Design Drivers of Energy-Efficient Transport Aircraft

Mark Drela

MIT Aeronautics and Astronautics
Cambridge, MA USA
Motivation – I

Historical trends indicate large future increases in air traffic


- North America
- Europe
- Asia and Pacific
- Rest of world

Passenger-Kilometers (billions)
Motivation – II

Jet transport R&D focus history:

• 1950’s – 1970’s: Range
• 1980’s – 1990’s: Fuel burn (direct costs)
• 2000’s – 2010’s: Fuel burn (direct + indirect costs from emissions)

Reasonable prediction:

With increases in air traffic providing more impetus, fuel burn will continue as key R&D driver in jet transports, for both economic and environmental reasons.
Outline

• Fundamental design tradeoffs for minimum fuel burn
• Importance of low-order modeling, optimization
• Design parameter sensitivity studies
  – Cruise Mach
  – Structural material properties
  – Engine materials and cycle parameters
  – Field length
  – Cabin room
  – Skin friction reduction
  – Alternative configurations
• Conclusions
Optimum Flight Altitude I

Fuel energy $\sim$ Drag $\times$ Range $= (D_{\text{fuse}} + D_{\text{rest}} + D_i) \times \text{Range}$

Drag from fuselage (payload container) is unavoidable:

$$D_{\text{fuse}} = \frac{\gamma}{2} p \, M^2 \, C_{f_{\text{wet}}} \, F_f \, A_{\text{wet}}$$

For fixed $M$, the only way to reduce $D_{\text{fuse}}$ is via $p$ (fly higher)

But the “overhead” $D_{\text{rest}} + D_i$ increases with altitude
Optimum Flight Altitude II

At optimum altitude, $D_{\text{fuse}} \sim p$ balances "overhead" $D_{\text{rest}} + D_i$
Breguet Relation I

\[ W_{\text{fuel}} \simeq W_{ZF} \times TSFC \times \frac{1}{M} \times \frac{D}{L} \times \frac{R}{a} \]  
(Linear approx.)

\[
\begin{array}{c|c|c|c|c}
 & TSFC & a & M & L/D \\
\hline
W_{\text{fuel}} & 0.5 / \text{hr} & 320 \text{ m/s} & 0.8 & 17 \\
W_{ZF} & & & & \\
\end{array}
\]

→ Linearized form is adequate for coarse analysis
Breguet Relation II

\[ W_{\text{fuel}} \simeq W_{ZF} \times TSFC \times \frac{1}{M} \times \frac{D}{L} \times \frac{R}{a} \]

- Fuel weight for fixed range \( R \) is product of:
  - \( W_{ZF} \) Zero-fuel weight (at landing)
  - \( TSFC \) Thrust-specific fuel consumption
  - \( 1/M \) Inverse Mach number
  - \( D/L \) Drag/lift ratio

- Can always reduce any one parameter, but the others will likely increase

- To reduce net fuel burn, must account for interactions

\( \rightarrow \) Use low-order models with Multi-Disciplinary Optimization
Low-Order Modeling

• Detail-design space is enormous — cannot optimize
• Optimization feasible only with small low-order models
• To be realistic, a low-order model must capture interactions between Breguet factors: . . .
  – structural weight
  – aerodynamic performance
  – propulsion performance
  – cruise altitude

→ Results here were obtained with TASOPT MDO method
TASOPT Summary – I

Collection of coupled low-order physical models . . .

• Primary structure
• Aero
• Engine
• Balance, trim, stability
• Flight trajectory

. . . wrapped with an optimizer
TASOPT Low-Order Model

Primary structure and weight models
TASOPT Low-Order Model

CFD-based profile and induced drag models
TASOPT Low-Order Model

Turbofan performance and turbine-cooling model

Flowpath is simulated to predict engine performance
TASOPT Low-Order Model

Trajectory simulation for takeoff and fuel burn

Trajectory-equation integration predicts fuel burn
TASOPT Summary – II

TASOPT does not use

- Historical correlations for primary structure weights
- Wetted-area \times\ form-factor methods for drag prediction
- Specified-thickness airfoils
- Assumed engine parameters and performance
- Assumed trim conditions

→ These cannot be trusted for “outside the box” designs
TASOPT Calculation Loops

**Design Inputs**

**Design Parameters**
- Range
- Nmax
- CMfuse
- Payload
- fstress
- IBFmax
- Mach
- Tmetal

**Model Parameters**
- Design Variables
  - (Sweep, CL, AR, Altitude, FPR, BPR, Tt4, ...)

**Optimization**

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

- Total Weight converged?
  - N
- Fuel burn minimized?
  - Y

**Design Outputs**
- Sweep
- FPR
- Weights
- Fuel burn
- Dimensions
- Engine size
- T/O perf
- CL
- BPR
- AR
- Tt4
- Altitude
- Gauges

Output = f(Input) results represent *closed, optimized* design
Importance of Global Optimization

Global optimization required to find true optimum
Parameter Sensitivity Studies

Free parameters studied here were chosen based on:

- significant effect on fuel burn
- strong dependence on technology
- subject of current or expected future R&D

→ For every parameter change, MDO procedure re-optimizes everything for maximum exploitation
Baseline Aircraft

<table>
<thead>
<tr>
<th>Class</th>
<th>B737,A320...</th>
<th>B777,A340...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuse.OML</td>
<td>737-800</td>
<td>777-300ER</td>
</tr>
<tr>
<td>Payload</td>
<td>37000 lb</td>
<td>115000 lb</td>
</tr>
<tr>
<td>Range</td>
<td>3000 nmi</td>
<td>6500 nmi</td>
</tr>
<tr>
<td>Mach</td>
<td>0.80</td>
<td>0.84</td>
</tr>
<tr>
<td>Field</td>
<td>8000 ft</td>
<td>9500 ft</td>
</tr>
</tbody>
</table>

Two largest segments of current air transportation market
Reduced Cruise Mach Number

• An “easy” way to reduce fuel burn, since

\[ W_{ZF}, \; TSFC, \; D/L \; \text{all decrease with} \; M_{CR} \]

• Has significant drawbacks from
  – Increased travel times for passengers
  – Reduced productivity for airlines

• It's still useful to examine the tradeoffs
Reduced Cruise Mach Number – Fuel Burn

$M_{CR} = 0.70$

$M_{CR} = 0.75$

$M_{CR} = 0.80$

$\frac{W_{fuel}}{W_{fuel_{0.8}}}$

span unconstrained

span < 118 ft
Reduced Cruise Mach Number – L/D

$M_{CR} = 0.70$

$M_{CR} = 0.75$

$M_{CR} = 0.80$
Reduced Cruise Mach Number – Weight

Smaller $W_{ZF}$ compensates for larger $D/L$ from span constraint.
Reduced Cruise Mach Number – Altitude

$M_{CR} = 0.70$

$M_{CR} = 0.75$

$M_{CR} = 0.80$

$D_{fuse}$ and its imperative to fly high

→ Produces lower optimum cruise altitude
Improved Materials

• Chosen material parameter is allowable-stress / density
• Modeled as “stress factor”, representing technology
• Both B737 and B777-class aircraft are examined
Improved Materials – B737 Fuel Burn

$\frac{\sigma}{\rho} \sim 1$

$\frac{\sigma}{\rho} \sim 1.25$

$\frac{\sigma}{\rho} \sim 1.5$

$\frac{W_{\text{fuel}}}{W_{\text{fuel}}^1}$

Allowable specific stress
Improved Materials – B737 L/D

$\sigma/\rho \sim 1$

$\sigma/\rho \sim 1.25$

$\sigma/\rho \sim 1.5$
Improved Materials – B737 Weight

\[ \frac{\sigma}{\rho} \sim 1 \]

\[ \frac{\sigma}{\rho} \sim 1.25 \]

\[ \frac{\sigma}{\rho} \sim 1.5 \]

span < 118 ft

span unconstrained

span < 118 ft
Lighter material reduces “overhead” of wing weight
→ Produces higher optimum cruise altitude
Improved Materials – B777 Fuel Burn

\[ \sigma/\rho \sim 1 \quad \sigma/\rho \sim 1.25 \quad \sigma/\rho \sim 1.5 \]

\[
\frac{W_{\text{fuel}}}{W_{\text{fuel}1}}
\]

Allowable specific stress
Improved Materials – B777 L/D

σ/ρ ~ 1  

σ/ρ ~ 1.25  

σ/ρ ~ 1.5  

$L/D$
Improved Materials – B777 Weight

Fuel benefits are \( \sim 1.5 \times \) greater for B777-class aircraft.
Engine Technology

1. Overall pressure ratio (\( OPR \))
   - Determines ideal Brayton-cycle thermal efficiency
   - Limited by compressor stability, materials

2. Turbine metal temperature (\( T_{metal} \))
   - Limits max turbine inlet temperature (\( T_{t4} \))
   - Biases \( T_{t4} \) / cooling tradeoff
Engine Technology

In aircraft/engine sizing, $OPR$ and $T_{\text{metal}}, T_{t4}$ interact via:

- Cruise fuel burn (increased by cooling losses)
- Thrust lapse and cruise altitude
- Takeoff thrust requirement
- Climb gradient requirement
- Engine weight

Complex interactions require MDO for maximum exploitation of improved $OPR, T_{\text{metal}}$
-> $OPR$ and $T_{metal}$ improvements are highly synergistic
Engine Technology – Turbine Temps. and Cooling Flow

![Graph showing the relationship between cooling flow ratio and maximum metal temperature for different OPR values.](image)

- OPR = 30
- OPR = 35
- OPR = 40
- OPR = 45
- OPR = 50
- OPR = 55

Maximum $T_{metal}$ [K]

- $T_{t4}$ CR
- $T_{t4}$ TO

Cooling flow ratio $m_{cool}/m_{core}$ vs. maximum $T_{metal}$ [K] for different OPR values.
Reduced Field Length

Congestion relief via use of smaller peripheral airfields, but requires aircraft with shorter-field capability

→ Want to optimize aircraft/engine/operation combination to minimize short-field fuel-burn penalty
Reduced Field Length – Fuel Burn

\[ l_{BF} = 3000 \text{ ft} \]

\[ l_{BF} = 5000 \text{ ft} \]

\[ l_{BF} = 8000 \text{ ft} \]

\[ W_{\text{fuel}} / W_{\text{fuel,8000}} \]

Balanced field length [ft]
Reduced Field Length – Bypass, Fan Pressure Ratios

- $l_{BF} = 3000$ ft
- $l_{BF} = 5000$ ft
- $l_{BF} = 8000$ ft

Graph showing BPR and FPR ratios for Takeoff and Cruise conditions.

**BPR**
- Takeoff: Blue line
- Cruise: Red line

**FPR**
- Takeoff: Red line
- Cruise: Blue line
Reduced Field Length – Cruise Altitude

$\ell_{BF} = 3000$ ft

$\ell_{BF} = 5000$ ft

$\ell_{BF} = 8000$ ft

$\rightarrow$ Fuel-optimized aircraft for shorter fields deviate substantially from current development trends
Increased Cabin Room

Passengers always want more cabin room . . .

But what’s the cost?

→ Re-optimize aircraft with specified larger cabin/fuselage to minimize fuel-burn penalty
Increased Cabin Room – Fuel Burn

座席幅とピッチ因子に対する燃油燃焼量の変化

座席幅

ピッチ

座席幅, ピッチ因子
Increased Cabin Room – Aircraft Weight

1.2× more width and 1.2× more pitch requires . . .

- 15% more fuel
- 8% larger gross takeoff weight
Skin Friction Reduction

1. Riblets
   - Relatively low risk
   - Modest reductions, typically 5% at most
   - Modest complications with installation, maintenance

2. Laminar flow, natural or via suction (NLF or LFC)
   - High risk
   - Potentially large reductions
   - Complex installation, operation, maintenance
Skin Friction Reduction

Full exploitation requires changes in airfoil architecture:

- Interacts with wave drag and cruise-Mach optimization
- Must account for possibility of occasional contamination
- Full optimization is beyond scope of conceptual design

\[ C_p \rightarrow \text{ideal transonic airfoil} \]

\[ \text{excessive wave drag} \]

\[ \text{lost lift} \]

\[ \text{required for laminar flow} \]

\[ \text{shock strength} \]

\[ \text{shock} \]

\[ -C_p^* \]

\[ C_f \]

→ Will only attempt simple benefit estimation via \( C_f \) scaling
Skin Friction Reduction – Fuel Burn and Aircraft Weight

Skin friction factor

- fuselage only
- wing+tails only

W_{MTO} / W_{MTO 1}

W_{fuel} / W_{fuel 1}

Skin friction factor

0.96
0.98
1

0.96
0.98
1

0.85
0.9
0.95
1
Alternative Configurations

Numerous alternative configurations examined in the past:

- Blended Wing Body
- C-wing
- Joined Wing
- Strut-Braced Wing
- D8 Concept

Evaluation of all concepts is beyond scope here (TASOPT assumes wing+tube topology)

→ Will examine only Strut-Braced Wing, D8 Concept
Strut Braced Wing – Fuel Burn vs Mach

$M_{CR} = 0.70$

$M_{CR} = 0.75$

$M_{CR} = 0.80$

$W_{fuel} / W_{fuel, 0.8, cantilever}$

- span < 118 ft
- span < 132 ft
- span unconstrained

$M_{CR}$
Strut Braced Wing – Aircraft Weight vs Mach

$M_{CR} = 0.70$

$M_{CR} = 0.75$

$M_{CR} = 0.80$

$W_{MTO} / W_{MTO\text{cantilever}} 0.8$

$W_{MTO} / W_{MTO\text{cantilever}} 0.8$

$cantilever$

$span \text{ unconstrained}$

$span < 132 \text{ ft}$

$span < 118 \text{ ft}$

$M_{CR}$

$0.7\quad 0.72\quad 0.74\quad 0.76\quad 0.78\quad 0.8$

$0.7\quad 0.72\quad 0.74\quad 0.76\quad 0.78\quad 0.8$
Strut Braced Wing

- Up to 8% fuel burn advantage relative to cantilever wing
- But numerous other issues must be addressed
  - Negative loads and strut buckling
  - Load path from landing gear to wing
  - High wing crash safety
  - Complex aeroelasticity

→ Further investigations are indicated
D8 Concept – Two Variants

D8.0
Mach = 0.80
span = 118 ft

D8.2
Mach = 0.72
span = 118 ft

span = 138 ft
(no span constraint)
D8 Concept – Fuselage Comparison

737–800

D8.x

D8.2

737–800
D8 Fuselage Features

- increased fuselage carryover lift
- less-negative wing-body pitching moment
- smaller CG travel due to the shorter cabin
- larger tail effectiveness at the high location
- lighter two-point supported horizontal tail
- rear engines with Boundary Layer Ingestion (BLI), on D8.2
D8 Fuselage Benefits

- fuselage lift and less tail download shrink wing area by 9%
- horizontal tail area shrinks by 20%
- tail download is less negative by 3% of aircraft weight
- BLI improves propulsive efficiency by 6–8% on D8.2

→ Global MDO optimizes engine+aircraft+operation to maximally exploit D8 fuselage
## D8.x Fuel Burn Comparison

<table>
<thead>
<tr>
<th></th>
<th>$M$</th>
<th>$C_L$</th>
<th>$L/D$</th>
<th>span [ft]</th>
<th>$W_{MTO}$ frac</th>
<th>$W_{fuel}$ frac</th>
</tr>
</thead>
<tbody>
<tr>
<td>B737</td>
<td>0.80</td>
<td>0.559</td>
<td>16.33</td>
<td>118</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>D8.0</td>
<td>0.80</td>
<td>0.567</td>
<td>16.39</td>
<td>118</td>
<td>0.894</td>
<td><strong>0.882</strong></td>
</tr>
<tr>
<td>D8.2</td>
<td>0.72</td>
<td>0.699</td>
<td>18.32</td>
<td>118</td>
<td>0.775</td>
<td><strong>0.671</strong></td>
</tr>
<tr>
<td>D8.2</td>
<td>0.72</td>
<td>0.688</td>
<td>19.84</td>
<td>138</td>
<td>0.815</td>
<td>0.658</td>
</tr>
</tbody>
</table>

- Low-risk D8.0 variant has 12% fuel burn reduction
- Medium-risk D8.2 variant has 33% fuel burn reduction, or 34% with no span constraint
Conclusions

• Effective conceptual design via low-order modeling
• Global optimization required to find optimum
• Design parameter sensitivity studies presented:
  – Cruise Mach
  – Structural material specific strength
  – Engine technology parameters
  – Field length
  – Cabin room
  – Skin friction reduction
  – Alternative configurations
• Results indicate paths for future fuel burn reductions