DLR Presentation for Safe Landing

EXACT Results

How Slow Can We Go

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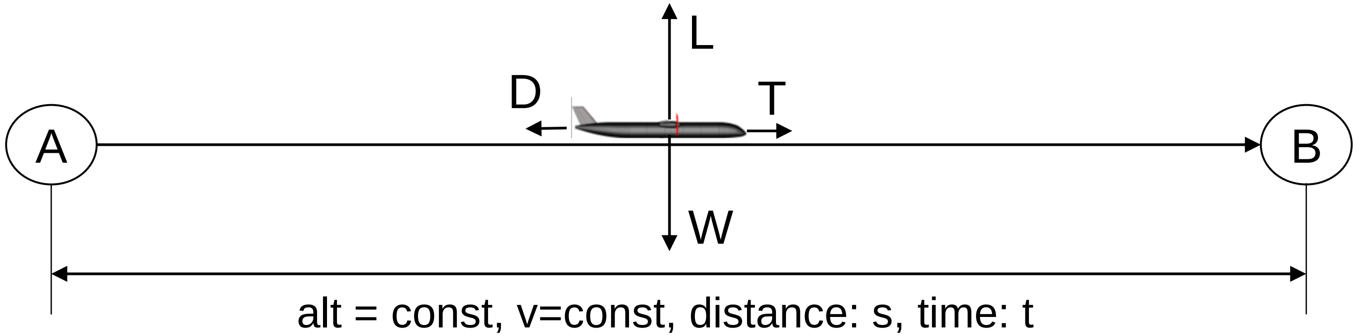
Basics – How is Flight Speed Important

Effect of Speed on Efficiency



alt = const, v=const, distance: s, time: t

In Cruise:

$$L = W = m \cdot g$$

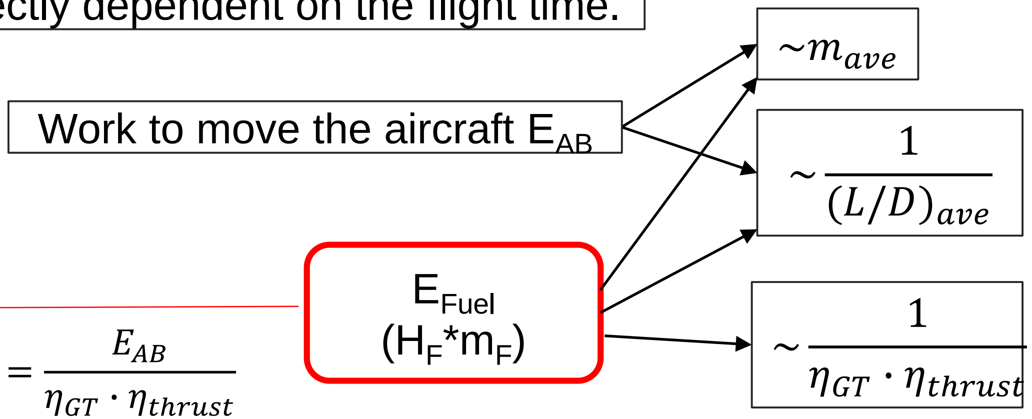
$$T = D = \frac{m \cdot g}{L/D}$$

Flight speed can affect these parameters, thus indirectly affecting fuel.

Energy (work) A->B: $E_{AB} \approx P_{ave} \cdot t = T_{ave} \cdot v \cdot t = T_{ave} \cdot \frac{s}{\cancel{t}} \cdot \cancel{t} = T_{ave} \cdot s$ (work equals force times distance)

The amount of work needed to move the aircraft is not directly dependent on the flight time.

Energy (work) A->B: $E_{AB} \approx T_{ave} \cdot s = \frac{m_{ave} \cdot g}{(L/D)_{ave}} \cdot s \Rightarrow$



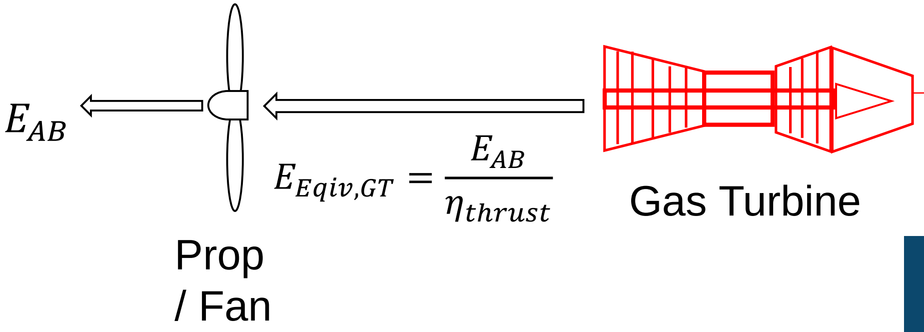
Work to move the aircraft E_{AB}

$\sim m_{ave}$

$\sim \frac{1}{(L/D)_{ave}}$

$\sim \frac{1}{\eta_{GT} \cdot \eta_{thrust}}$

E_{Fuel}
(H_F*m_F)



$$E_{Eqiv,GT} = \frac{E_{AB}}{\eta_{thrust}}$$

$$E_{fuel} = \frac{E_{Eqiv,GT}}{\eta_{GT}} = \frac{E_{AB}}{\eta_{GT} \cdot \eta_{thrust}}$$

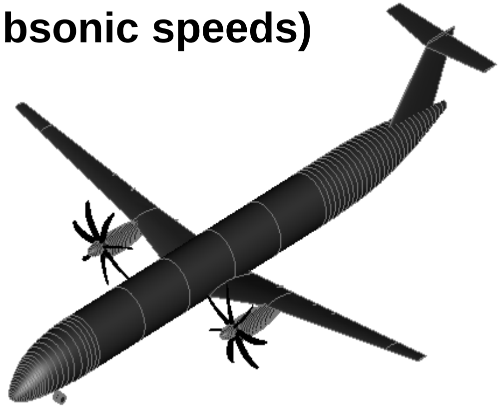
Cruise fuel is proportional to the aicraft mass and inversely proportional to L/D, poropulsor efficiency and gas turbine efficiency.

Aircraft Design Features for Slower Flight

Mach Numbers > 0.76
(Transonic speeds)

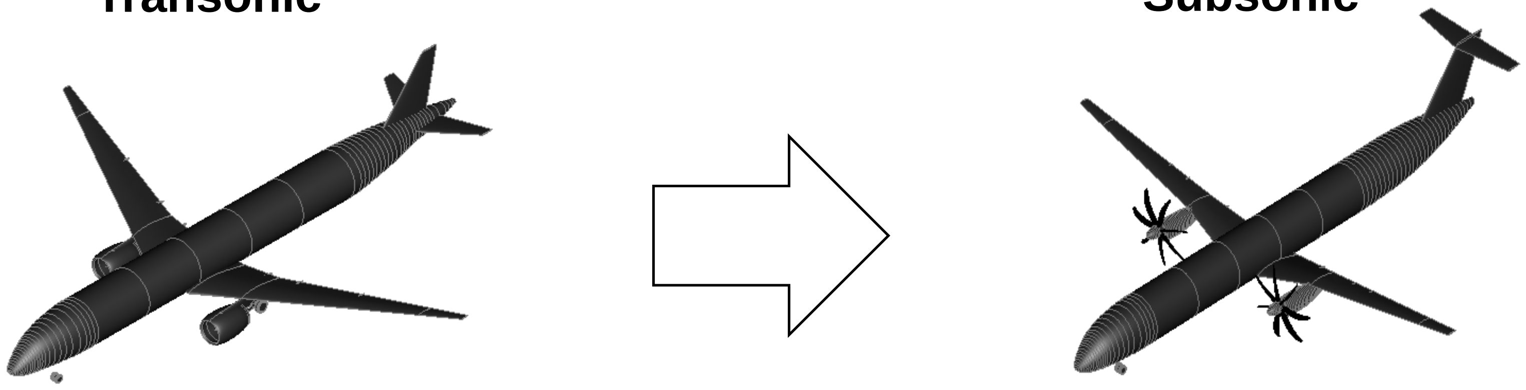
- Typical modern airliners
  → Typical characteristics due to the proximity to the sound barrier:
  - **A swept back wing**
  - **Turbofan engines** are the usual design choise.
- Turboprop propellers → non-competitive efficiency levels at transonic speeds.
- Counter-rotating propellers or „open fans“ can be very efficient at such speeds
  → at the cost of high engine noise levels

Mach Numbers < 0.7
(Subsonic speeds)



- **Turboprop engines** are a suitable design choise:
  - Propellers designed for subsonic speeds can be extremely efficient
  - Propellers are usually much larger than fans
    → less take-off power required for thrust
- **Non-swept wings:**
  - Higher lift coefficients attainable → smaller wings possible
  - Better compatibility with laminar flow technologies
  - Can be typically built thicker (lighter) due to more relaxed tranonic effects.

Slower Flight Summary



Transonic

Mach Numbers > 0.76

Subsonic

Mach Numbers < 0.7

Shifting from transonic cruise speeds to subsonic cruise speeds can enable:

- More efficient propulsion
- Lighter structures
- Improved aerodynamics

Improved flight efficiency usually enhances any additional sustainability solutions.

DLR Project EXACT (2020-2023)

Facts And Challenge

- About **2%** of global energy-related **CO2 emissions** from aviation
- **5%** of current anthropogenic **climate change** caused by global aviation
- Non-CO2 effects play a major role
- Despite increasing global fleet efficiency, aviation's impact is increasing due to the projected growth in aviation
- Operation is the predominant phase in terms of climate impact
- Long-lifetime of aircraft causing long fleet renewing
- Huge investments and long development times needed for new aircraft
- Challenging technical requirements
- Economically viable solutions

eXACT®

The Project EXACT (2020-2023) – Contents

Which concepts have the potential to drastically reduce aviation's climate impact while maintaining a high economical competitiveness?

Green energy
- Energy carrier production
- Energy carrier transport
- Energy carrier storage
- Airport infrastructure

Climate impact
- In-flight emissions
- Ground based emissions
- Manufacturing / End-of-Life

Future air-traffic demand
- Fleet network optimization
- Maintenance
- Ground handling

Aircraft Design
- Propulsion architectures
- On-board systems
- Structural design

- Funding Volume: 20M€
- Consortium: 20 DLR Institutes

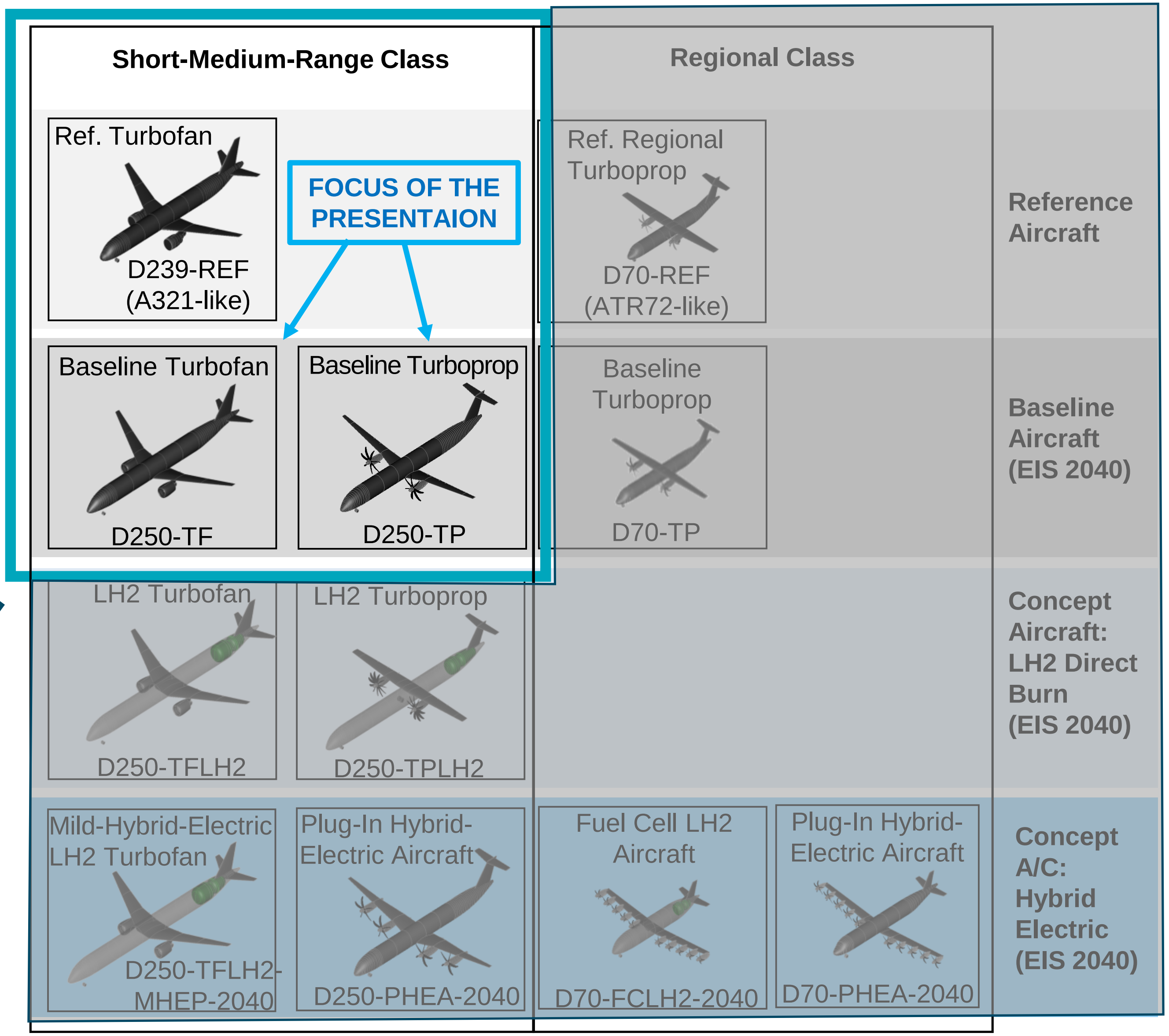
EXACT Aircraft Models

Aircraft Design Work Package:

- Expand tools and know how for consistent aircraft design throughout different aircraft classess and a multitude of concepts.
- Explore aircraft design synergies and market sweet-spots for different power providers and energy carriers at each aircraft class.
- Focus on most fitting concepts for reduced climate impact combined with market competitiveness.

The study **„speed vs sustainability“** lead to improved understanding of the effects and enablers of switching to subsonic flight at the larger aircrat classes!

„EXACT“ Project Aircraft Models



Short-Medium-Range Class

Regional Class

Ref. Turbofan
D239-REF
(A321-like)

FOCUS OF THE PRESENTAION

Ref. Regional Turboprop
D70-REF
(ATR72-like)

Reference Aircraft

Baseline Turbofan
D250-TF

Baseline Turboprop
D250-TP

Baseline Turboprop
D70-TP

Baseline Aircraft (EIS 2040)

LH2 Turbofan
D250-TFLH2

LH2 Turboprop
D250-TPLH2

Concept Aircraft: LH2 Direct Burn (EIS 2040)

Mild-Hybrid-Electric LH2 Turbofan
D250-TFLH2-MHEP-2040

Plug-In Hybrid-Electric Aircraft
D250-PHEA-2040

Fuel Cell LH2 Aircraft
D70-FCLH2-2040

Plug-In Hybrid-Electric Aircraft
D70-PHEA-2040

Concept A/C: Hybrid Electric (EIS 2040)

EXACT Short-Range Turboprop

Aircraft Design Boundary Conditions

Reference A/C:

DLR A321neo
interpretation
(EIS2016)

D239-REF

Top-Level-Aircraft Requirements

Design Range	[nm]	2500
Design PAX (single class)	[-]	239
Max. Payload	[kg]	25000
Cruise Mach number	[-]	0.78
TOFL (ISA +0K SL)	[m]	2200
Approach Speed (CAS)	[kt]	136
Wing span limit	[m]	<=36

Redesign for EIS2040:

❖ **TLAR changes:**

- Range 1500nm
- TOFL (ISA +0K SL) 1900m
- 250 PAX (economy);
  Design payload 23750kg
- Appr. speed <140kts

❖ **Technology changes:**

- Gas turbine +5% efficiency vs state of the art & no thrust reversers for the turbofan engines.
- Alu fuselage -5% mass vs state of the art.
- Empennage: -8% mass
- CFRP Wing with foldable wing tip (42m span)
- Bleedless systems architecture

EXACT Turbofan Baseline

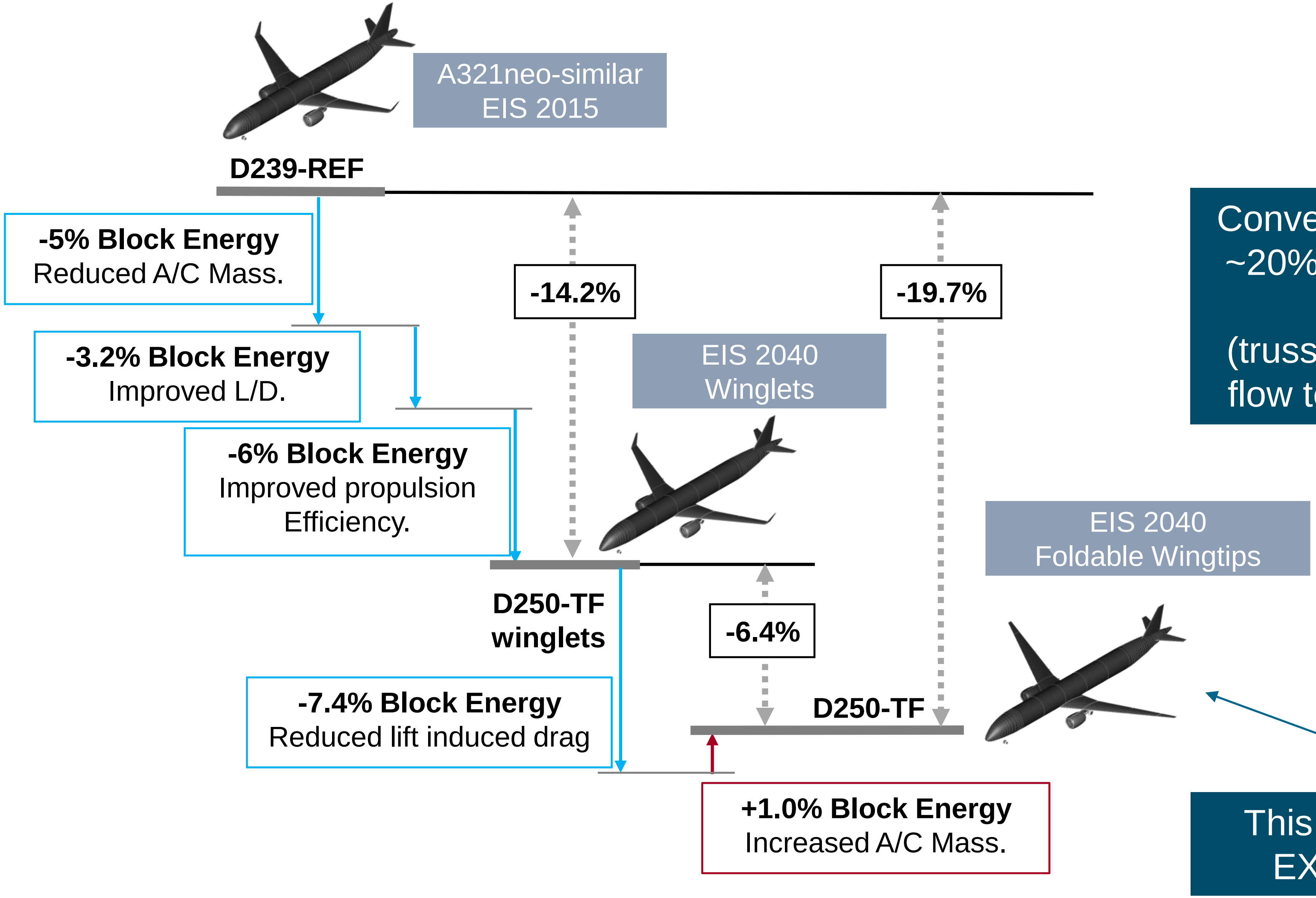
D250-TF

EXACT Turboprop Baseline

D250-TP

Cruise Mach Optimization

EXACT Advanced Turbofan D250-TF



A321neo-similar
EIS 2015

D239-REF

-5% Block Energy
Reduced A/C Mass.

-3.2% Block Energy
Improved L/D.

-6% Block Energy
Improved propulsion Efficiency.

-14.2%

-19.7%

EIS 2040
Winglets

D250-TF winglets

-6.4%

EIS 2040
Foldable Wingtips

-7.4% Block Energy
Reduced lift induced drag

D250-TF

+1.0% Block Energy
Increased A/C Mass.

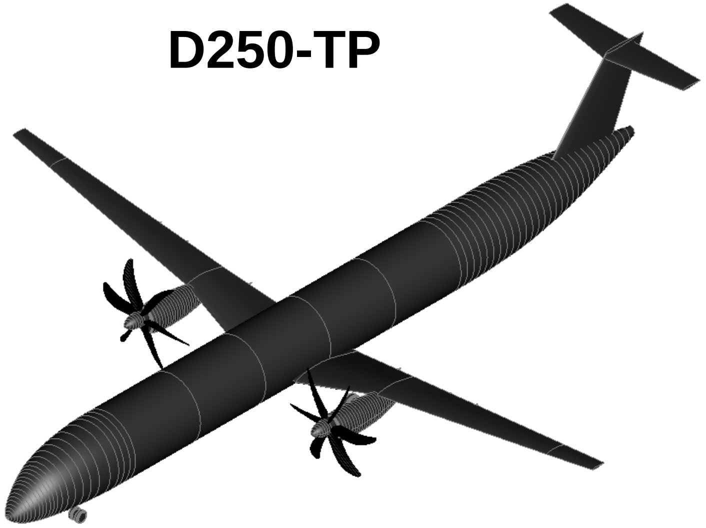
Conventional technologies allow ~20% fuel improvement of next generation aircraft.
(truss-braced wing and laminar flow technologies not included)

This is the comparison to the EXACT turboprop aircraft

Turboprop Propulsion Instead of a Turbofan

The turboprop aircraft D250-TP → speed vs fuel efficiency:

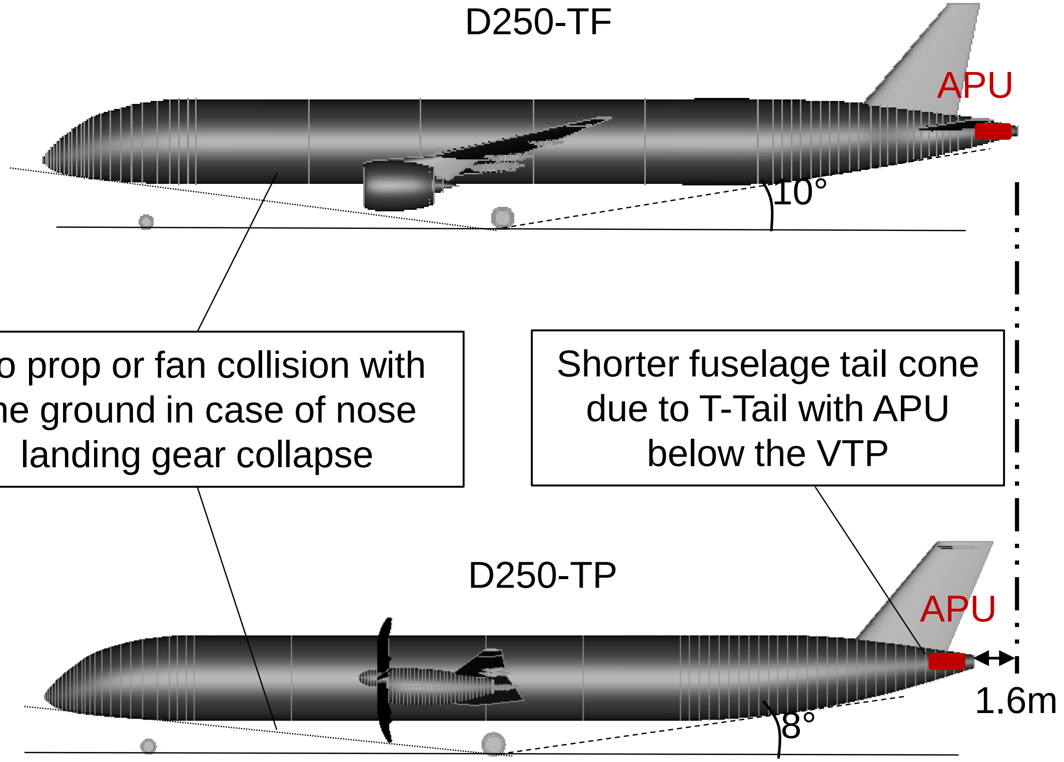
D250-TP



- Global fleet operating cost as a KPI.
- Only unswept wing design considered → Mach numbers below Ma 0.7
- Low-wing config. possible with gull-wing despite the large propellers (D=6.2m).
- Propeller blade-off shielding at the fuselage included in the mass model.
- T-tail to avoid having the empennage in the propeller slipstream

This configuration is fixed and the cruise Mach number is optimized in terms of fleet operating costs.

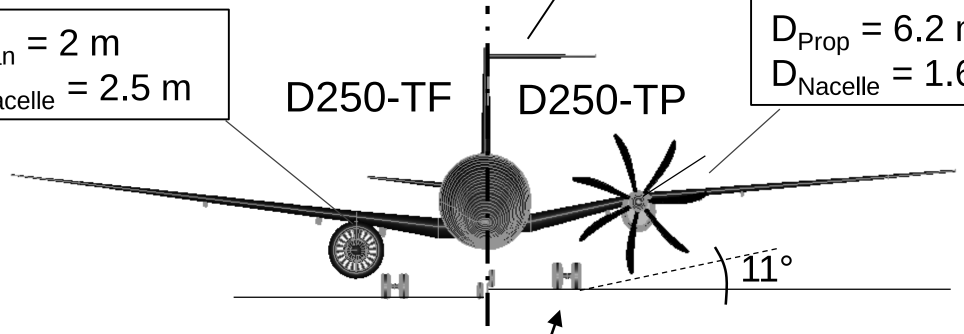
Configurational Aspects



No prop or fan collision with the ground in case of nose landing gear collapse

Shorter fuselage tail cone due to T-Tail with APU below the VTP

Less take-off rotation needed due to unswept wing (higher $c_{L\alpha}$)



T-Tail to avoid the empennage in the prop wake

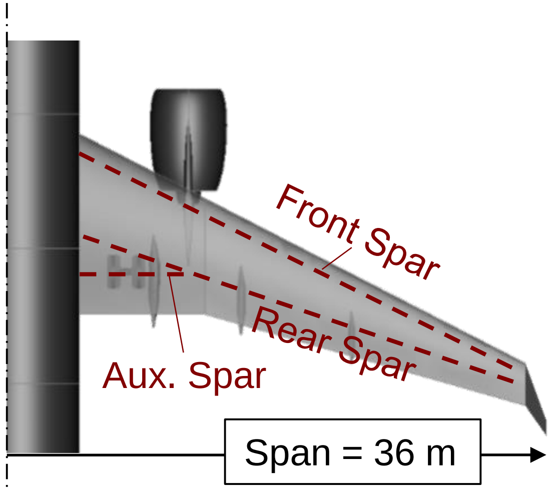
$D_{Fan} = 2$ m
$D_{Nacelle} = 2.5$ m

$D_{Prop} = 6.2$ m
$D_{Nacelle} = 1.6$ m

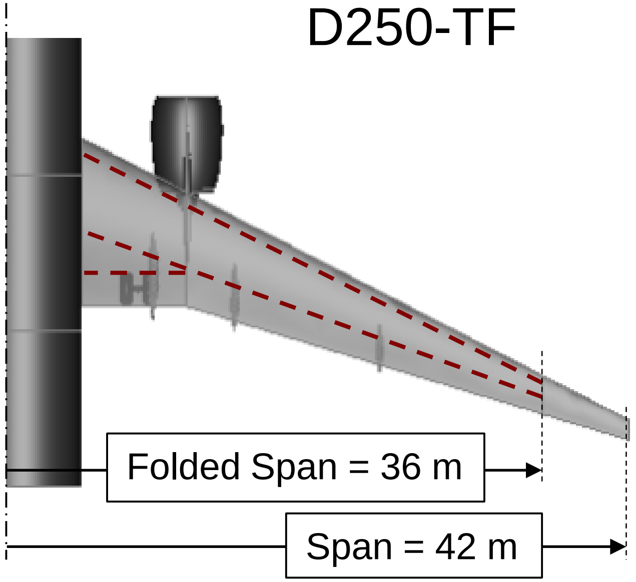
Shorter landing gear possible due to reduced rotation angle, combined with gull-wing design

Wing design

Reference Aircraft

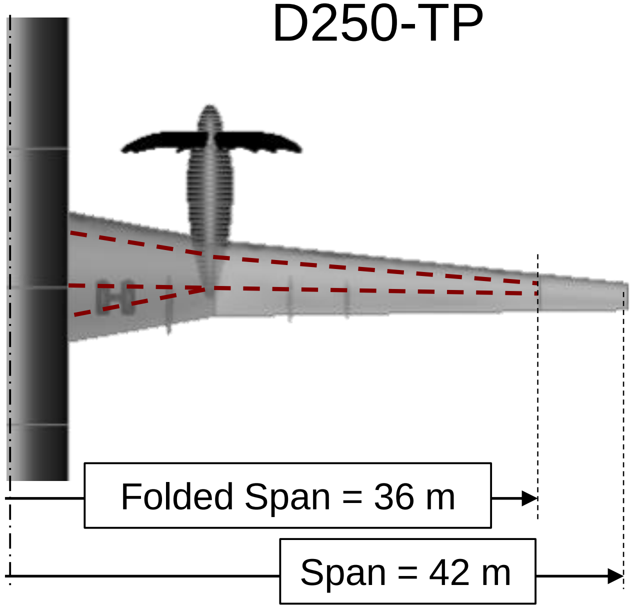


Study A/C: D250-TF



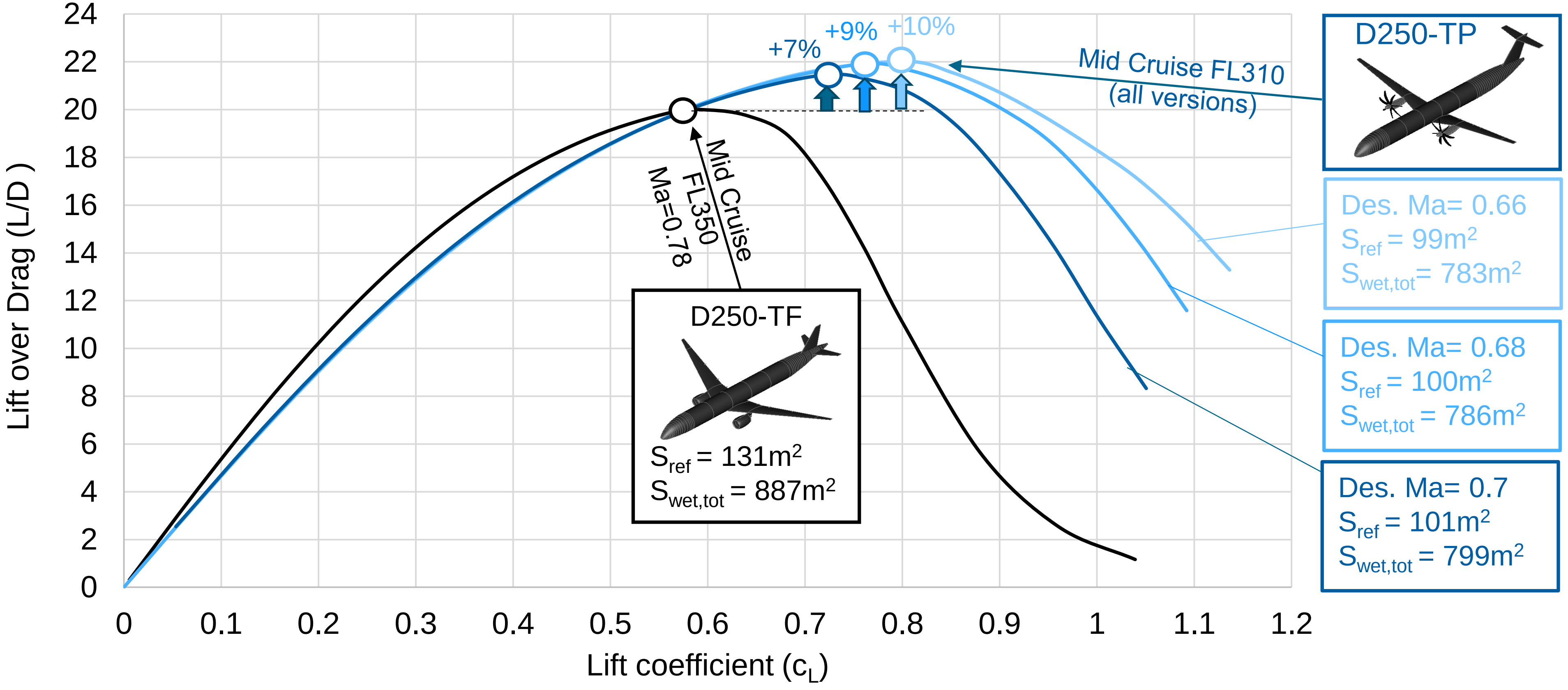
The landing gear integration is more difficult due to the thinner root chord and backwards MAC shift

Study A/C: D250-TP



The unswept wing allowes for an easier landing gear integration even for higher aspect ratios.

Aerodynamic Performance

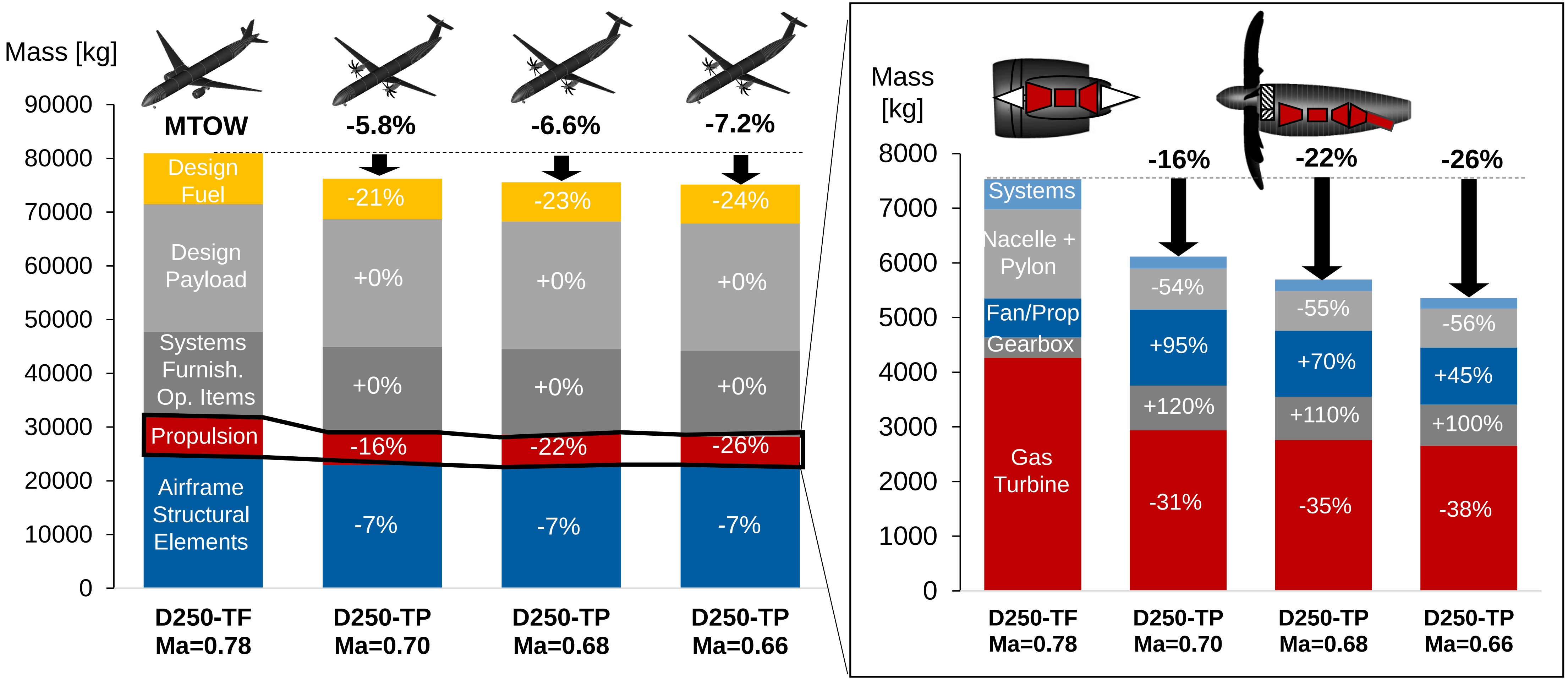


The turboprop aerodynamic performance is improved:

- **Smaller nacelles**
- **Higher aspect ratio wing**
- **Higher lift coefficient in cruise because of non-swept wing & reduced transonic effects**

The aerodynamic improvement potential flattens out at around Ma 0.66

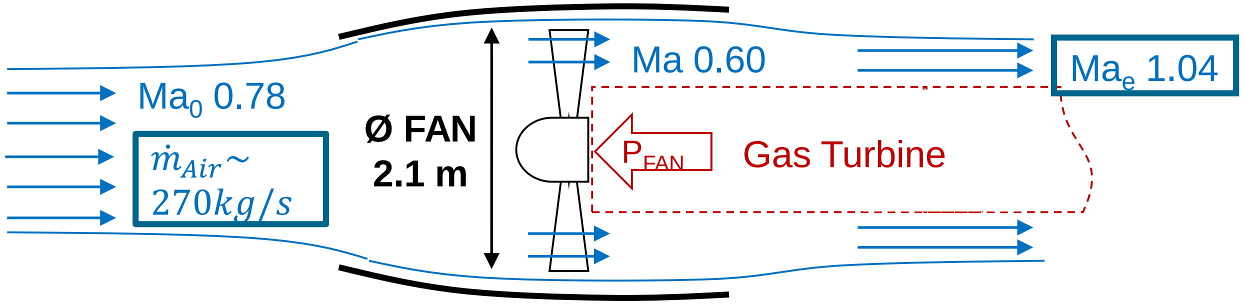
Aircraft Mass

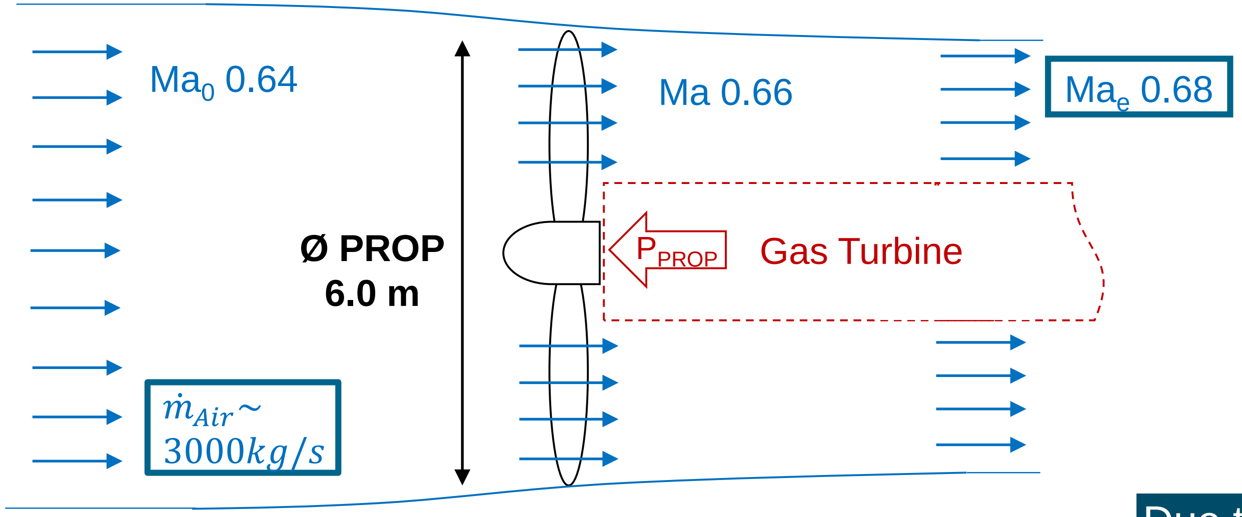


The mass advantage is mainly due to reduced fuel & gas turbine mass + snowball effects.

The advantages flatten out at around Ma 0.66, as the gas turbine mass starts being dominated by the take-off requirements.

Example Turboprop vs Turbofan Efficiency in Cruise





Ducted fan (FPR ~ 1.35) efficiency:

- Propulsive efficiency: $\eta_P = \dfrac{2}{1+v_e/v_0} = 0.86$
- Pressure losses: $\pi_{inlet} = 0.99; \pi_{nozzle} = 0.995$
- Fan isentropic efficiency: $\eta_{is,Fan} = 0.915$

$$\boxed{\eta_{thrust} = \frac{T_{FAN} \cdot v_0}{P_{FAN}} = 0.76}$$

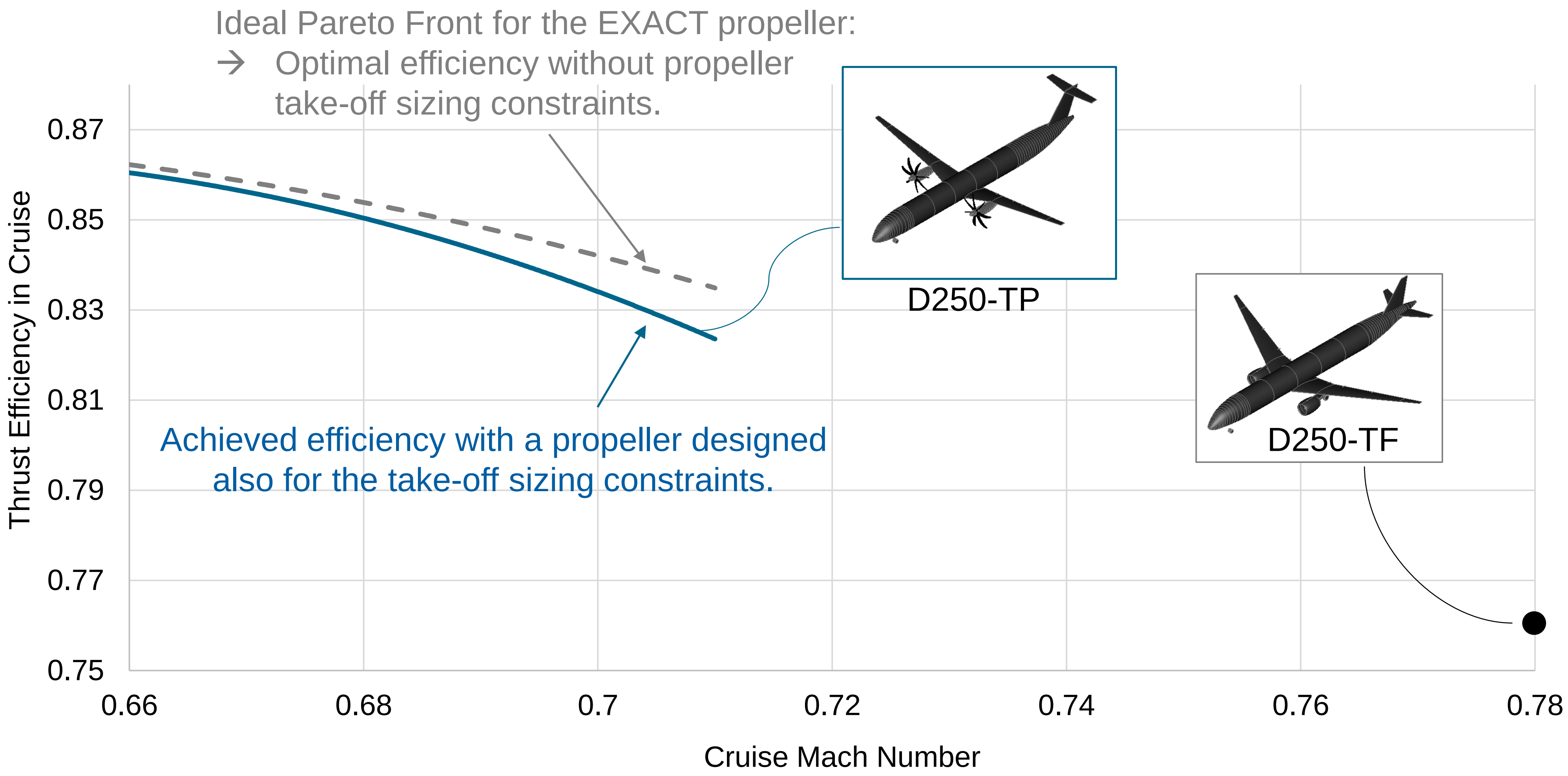
Propeller (FPR ~ 1.02) efficiency:

- Propulsive efficiency: $\eta_P = \dfrac{2}{1+v_e/v_0} = 0.98$
- Prop isentropic efficiency: $\eta_{is,Prop} = 0.88$

$$\boxed{\eta_{thrust} = \frac{T_{Prop} \cdot v_0}{P_{Prop}} = 0.86}$$

Due to the lack of duct losses, a propeller can have a much lower pressure ratio (can be built much larger), which leads to a more efficient thrust generation.

Propeller Efficiency in Cruise

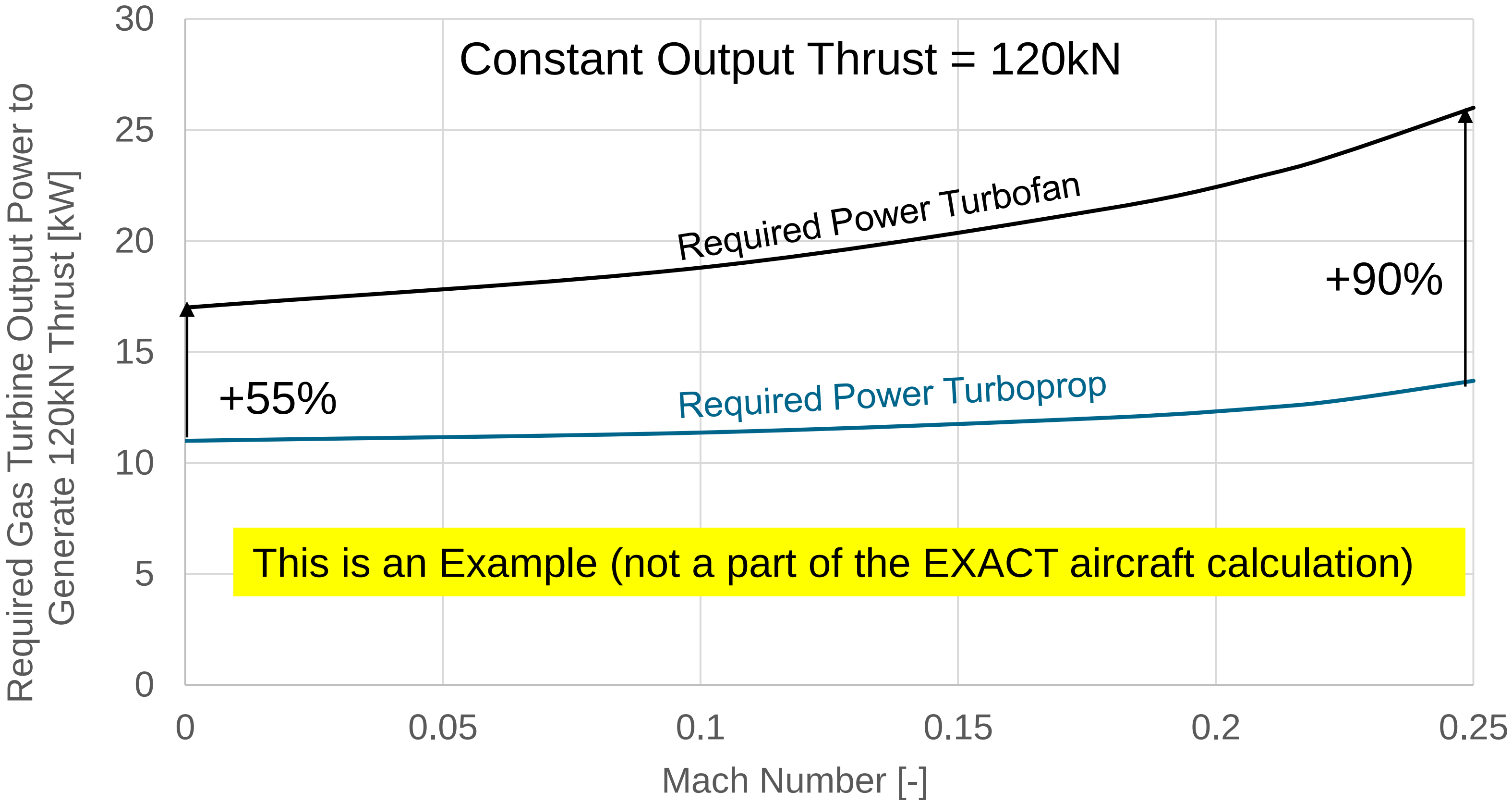


Ideal Pareto Front for the EXACT propeller:

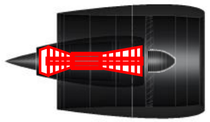
→ Optimal efficiency without propeller take-off sizing constraints.

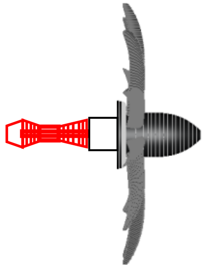
Achieved efficiency with a propeller designed also for the take-off sizing constraints.

Example - Turboprop vs Turbofan Power for Take-Off



This is an Example (not a part of the EXACT aircraft calculation)

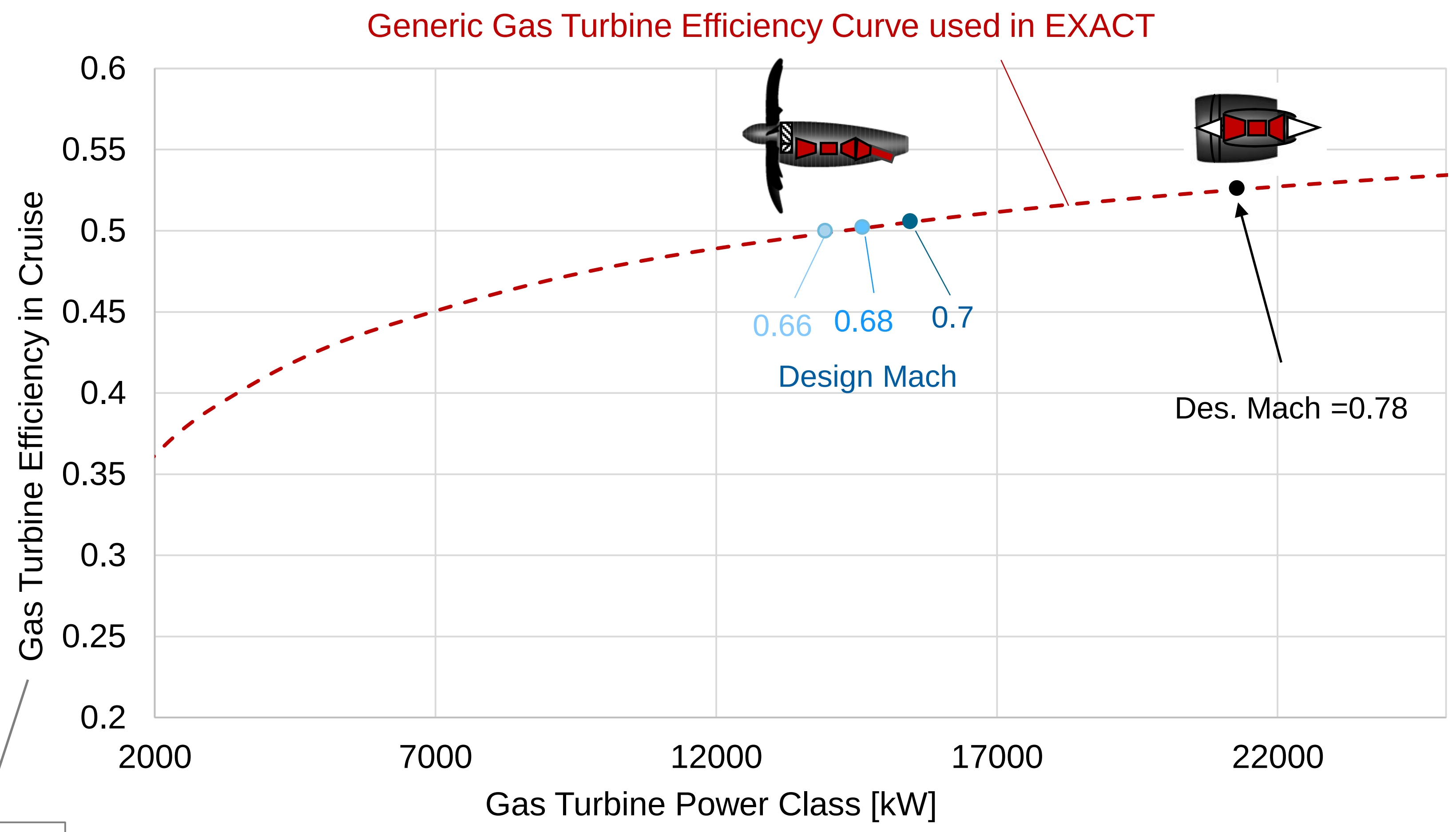




Due to the large propeller, turboprop aircraft tend to require significantly smaller gas turbines for take-off.

To avoid oversizing the gas turbines for climb, turboprops tend to be designed for lower flight altitudes.

Gas Turbine Scaling Effects

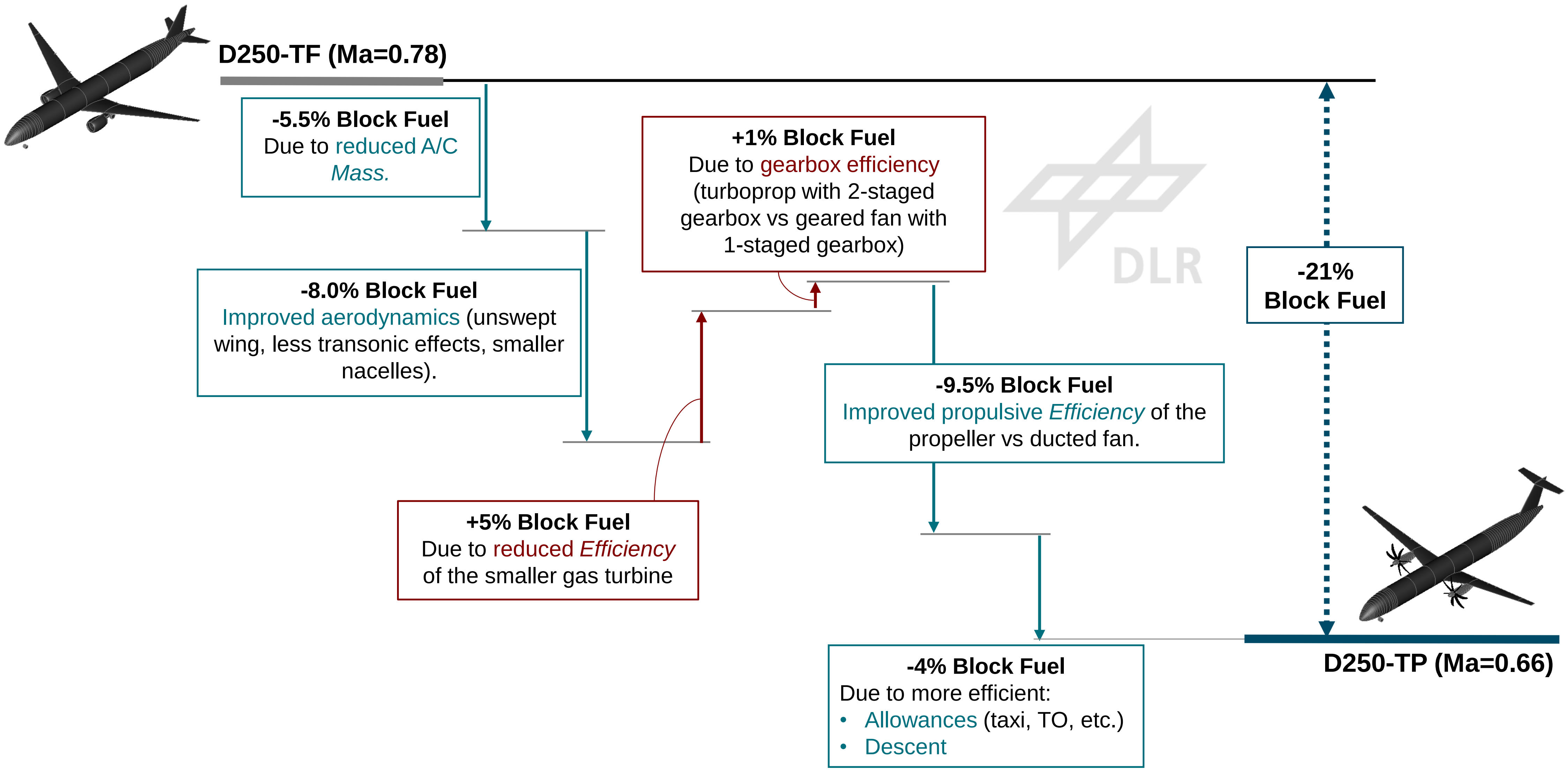


The total useful power output divided by the fuel energy flow.

Gas Turbine Size Comparison Point:
Max. TET at SL, ISA

A smaller gas turbine tends to be less efficient, dampening some of the advantages.

Ladder Chart Design Mission – 1500 nm



D250-TF (Ma=0.78)

-5.5% Block Fuel
Due to reduced A/C *Mass.*

-8.0% Block Fuel
Improved aerodynamics (unswept wing, less transonic effects, smaller nacelles).

+5% Block Fuel
Due to reduced *Efficiency* of the smaller gas turbine

+1% Block Fuel
Due to gearbox efficiency (turboprop with 2-staged gearbox vs geared fan with 1-staged gearbox)

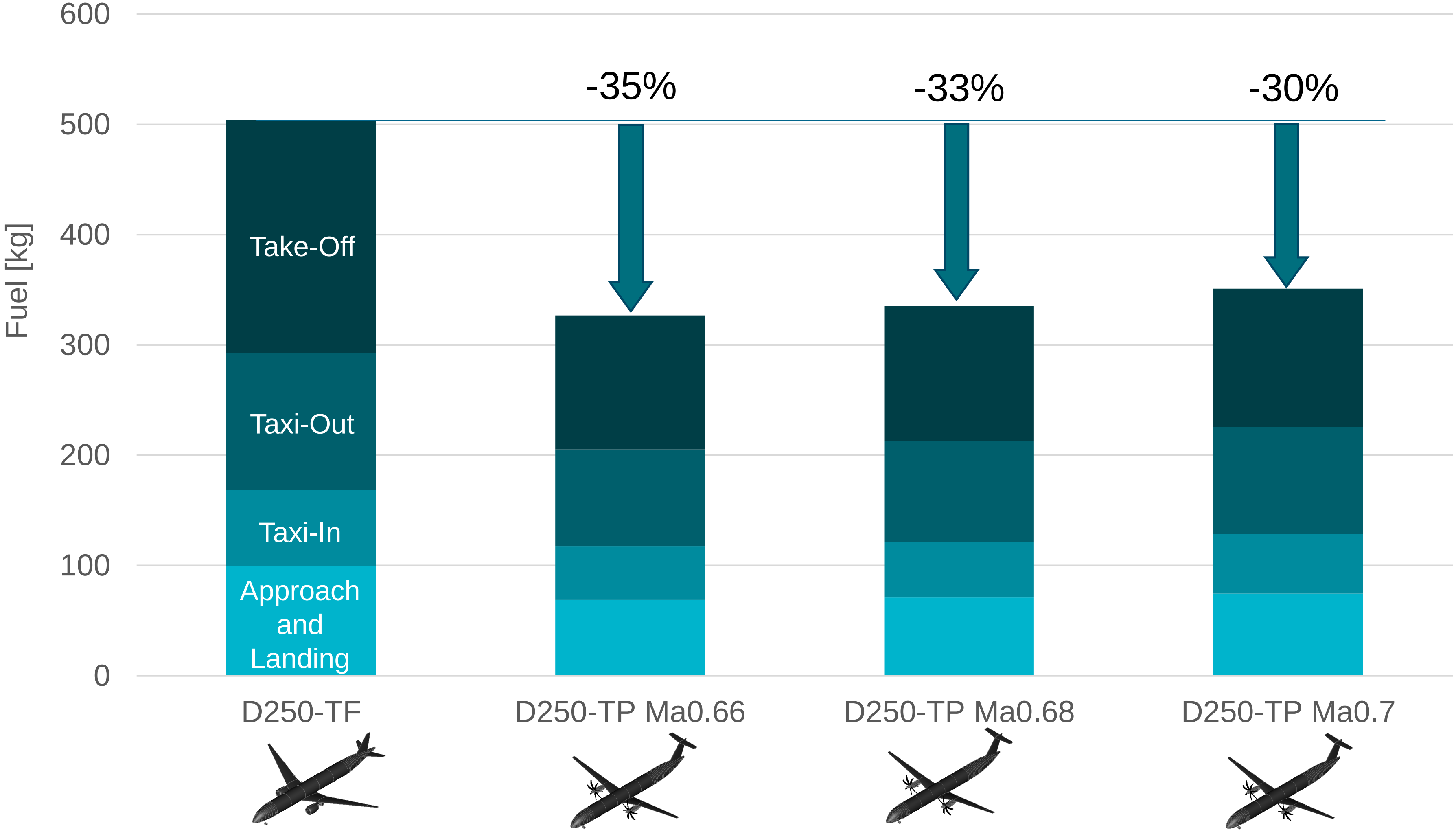
-9.5% Block Fuel
Improved propulsive *Efficiency* of the propeller vs ducted fan.

-4% Block Fuel
Due to more efficient:
- Allowances (taxi, TO, etc.)
- Descent

-21%
Block Fuel

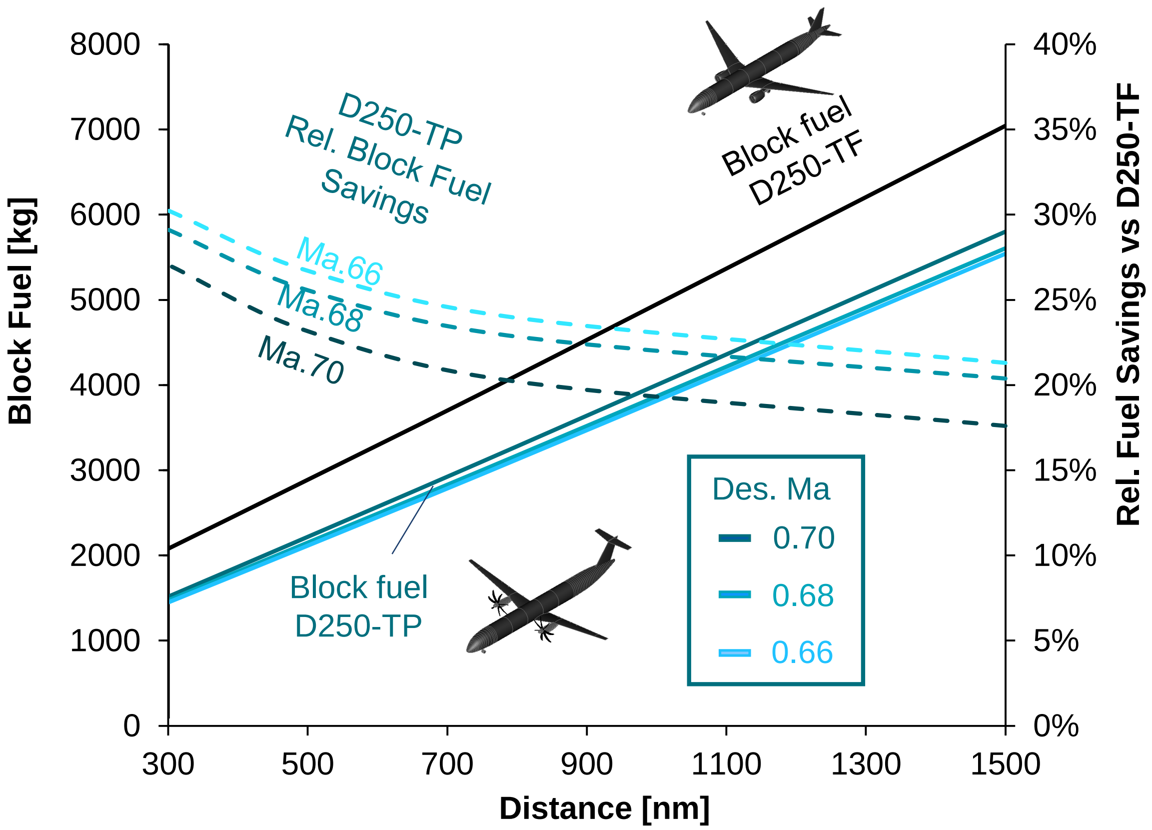
D250-TP (Ma=0.66)

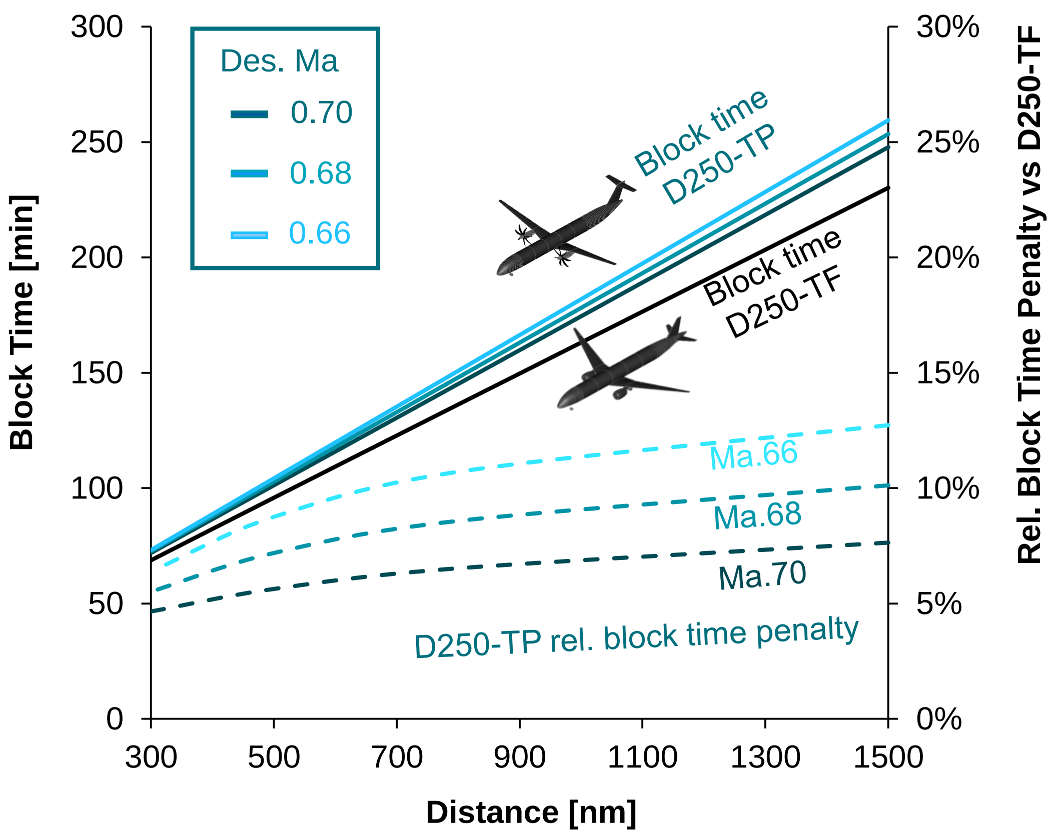
Landing-Take-Off (LTO) Cycle



Significant savings in take-off & idle operation due to the significantly smaller gas turbines
→ thus the slower turboprop versions burn less fuel during the LTO cycle.

Block Fuel & Block Time vs Design Mach Number



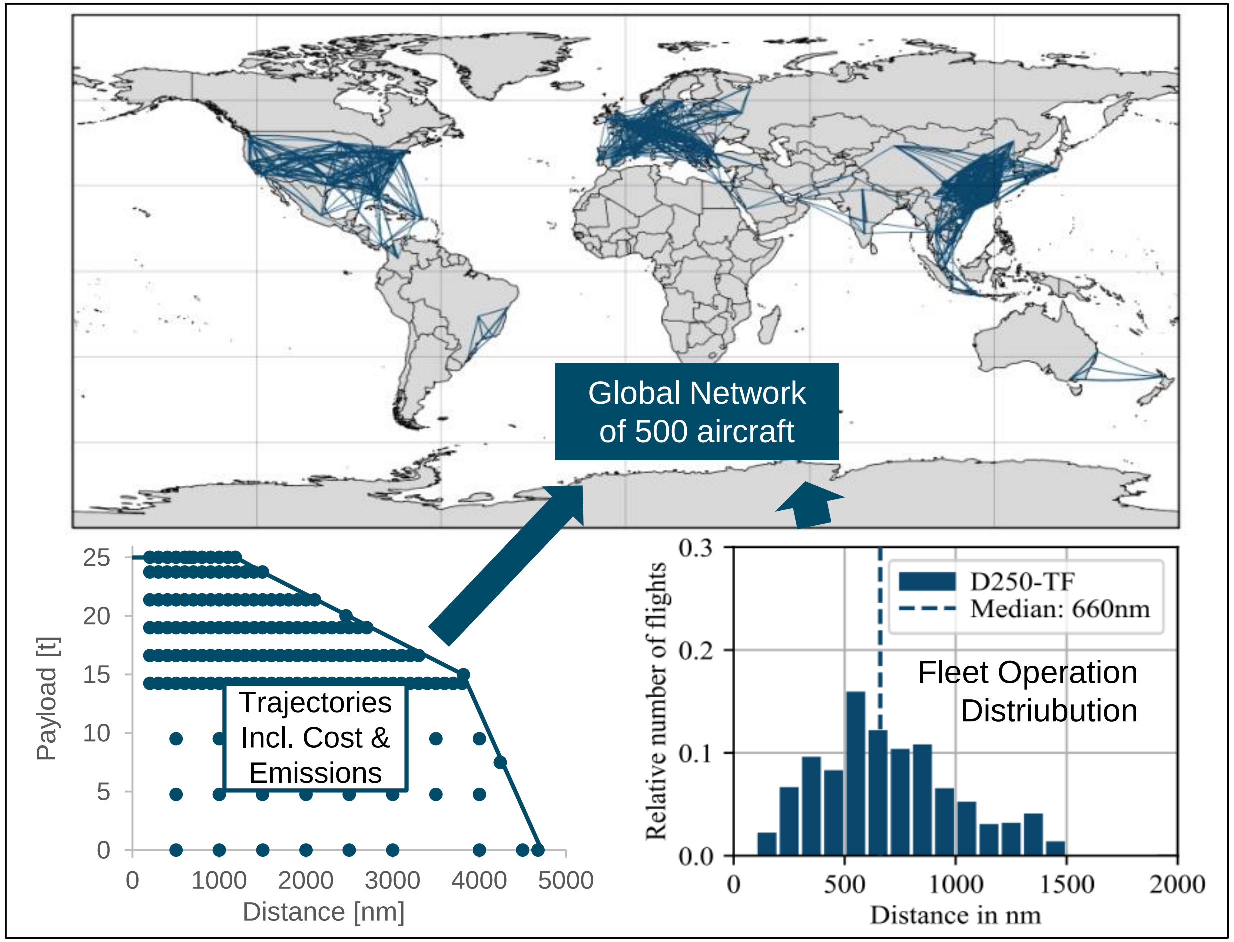


Effect of turnaourn time and fuel:
The turboprop aircraft has the highest efficiency advantage and lowest time penalty at shorter missions

EXACT Global Fleet Assessment

EXACT Fleet-Level Assessment

A typical short-range turbofan operator is simulated



Global Network of 500 aircraft

Trajectories Incl. Cost & Emissions

Fleet Operation Distriubution

D250-TP

vs

D250-TF

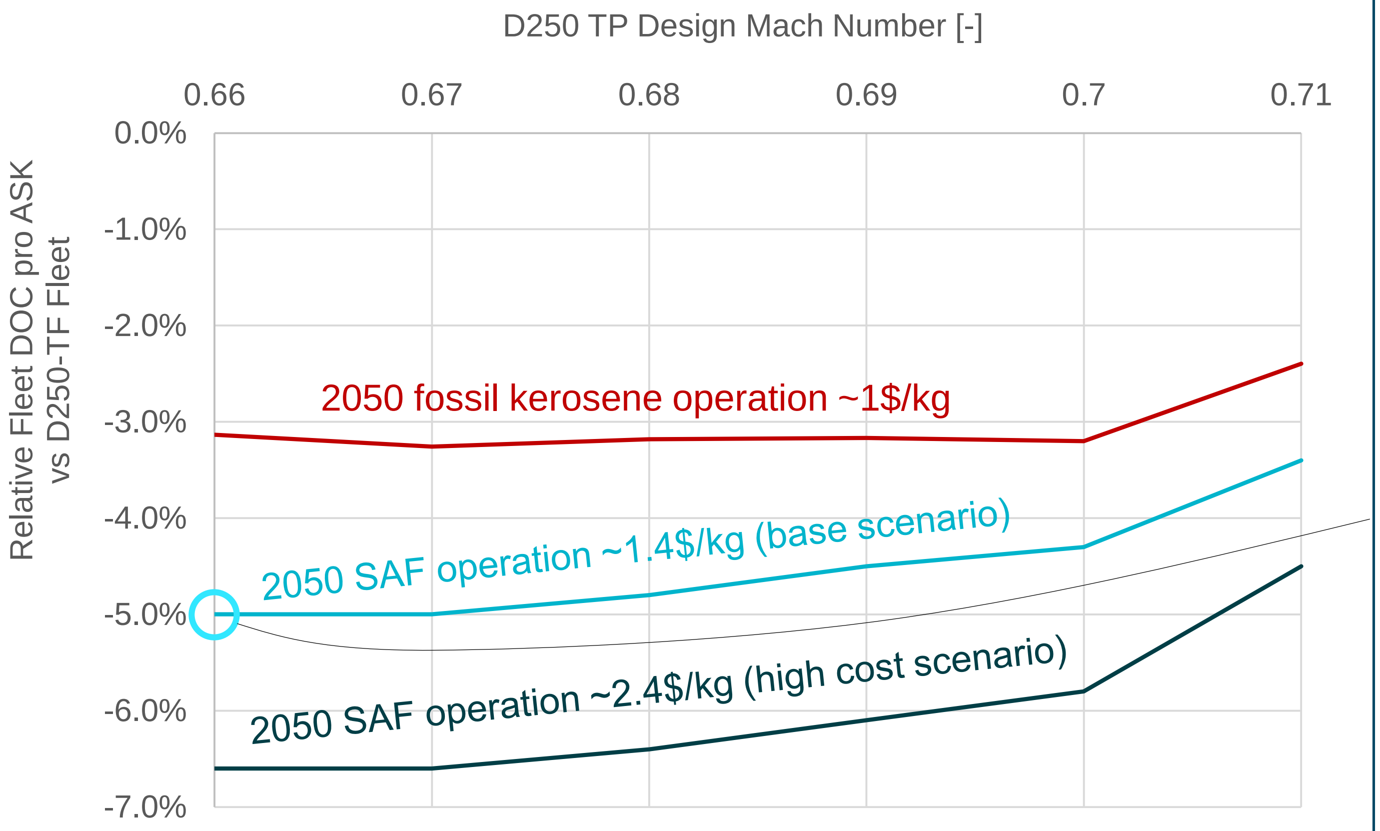
Both aircraft are compared on a global network of 500 vehicles simulated over a course of the aircraft life.

The simulation is used to calculate:

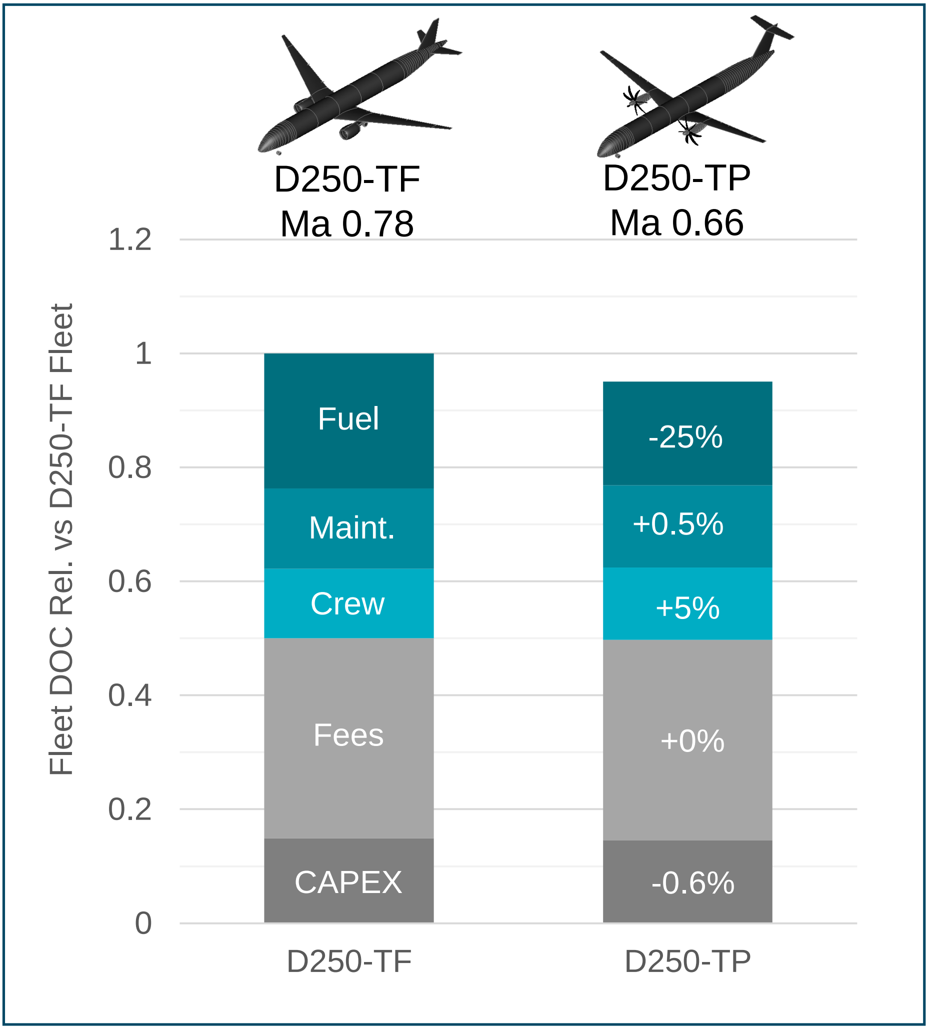
- **Fleet yearly operating costs** (including maintenance checks & overhaul, crew costs, day-night cycle etc.)
- **Total fleet climate impact** (including materials production & logistics)

Collaboration effort of 12 institutes

Operating Costs



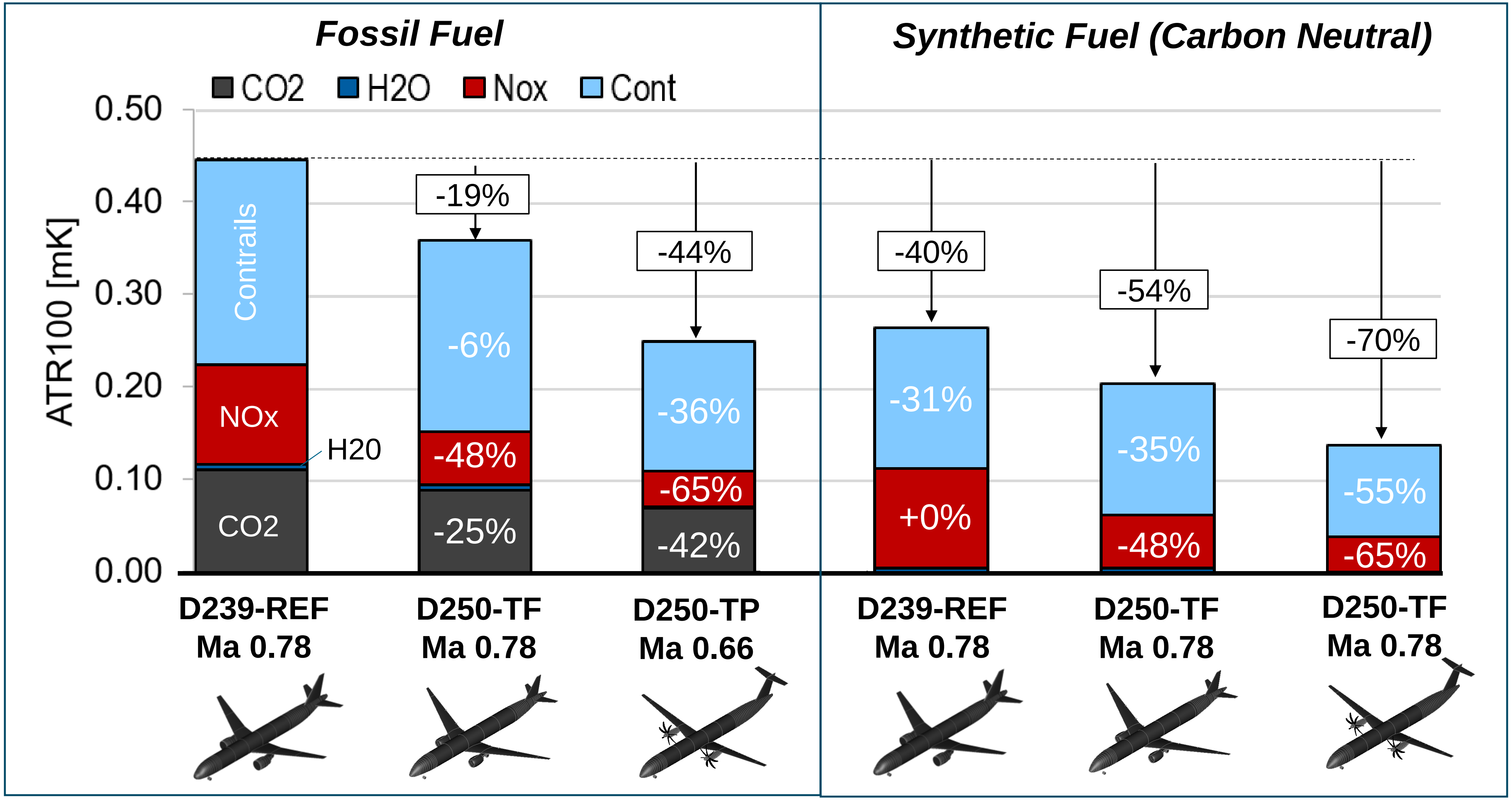
Base fuel costs scenaro
Turboprop Design Mach 0.66



The turboprop aircraft offers reduced overall operating costs in all fuel cost scenarios

Cost optimum is around design Mach 0.66-067

Climate Impact



The turboprop advantages result from higher efficiency and lower optimal cruise altude.

Summary


sustainable fuel powered
DLR
exACT
hydrogen propulsion
exACT[mhep]
DLR
exACT[mhep]
DLR
exACT

Study Implications

Flying slower can be a means to significantly improve aircraft efficiency:

- **Enabler for highly efficient subsonic propellers:**
    - Significant cruise efficiency improvement vs turbofans
    - Tendency for lower altitude operation (good for non-CO2 effects)
    - Tendency for significantly reducing gas turbine size → less fuel consumed around the airport
    - Less shaft power for take-off is well compatible with more radical propulsion systems: e.g. electric propulsion
- **Enabler for lighter and more aerodynamically efficient unswept wings:**
    - Well compatible with additional efficiency improvement with laminar flow technologies (not assessed in the study)

Significant advantage of climate impact reduction, compared to transonic turbofan aircraft

Can be advantageous in terms of operating costs, especially when fuel costs are high.

Only approximately 15% speed reduction needed to enable most benefits: Mach ~0.8 → Mach ~0.7

Study Uncertainties

Aircraft modelling:

- Propeller calculation did not consider specialized transonic airfoils → <u>some improvement potential</u>
- Aerodynamic propulsion integration effects of the high-speed turboprops
- The impact of truss-braced wings or laminar flow technologies was not a part of the study
  → <u>additional improvement potential for unswept wings</u>

Cost assessment:

- Uncertainty and lack of validation of the airframe & engine components aquisition and maintenance costs
- Some uncertainty in the projections of crew and maintenance personel costs

Climate impact:

- Only basic empirical NOx emissions model
- Some uncertainties in the impact of the non-CO2 effects

Thank you for your attention!