Simultaneous Optimization of the Airframe, Powerplant, and Operation of Transport Aircraft

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Objective

Find global optimum in Airframe + Engine + Ops design space

- Fuel economy isocontours
- Existing engines
- Common apparent (false) optimum
- True optimum
- Pratt’s, GE’s design domain
- Boeing’s, Airbus’s design domain
- Existing airplanes
- FPR, $T_{14}$
- W/S, $M_\infty$
Presentation Outline

- Transport Aircraft System OPTimization (TASOPT)
- Global optimization effectiveness study
- D8.x “Double Bubble” transport aircraft concept
TASOPT Summary

Collection of coupled low-order physical models

- Primary structure
- Aero
- Engine
- Trim, stability
- Flight trajectory (Ops)
Fuselage Primary Structure

\[ N(W_{pay} + W_{padd} + W_{shell} + W_{window} + W_{insul} + W_{floor} + W_{seat}) \]

\[ \Delta \rho \]

\[ r_{Mv} L_v \]

\[ NW_{tail} + r_{Mh} L_h \]

\[ x \]

\[ \frac{M}{x_{wbox}} \]

\[ M_h(x) \]

\[ M_v(x) \]

\[ t_{skin} \]

\[ R_{fuse} \]

\[ P_{floor} \]

\[ A_{skin} \]

\[ A_{fuse} \]

\[ Q_v \]

\[ L_{v_{max}} \]
Wing, Tail Primary Structure

$$\eta = 2 \frac{y}{b}$$
Transonic Airfoil Family

- Airfoil family designed offline for good transonic drag rise
- Viscous/Inviscid CFD database for any $\frac{t}{c}$, $c$, $M_\perp$, $Re_c$
- Dispenses with wetted-area drag prediction methods
- Provides “rubber airfoil” for optimizer

<table>
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<tr>
<th>area</th>
<th>NC090</th>
<th>NC100</th>
<th>NC110</th>
<th>NC120</th>
<th>NC130</th>
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</table>

$\Delta \theta_{TE}$ values:
- NC090: 11.70°
- NC100: 11.74°
- NC110: 11.71°
- NC120: 11.68°
- NC130: 11.54°
- NC140: 11.62°
Fuselage Drag Model

- Viscous/Inviscid calculation for any area, perimeter $A(x), b_0(x)$
- Dispenses with wetted-area drag prediction methods
- Also provides accurate input for BLI accounting

**Diagram**: Illustration of fuselage drag model with variables $A(x), b_0(x), \Lambda(x), \lambda(x)$, and other relevant parameters.
Engine Performance Model

- Complete flowpath simulation for . . .
  - . . . sizing at cruise design point,
  - . . . operation at off-design takeoff, climb, descent, static.
  - Includes effects of Boundary Layer Ingestion (BLI), if any

- Dispenses with engine-performance correlations

- Provides “rubber engine” for optimizer
Mission Profiles

- Each design “flown” over specified total range mission to
  - ...size fuel weight,
  - ...evaluate takeoff performance

- Provides “rubber trajectory” for optimizer

\[
W_{\text{reserve}} = W_{\text{MTO}} - W_{\text{burn}}
\]

\[
W_{\text{dry}} = W_{\text{MTO}} - W_{\text{fuel}}
\]
TASOPT Calculation Loops

Parameter Sampling

Optimization

Design Closure

Design Variables

- Surface spans, areas
- Loads, Shears, Moments
- Structural gauges
- Volumes and Weights
- Drag, Engine size+weight
- Trajectory, Fuel Weight

Total Weight converged?

Optimize Design Variables

Fuel burn minimized?

- Configuration, Weight, Fuel burn, T/O perf, ...
  - Sweep, CL, AR, Altitude, FPR, BPR, Tt4 ...

Design Parameters

- ( Range, Payload, Mach (j) 
  - Nmax, fstress (i) 
  - Tmetal, IBFmax ... )
### TASOPT Calibration/Verification

**B737-800 Sizing, Airframe+Ops Optimization**

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<tr>
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<th>$W_{\text{fuel}}$</th>
<th>$S$</th>
<th>$\Lambda^\circ$</th>
<th>$\lambda_t$</th>
<th>$AR$</th>
<th>$C_{L\text{CR}}$</th>
<th>$h_{\text{CR}}$</th>
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</table>

![Diagram of B737-800 aircraft showing optimized and sized only configurations.](image-url)
Effect of Design Space Expansion

Addition of airfoil, engine, trajectory to design space gives significantly reduced fuel burn
Optimum Aircraft Variation vs Mach, Material Stress

Airframe, engine, trajectory all vary on min-fuel airplane
TASOPT Application — NASA’s N+3 Program

N+3 Program Objective:

Identify concepts and technologies needed for
70% (!) reduction in Fuel / PAX-mile by 2025

Early Realization:
Tweaking conventional designs (B737-800) won’t do it

Solution:
Optimize non-conventional designs (D8.x) in global design space
D8.x Designs for B737-800 Replacement

**D8.1 (Aluminum)**
- 0.72 Mach
- 22.0 L/D
- 130k MTOW
- 5000 ft field
- -49% Fuel Burn

**D8.5 (Composite)**
- 0.74 Mach
- 24.9 L/D
- 100k MTOW
- 5000 ft field
- -70% Fuel Burn

**B737-800**
- 0.80 Mach
- 15.2 L/D
- 166k MTOW
- 8000 ft field

**D8.1b**
- 19.5 L/D
- 120k MTOW
- -45% Fuel Burn
Fuselage Comparison

D8.x

B737–800
D8.x Configuration (vs B737)

Lifting nose, rear flat fuselage

- increased fuselage carryover lift $\rightarrow$ smaller wing
- built-in nose-up moment from nose lift $\rightarrow$ smaller tail
D8.x Configuration (vs B737)

Wide double-bubble fuselage

- partial span loading via 216” wide fuselage (vs 154”)
- reduced floor-beam weight via center floor support
- shorter landing gear and load path
Horizontal Tail Size and Loads Comparison

D8.1 horizontal tail is 28% smaller and 27% lighter. Two-point support reduces bending moment and weight.

B737

\[ Sh = 350 \text{ ft}^2 \]
\[ Wh = 2320 \text{ lb} \]

D8.1

\[ Sh = 252 \text{ ft}^2 \]
\[ Wh = 1690 \text{ lb} \]
Vertical Tail Size and Loads Comparison

D8.1 vertical tail total is 50% smaller and 70% lighter. 5x smaller engine-out yaw moment no longer sizes the VT.

B737
- $S_v = 284 \text{ ft}^2$
- $W_v = 1570 \text{ lb}$

D8.1
- $S_v = 144 \text{ ft}^2$
- $W_v = 470 \text{ lb}$
D8.x Configuration (vs B737)

Reduced $M = 0.72$ with unswept wing (vs $M = 0.80$)

- reduced $C_{Di}$, via larger $AR$ allowed by unsweep
- LE slat can be eliminated, via increased $C_{L_{\text{max}}}$ from unsweep
- NLF on wing bottom possible, via unsweep and no slat
- faster load/unload of two aisles compensates for slower cruise

**B737–800**
30 x 6 per aisle
(30 minutes load, unload)

**D8.x**
23 x 4 per aisle
(15 minutes load, unload)
D8.x Engine/Tail Configuration

• Rear fuselage and tails double as flow-aligning nacelles
  — only minimal nacelles needed
  — shield fan faces from ground observers

• Provides Boundary Layer Ingestion (BLI)
  — local potential flow $M \approx 0.6$ matches fan requirement
  — no additional BL diffusion – no streamwise vorticity into fan

• Fin strakes synergystically exploited:
  — function as pylons carrying engine loads and tail surface loads
  — shield fan faces from ground observers
Breguet Parameter Comparison

\[ W_{\text{fuel}} = W_{ZF} \left[ \exp \left( \frac{TSFC \ D \ R}{M \ L \ a} \right) - 1 \right] \approx W_{ZF} \frac{TSFC}{M} \frac{D}{L} \frac{R}{a} \]

<table>
<thead>
<tr>
<th></th>
<th>B737-800</th>
<th>D8.1</th>
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\[ W_{ZF} \frac{TSFC}{M} \frac{D}{L} = W_{\text{fuel}} \]
Summary

- Examination of entire Airframe+Engine+Ops design space (TASOPT)
- Global optimization for minimum fuel burn
- N+3 D8.x configuration, reduced Mach, give up to 49% fuel burn decrease with conventional technology (45% decrease with 118 ft span constraint)