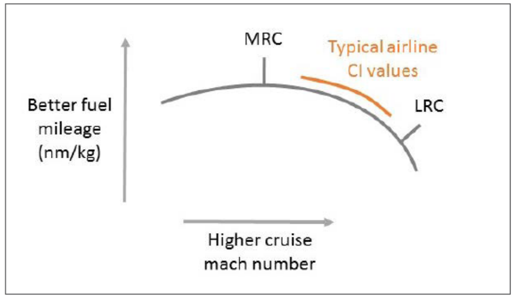
FIGURE 1: Phases of Flight



Redistribution of Necessary Delay in the US National Airspace System: Benefits from Trajectory-based Operations

Optimize trajectories, reduce delays

FIGURE 3: The Relationship between MRC and LRC Speeds

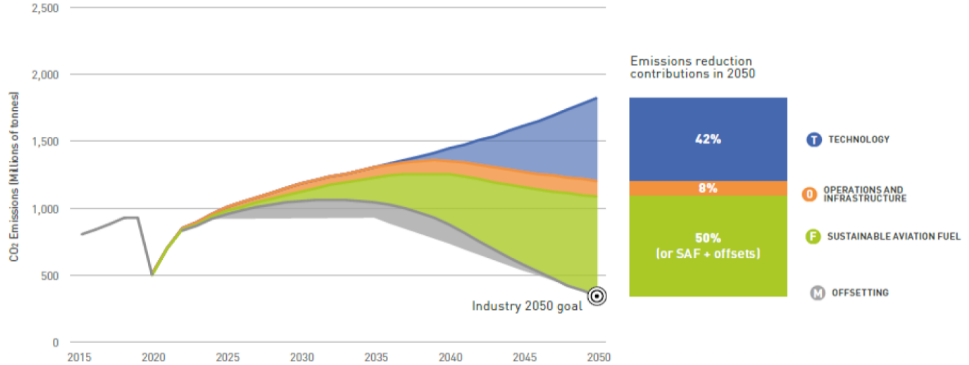


Cost Index: Optimize Speed (Mach number)

Formation flight…

ATAG -Waypoint 2050: international aviation scenarii to achieve industry targets

Example of Scenario: aspirational and aggressive technology perspective



ATAG scenarii built to stay within the 2° temperature rise vs pre-industrial level

-8% fuel

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Agenda

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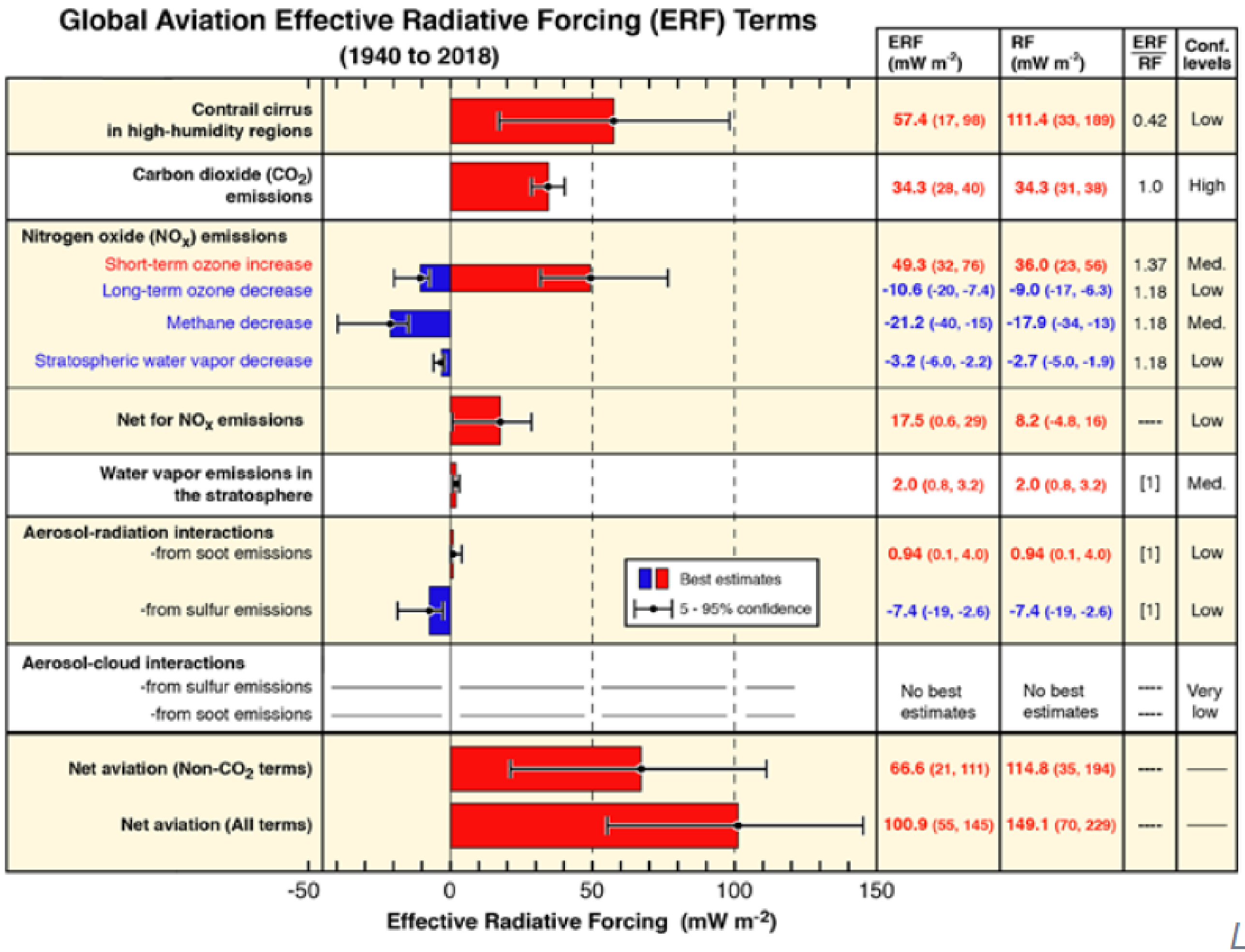
- **Other considerations on Climate Impact**
- Alternative fuels & energies
- Conclusion

Climate Impact

[Airbus Amber]



	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions -from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions -from sulfur emissions / -from soot emissions	No best estimates	No best estimates	---- / ----	Very low
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	—
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	—

[Airbus Amber]

Total anthropogenic forcing in 2011:
2.29 W/m^2 (mainly CO_2 & CH_4)

Aviation fraction vs anthropogenic:

CO_2 (in 2018)	2.4 %
total (in 2011)	3.5 %

Aviation ERF by origin:
- 33% from CO_2
- 17% from NOx (net effect)
- 55% from contrail-cirrus
- Others: water, soot, sulfur

Black bar is confidence level at 90%:
Total impact is between 1.7 to 4.3 of impact of CO2 only.
At 1 "sigma" (standard deviation= 68.2'
this reduces to a ratio between 2.2 to 3

Lee et al., 2020

But this ERF chart is not fully suitable for aviation policy makers:
- look at past emissions, not future; non CO_2 effects seem to increasing faster than CO_2 alone
- Challenges related to comparing short-lived & long-lived forcing components
- *No direct link to T° objectives quantification*

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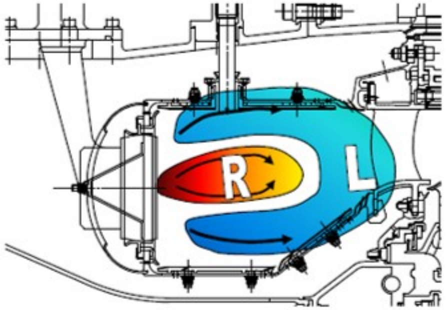
Aviation with reduced climate impact - September 2022



LEAN Burn Combustion – Engine

- NOx significantly reduced
- nvPM (non volatile Particle Matters) hugely reduced which would lead to much less persistent contrail formation

CONTRAILS

- The current issue is about **persistent**, “Long-lasting contrails”, especially formed at the end of the day and during night (some daytime contrails are even cooling)
- They appear when crossing **ISSR** (Ice-Supersaturated) regions, depending on **exhaust gas composition & properties**

Aviation with reduced climate impact - September 2022

- Most of the sources tend to show that flying at much lower altitudes, let's say at ~25,000 ft (instead of current 33,0000 ft – 39,000 ft "average" altitudes) would significantly reduce both NOx effects & persistent contrails formation
- However, for current Aircraft that would go with a fuel penalty of 20-25% at iso Mach number; Reducing the Mach number at these low altitudes would "damp" this penalty (by ~10%) but it would remain significant
- For a new design, in order to target these low altitudes, the Mach number should significantly be reduced, lets' say M<0.6; this raises several operational, economical challenges and which may hardly acceptable for Long Range applications (at the opposite, this is acceptable for Regional applications)
- Previous options (Lean Engine - Contrail avoidance – SAF= next page) are probably much better

Flying always low does not appear as the best option
(at least with current Mach)

Agenda

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- **Alternative fuels & energies**
- Conclusion

Aviation with reduced climate impact - September 2022

- "Sustainable" means (much) "reduced CO2" Life Cycle (LC) Vs Kerozene and also acceptable on a societal / food point of view
- SAF include a lot of different fuels, definitions, processes… such as:
  - ➢ Biofuels (from crops) but with food competition risk
  - ➢ From biomass: from forestry or agricultural wastes & residues = Up to 80% CO2 reduction (LC)

    - Airbus target ~ 2 to 3% by 2025 (still quite high costs) – certification under progress (up to 100% SAF)
  - ➢ **"Clean" PtL** (Power to Liquid): CO2 capture + clean H2 production (**maturity still low** & cost high)
- These fuels should also have "better properties", leading to much less NOx and nvPM (non volative Particule Matter) significantly beneficial on a climate impact point of view (but at very high cost today and with "scalability issues", at least at short-mid term).

SAF should significantly reduce Aircraft climate impact

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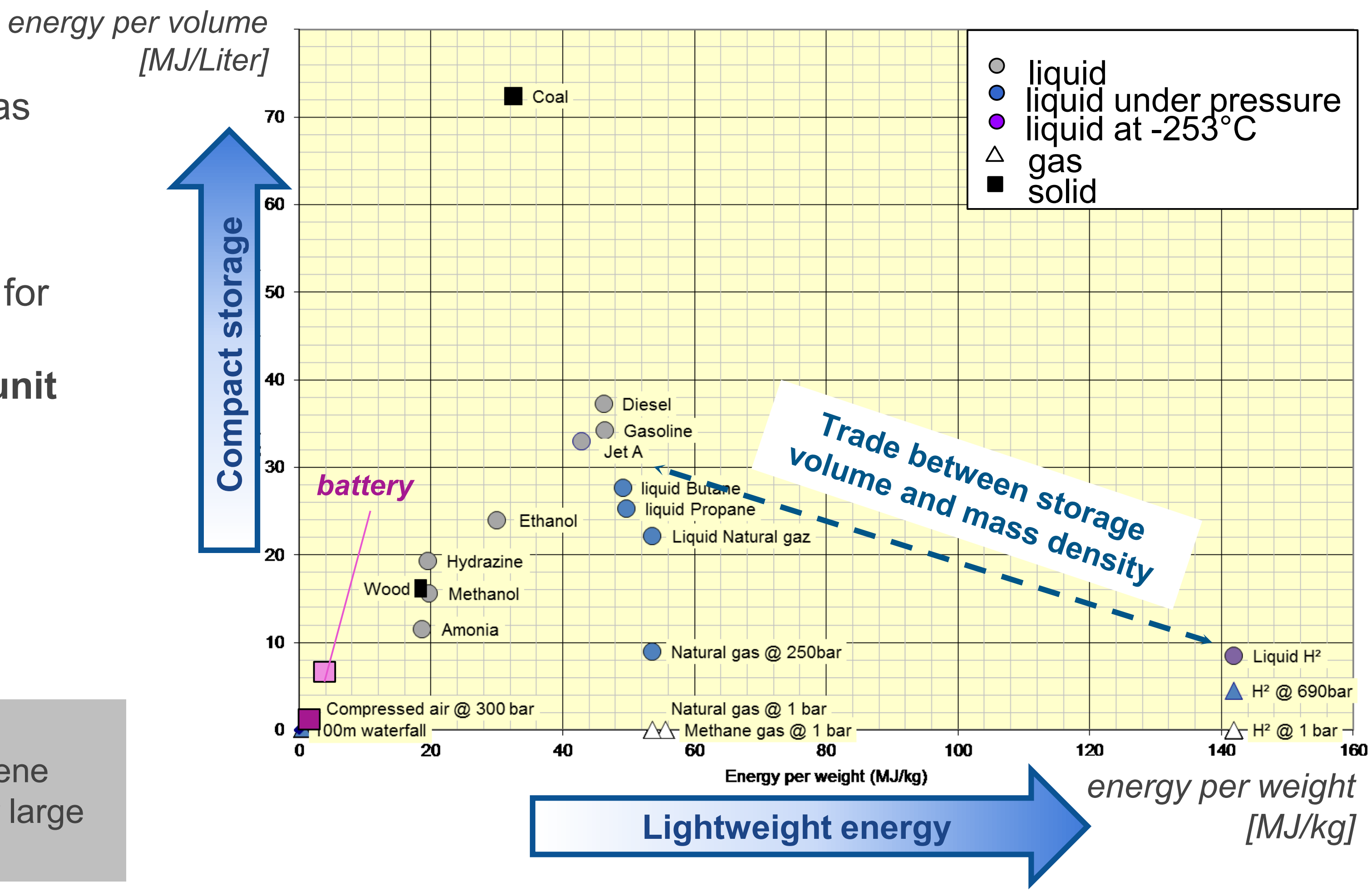
Hydrogen specificities | Why considering Hydrogen as fuel?

Most of fuel candidates are "carbon carrier" as kerozene ⇒ CO2 emissions remain

Amongst the **"carbon-free" energy carriers**, **Hydrogen** is expected to provide best efficiency for aeronautics:

- Hydrogen offers much **higher energy per unit of mass** than the other fuel candidates
- But Hydrogen as very low density => much **higher volume required for storage**

⇒ trade between mass efficiency and volumetric penalty



Batteries as main power supply?
Currently **50x higher weight** for same energy as kerosene (Panasonic 18650 as in Tesla or BMW) ⇒ not viable for large commercial aircraft

Hydrogen is the most promising "carbon-free" energy carrier for aeronautics

H2 aircraft architecture

[Airbus Amber]

Main aircraft architecture choices to define H2 aircraft concept

Hydrogen storage concept	Gazeous (high pressure); Liquid (cryogenic); Through NH3; ...
Hydrogen storage location	In wings; In fuselage; Above fuselage; Below wings; ...
Propulsion generation	Direct burn; Fuel Cells; Hybrid

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Hydrogen storage

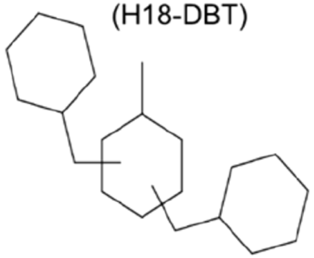
weight of storage per 1kg H2 for different carriers / technologies:

metal hydrid

50kg

Liquid Organic Hydrogen Carriers

perhydro dibenzyltoluene
(H18-DBT)



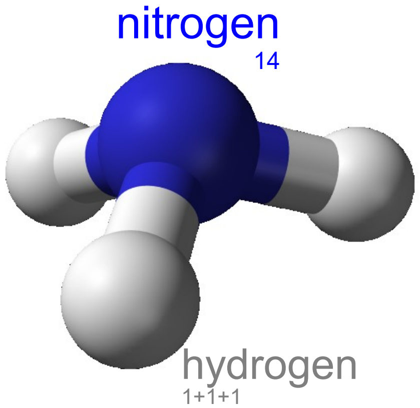
6.2 mass% H_2
(2.05 kWh/kg LOHC)

20-30kg

GH2 in pressure gas tank 300/700bar

15kg

Ammonia



liquid at -80 to -30°C

10kg

LH2 in double wall vacumm isolated tank

liquid at -273 to -252°C

2/3/4kg

LH2 in foam isolated tank

1kg

Cryogenic storage of liquid hydrogen is far lighter than any other means ⇒ most promising option for aeronautics

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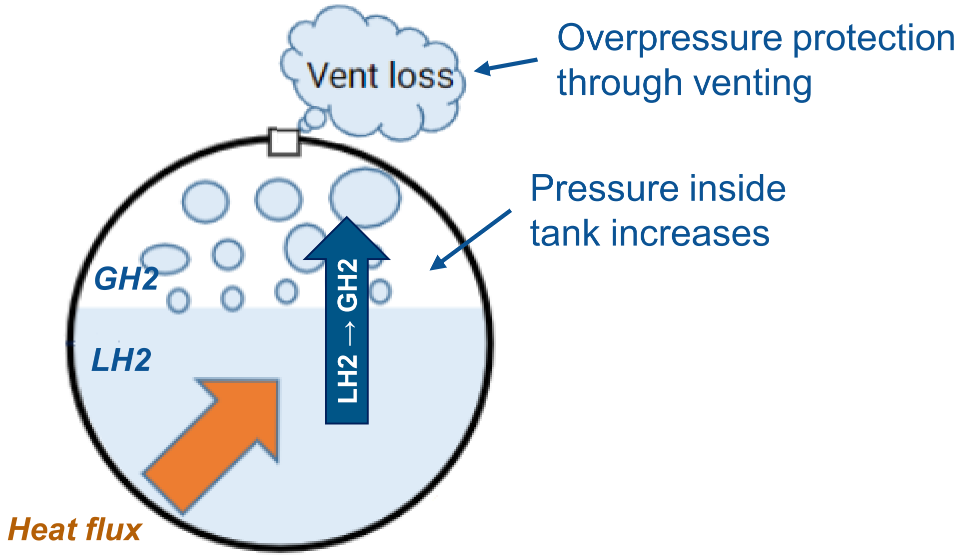
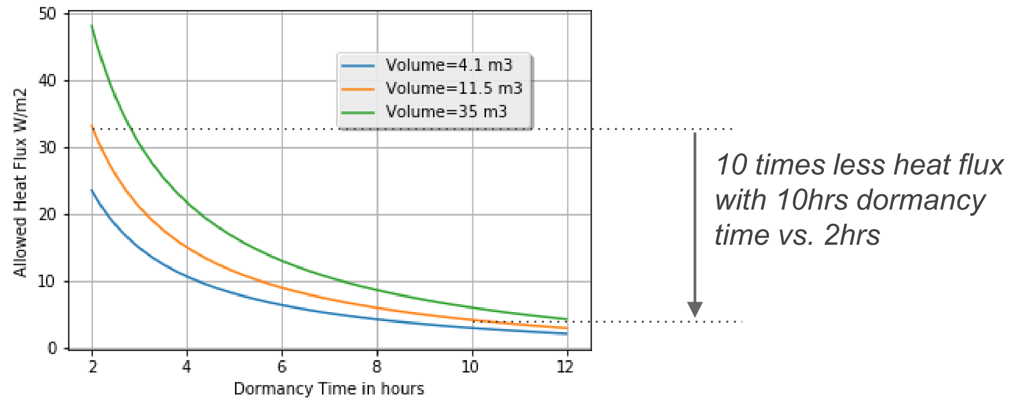
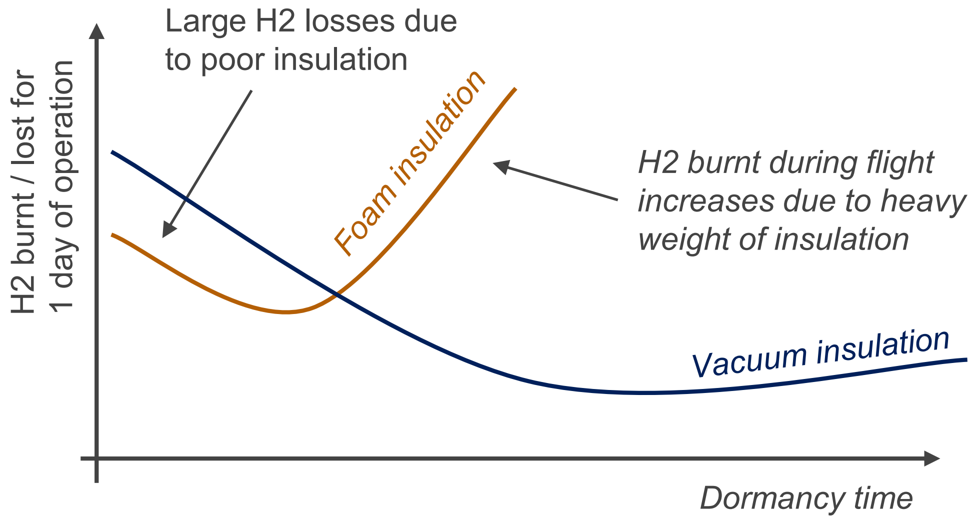
Hydrogen storage







Dormancy time: time before reaching max tank pressure leading to venting

Dormancy time objective depends of operational concept:

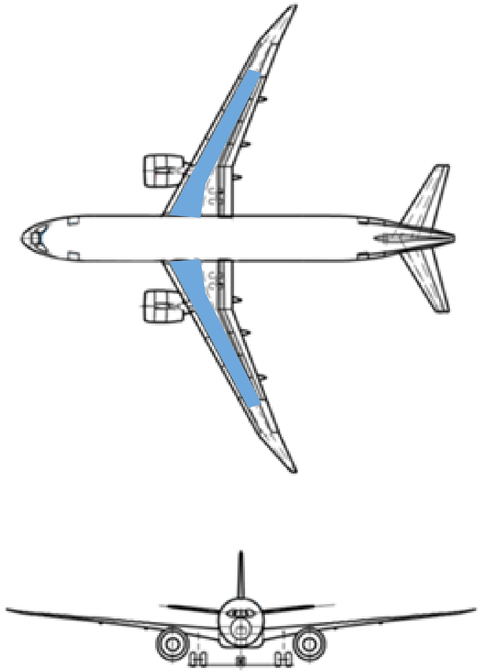
- Low dormancy time if to cover only the mission duration (ex: rocket launchers)
- Long dormancy time if we want to maintain filled LH2 tanks between operations (at airport gate for instance)

Choice of insulation technology depends on dormancy time requirements and operations concept

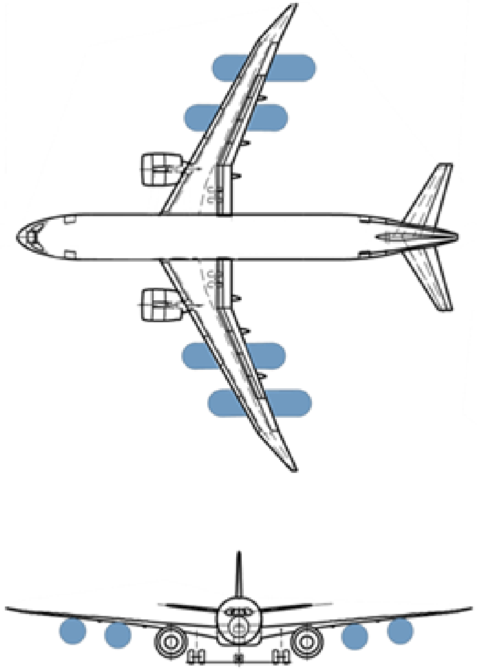
Where to store Liquid Hydrogen Tank ?

[Airbus Amber]

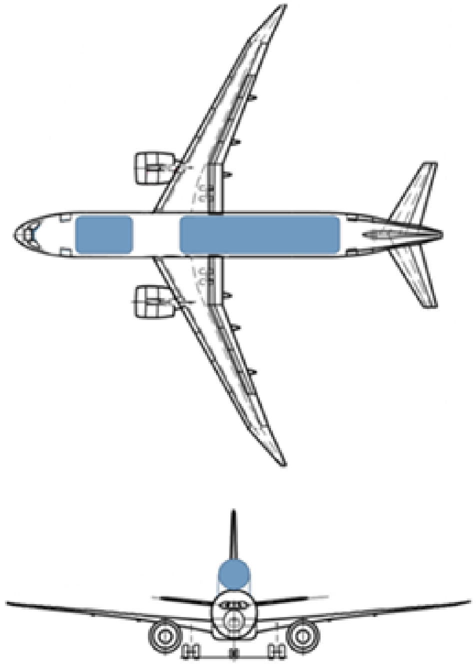
In wings??



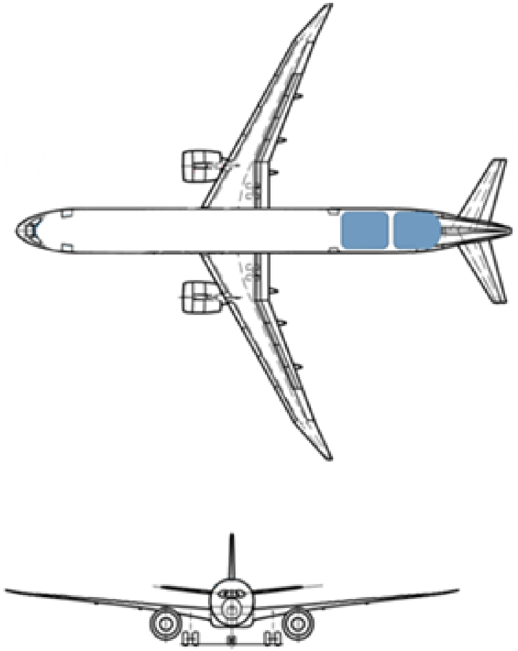
Podded



On top of fuselage



In aft fuselage



Other options

...

Liquid Hydrogen Tank storage | in pods

[Airbus Amber]

LH2 tanks installed in underwing pods

- New LH2 tank component decoupled from main airframe
- Can be manufactured as separate component
- Easy accessibility of the LH2 tanks for maintenance, replacement

- Additional wetted area ⇒ more aircraft drag
- Tanks exposed to external threats: bird strike, crash, ground equipments
- Limited H2 volume capability

- Aerodynamics interaction with wing
- Attaching heavy mass on the outboard wing: structural concept? Risk of flutter?

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Liquid Hydrogen Tank storage | on top of the fuselage

LH2 tanks installed on top of the fuselage

Limited wetted area increase, because of covered upper fuselage

Requires to create access door for daily maintenance and tank removal
Accessibility of the tank difficult due to height (≈5m to 7m)
Degraded lateral handling qualities

Structural attachment of heavy mass on top of the fuselage, crashworthiness
Structural concept and weight efficiency of such big fairing

Liquid Hydrogen Tank storage | in rear fuselage

LH2 tanks installed in rear fuselage

Very much integrated installation in standard fuselage concept
Very good ratio additional wetted area / available volume
Looks like a conventional aircraft

Requires to create access door for daily maintenance
Requires to define concept to allow full tank removal if needed
Aircraft longitudinal CG more aft

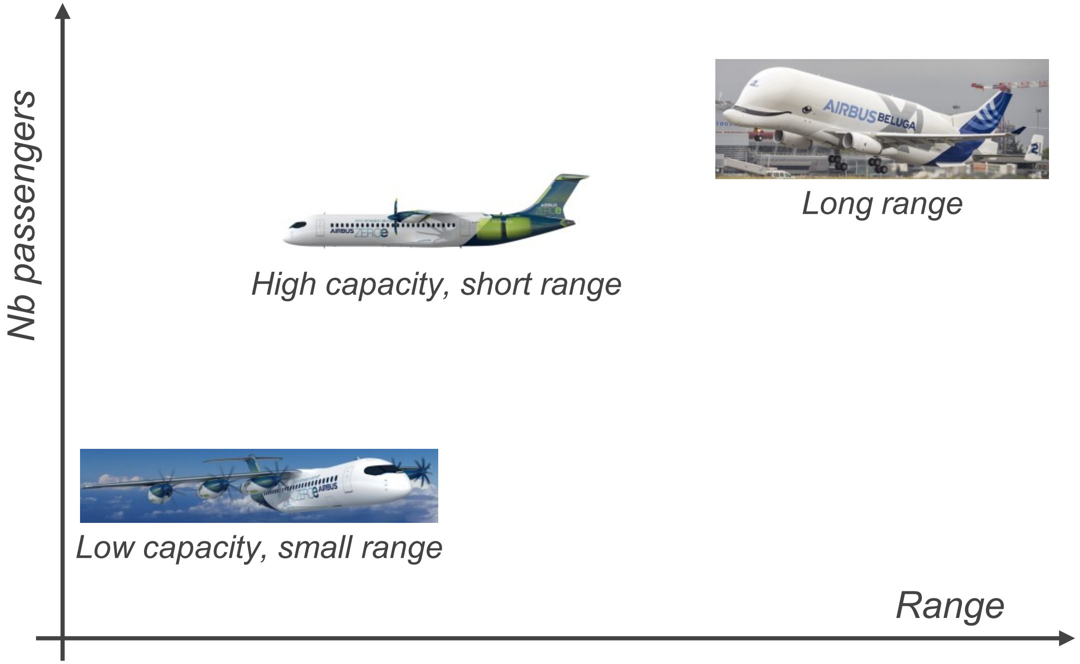
Safety acceptability of the close location of the two tanks
Impact of conical shape for the most aft tank on weight efficiency, manufacturing process

Liquid Hydrogen Tank storage | Conclusion

No obvious solution for LH2 tank installation on an aircraft

The choice of location of the LH2 tank depends on many parameters:

- Aircraft concept
- Market positioning
- Balance between accessibility / performance



Whatever the configuration, the installation of H2 tanks on the aircraft comes with **significant performance impact**:

- Additional wetted area
- Additional mass
- Additional complexity, maintenance

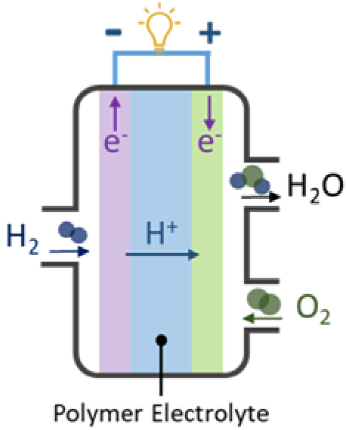
H2 tanks cannot be installed in standard airframe, requires additional volume and impacts aircraft efficiency

How to convert H_2 into thrust ?

H_2 Direct Burn

- Same principle as kerosene gas turbine but many components changed: (combustion chamber, Injectors, Cryo heat exchangers, H2 pumps…)
- Feasibility demonstrated since the 50's (B57)
- Small / no impact on overall aircraft architecture

H_2 Fuel Cells



- Produce electricity to power electric motors
- Water is the only by-product
- High efficiency
- Zero emissions (only water)

Propulsion system summary

[Airbus Amber]

H2 can be used to generate thrust either through direct burn or through Fuel Cell and electrical chain

		H2 direct Burn engine	Fuel Cell engine
	Mass	Lighter *≈ 2.5 to 3.5 kW / kg*	Heavier *≈ 2.0 to 4.0 kW / kg for FC stack alone* *+ all surrounding systems*
	Wetted area	Smaller	Larger
	Thermo-Propulsive efficiency	Worse *η≈ 35% to 40%*	Better *η≈ 55% to 60% for FC stack alone* *+ all surrounding systems*
	Overall efficiency @ aircraft level	Highly dependant on technology assumption	
In operations	**CO2 emissions**	None	None
In operations	**NOx emissions**	Reduced	None
In operations	**Contrails**	???	??? to none
In operations	**Overall climate impact**	Reduced	None?

H2 propulsion reduces significantly aircraft operations impact on emissions
Fuel Cell propulsion targets the ambition of zero emission

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H2 safety | main H2 risks

H2 physical characteristics lead to threats for the aircraft structure / systems:

- **<u>Liquid hydrogen</u>** ⇒ cryogenic risks:
  - LH2 release: may impact surrounding structure and systems: temperature below systems qualification, mechanical strength altered, ice accretion, overpressure following released LH2 gazeification, ...
  - Accidental heat ingress on H2 cryogenic devices, leading to overpressure

- **<u>Gazeous hydrogen</u>** ⇒ fire / explosion risks

H2 physical characteristics: Auto ignition temperature *~ 520°C [Jet A = 232°C]* **Min ignition energy** ~0,02mJ [Jet A = 0.2mJ] **Density** = 9E-5g/ml [He = 2E-4g/ml / air = 1E-3g/l]

Volumic concentration of GH2 in ambient air at sea level

4% - start of flammability range **~18% - start of detonation range** 59% 75%

With more than 4% of H2 in air, **fire** will most likely occur (type of flame depending on flow)

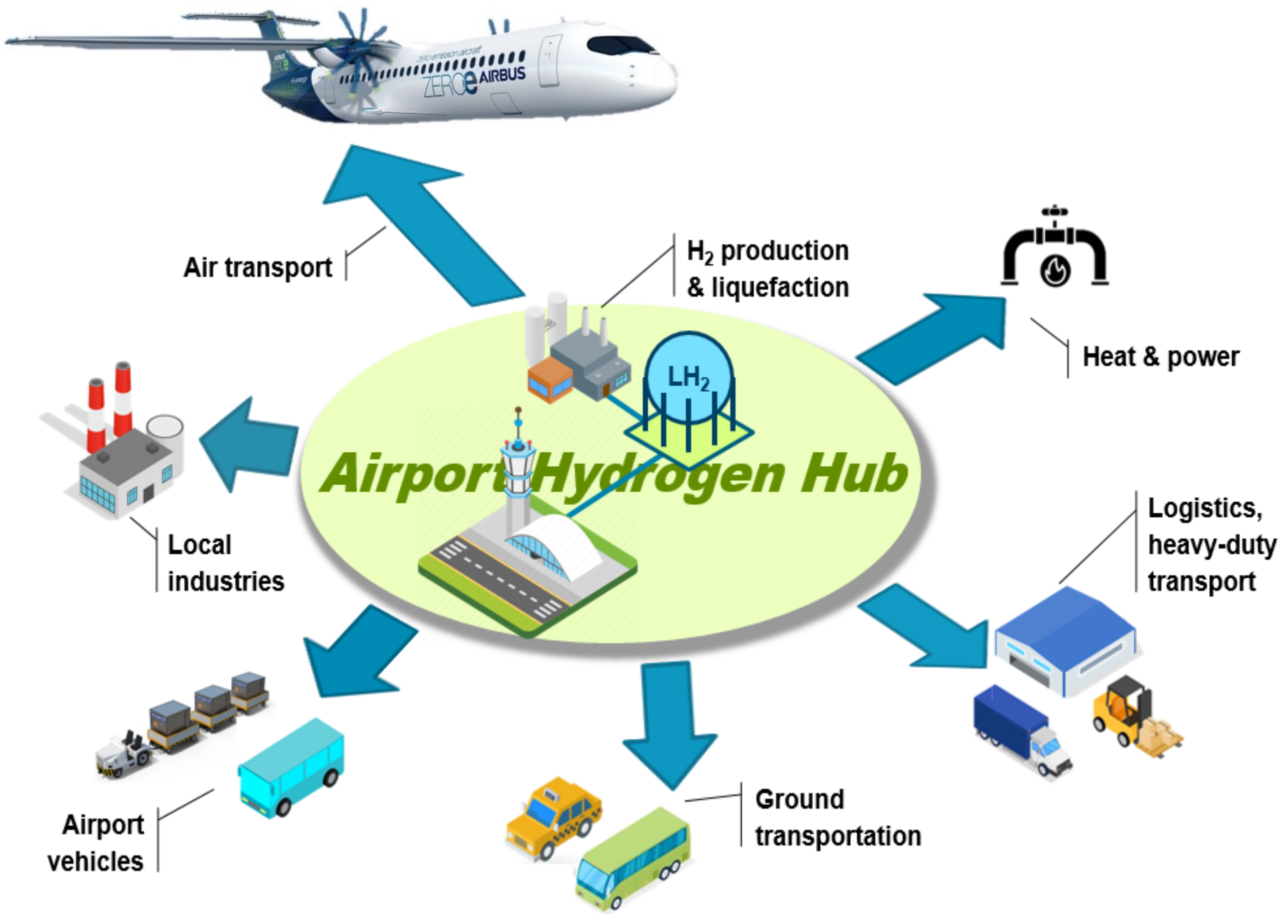
If H2 accumulates in a cloud, **deflagration** may occur

For higher concentration, **detonation** may occur (depending on %, flow perturbations,…)

Appropriate design principles and precautions have to be implemented in order to address and mitigate H2 risks

Aircraft ground ops | airport hydrogen hub

To prepare for the advent of hydrogen aviation, airports will need to become **hydrogen hubs:**



Airport hydrogen hubs will help:

- Preparing regulations and standards for the handling of hydrogen at airports
- Ensure that a large number of airports worldwide are supplied with LH_2 by 2035
- Foster efficiency improvements and cost reductions in hydrogen liquefaction, storage and distribution.

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Airbus ambition

Airbus Ambition

- Bring zero emission aircraft to market by 2035
- Market and technology selection in 2024 - 2025

Roadmap

2018	2020		2022		2024-2025		2035
Project Start	**Pre-Programme Launch**		**Concept & Technology selection (TRL3)**		**Product selection (TRL 5-6)**		**Entry Into Service**
		Concept studies Technology maturation Eco-system & Market Analysis Airport as Hydrogen Hub Aircraft Requirements Finalisation		Product definition Flight test demonstration Propulsion system demonstration Infrastructure Deployment & Evolution Plan Market validation		Product design	

De-risking of technology, regulation, and infrastructure will be required before 2025

Introducing Airbus ZEROe

Turboprop

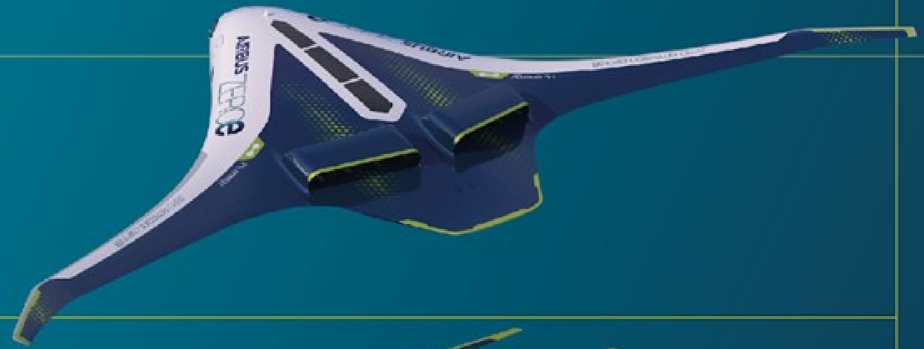
<100 Passengers

1,000+nm Range

Hydrogen Hybrid Turboprop Engines (x 2)

Liquid Hydrogen Storage & Distribution System

Blended-Wing Body



<200 Passengers

2,000+nm Range

Hydrogen Hybrid Turbofan Engines (x 2)

Liquid Hydrogen Storage & Distribution System

Turbofan

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- **Conclusion**

Conclusion

- By 2050, the potential of fuel reduction from an **Aircraft** point of view (at iso requirements, TLARs) is guessed at ~ **25-30%**
- Reduction of the **Requirements** (TLARs, esp. Range & Mach) could offer 10 to 15% more benefit (with new engine types in particular)
- The gain from the **Operations** is presented at ~ **8%**
- On a more global climate impact point of view, still with Kerozene type (can be synthetic fuel), capability to produce much **less NOx and less nvPM** (so less persistent contrails) combined with **contrail avoidance strategy** should offer a significant reduction potential
- **SAF** (Sustainable Aviation Fuel) should contribute to Aviation Climate Impact Reduction
- Other energies, such as **LH2**, are a strong means to reduce climate impact at mid-long term

[Airbus Amber]

Glossary

Glossary and symbols

A

a	Sound speed
A/C	Aircraft
ACARE	*Advisory Council for Aeronautics Research in Europe*
ADC	*Air Data Computer*
AoA or α	Angle of Attack
α_e	Angle of Attack at horizontal empennage position
ATC	Air Traffic Control
ATM	Air Traffic Management
AR	Aspect Ratio

B

β	Sideslip
BC	Business Class
BPR	By-Pass Ratio
BF	Block Fuel

C

CAS	Calibrated Air Speed
CC	Climb Ceiling
CFC	ChloroFluoroCarbon
CG	Center of Gravity
CAEP	Committee on Aviation Environmental Protection
C_D	Drag Coefficient
C_L	Lift Coefficient
Cl	Roll moment coefficient
Cm	Pitch moment Coefficient
Cn	Yaw moment coefficient
Cm_0	Pitch moment Coefficient at zero lift (Pitch moment coef at neutral point)
Cm_{0w}	Pitch moment Coefficient at zero aircraft without empennage lift
COC	Cash Operating Cost
COP	Centre of pressure
C_Y	Lateral force coefficient

[Airbus Amber]

Glossary

D

DOC	Direct Operating Cost
δl	Aileron deflection
δm	Elevator deflection
δn	Rudder deflection

E

EAS	Equivalent Air Speed
EIS	Entry Into Service
EM	Engine Manufacturer
EPNdB	Effective Perceived Noise decibel
ETS	European Union Trading Scheme

F

F or Fn	Net thrust
F	Neutral point (Aircraft neutral point otherwise specified)
FB	Fuel Burn
FC	First Class
FF	Fuel Flow
FG	Growth Thrust
FL	Flight Level
Fq	Maneuver point
FRAM	Ram Drag
Fw	Neutral Point of aircraft without empennage (w for “wing”)

G

g	Gravity acceleration
g_0	Gravity acceleration at Sea Level (SL)
γ	Flight path angle (“Climb angle”)
γ_a	Aerodynamic Flight path angle

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[Airbus Amber]

Glossary

H

H	Geopotential altitude
HQ	Handling Qualities
HTP	Horizontal Tail Plane
HS	High Speed

I

ICA	Initial Cruise Altitude
ICAO	International Civil Aviation Organization
I_H	THS (Trimable Horizontal Stabilizer) setting
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere

L

L	Lift
L	Roll moment
L/D	Lift-over-Drag ratio
LG	Landing Gear
L_{HTP}	HTP x lever arm
L_{VTP}	VTP x lever arm
LTO	Landing and Take-Off (cycle)
LW	Landing Weight
L_W	Lift of aircraft without empennage (w for “wing”)

M

M or Mach	Mach Number
M	Pitch moment
MAC	Mean Aerodynamic Chord
MCL	Max Climb
MLG	Main Landing Gear
MLW	Max Landing Weight
MMO	Mach Maximum Operational
M_{opt}	Mach optimal
MRW	Max Ramp Weight
MTOW	Max Take-Off Weight
MWE	Manufacturer Weight Empty
MZFW	Max Zero Fuel Weight
μ	Dynamic viscosity (Pl or kg/(m.s))

AIRBUS

[Airbus Amber]

Glossary

N

N	Yaw moment
NLG	Nose Landing Gear
NM	Nautical Mile
NOx	Nitrogen oxides
N_z	Vertical load factor

O

OAD	Overall Aircraft Design
OPR	Overall Pressure Ratio
OWE	Operating Weight Empty

P

P or p	Pressure (static pressure otherwise specified)
Ps	Static Pressure
Pt	Total Pressure
P_W	Centre of Pressure of aircraft without empennage (w for “wing”)
P/L	Payload

Q

q	Kinetic pressure
q	Pitch rotation speed
QC	Quota Counts

R

ρ	Volumetric mass

S

S or Sref	Wing reference area
SAR	Specific Air Range
SAT (or T)	Static Air Temperature
SFC	Specific Fuel Consumption
SL	Sea Level
SR	Specific Range
S_{HTP}	HTP area
S_{VTP}	VTP area

[Airbus Amber]

Glossary

N

N	Yaw moment
NLG	Nose Landing Gear
NM	Nautical Mile
NOx	Nitrogen oxides
N_z	Vertical load factor

O

OAD	Overall Aircraft Design
OPR	Overall Pressure Ratio
OWE	Operating Weight Empty

P

P or p	Pressure (static pressure otherwise specified)
Ps	Static Pressure
Pt	Total Pressure
P_W	Centre of Pressure of aircraft without empennage (w for “wing”)
P/L	Payload

Q

q	Kinetic pressure
q	Pitch rotation speed
QC	Quota Counts

R

ρ	Volumetric mass

S

S or Sref	Wing reference area
SAR	Specific Air Range
SAT (or T)	Static Air Temperature
SFC	Specific Fuel Consumption
SL	Sea Level
SR	Specific Range
S_{HTP}	HTP area
S_{VTP}	VTP area

[Airbus Amber]

Glossary

T

TAS or V	True Air Speed
TAT	Turn Around Time
TAT	Total Air Temperature
TLAR	Top Level Aircraft Requirement
TO	Take-Off
TOFL	Take-Off Field Length
TOW	Take-Off Weight
TR	Taper ratio
TTC	Time To Climb

U

UHC	Unburnt HydroCarbons

V

V or TAS	True Air Speed
V_{app}	Approach Speed
GS	Ground Speed
VMC	Velocity of Miminum Control
VMCA	Velocity of Miminum Control in air (at take-off)
VMCL	Velocity of Miminum Control at Landing
VMO	Velocity Maximum Operational
VTP	Vertical Tail Plane
V_{HTP}	HTP volume coefficient
V_{VTP}	VTP volume coefficient

Y

YC	Yankee Class

Z

Z	Geometrical altitude
ZFW	Zero Fuel Weight
Zp	Altitude Pressure