Development of the D8 Transport Configuration

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Presentation Outline

- Background
- Design Optimization (TASOPT)
- D8.x Configurations
- Aerodynamic Features and Analysis

Background

NASA's N+3 Program:

Identify concepts and technologies needed
for 70% (!) reduction in Fuel / PAX-mile
from current-technology baseline by 2035

MIT/Aurora/Pratt team's response for Phase I:

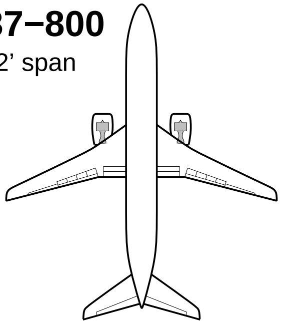
- D8.5 advanced-tech configuration, for 2035 timeframe
- D8.1 current-tech configuration, for today

D8.x Family Tree

N+3 Project

737–800

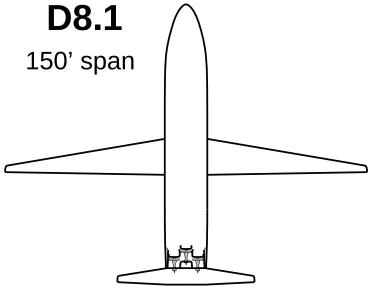
112’ span



Baseline

D8.1

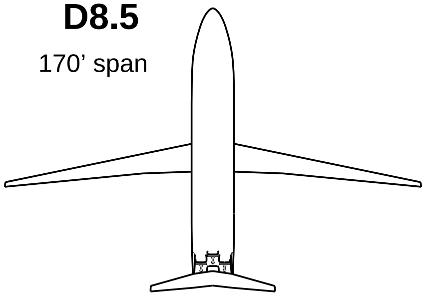
150’ span



Current Tech (+ BLI)

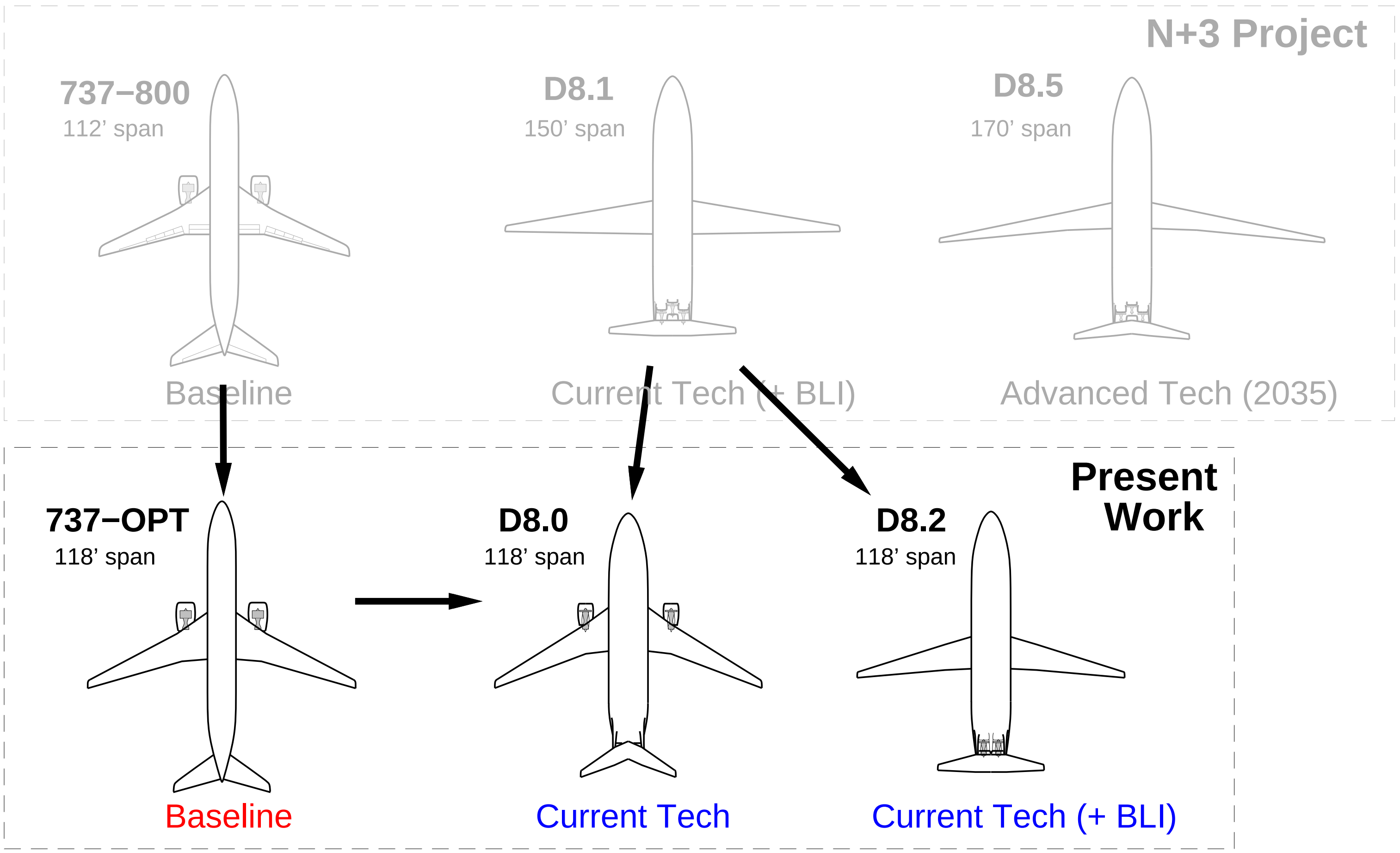
D8.5

170’ span



Advanced Tech (2035)

D8.x Family Tree



N+3 Project

737−800
112’ span
Baseline

D8.1
150’ span
Current Tech (+ BLI)

D8.5
170’ span
Advanced Tech (2035)

Present Work

737−OPT
118’ span
Baseline

D8.0
118’ span
Current Tech

D8.2
118’ span
Current Tech (+ BLI)

- New baseline (optimized 737-800)
- Constrained span at 118’ (same as new baseline’s)
- Two engines (from three)
- New conventional wing/engine D8.0 version

Fuel Burn

Breguet relation:

$$W_{\text{fuel}} \;=\; W_{\text{ZF}}\left[\exp\left(\frac{\mathit{TSFC}}{M}\,\frac{C_D}{C_L}\,\frac{R}{a}\right) \,-\, 1\right] \;\simeq\; W_{\text{ZF}} \times \frac{\mathit{TSFC}}{M} \times \frac{C_D}{C_L} \times \frac{R}{a}$$

- Fuel burn is approximately the product of . . .

W_{ZF}	zero-fuel weight (at landing)
TSFC/M	specific fuel consumption
C_D/C_L	drag/lift ratio

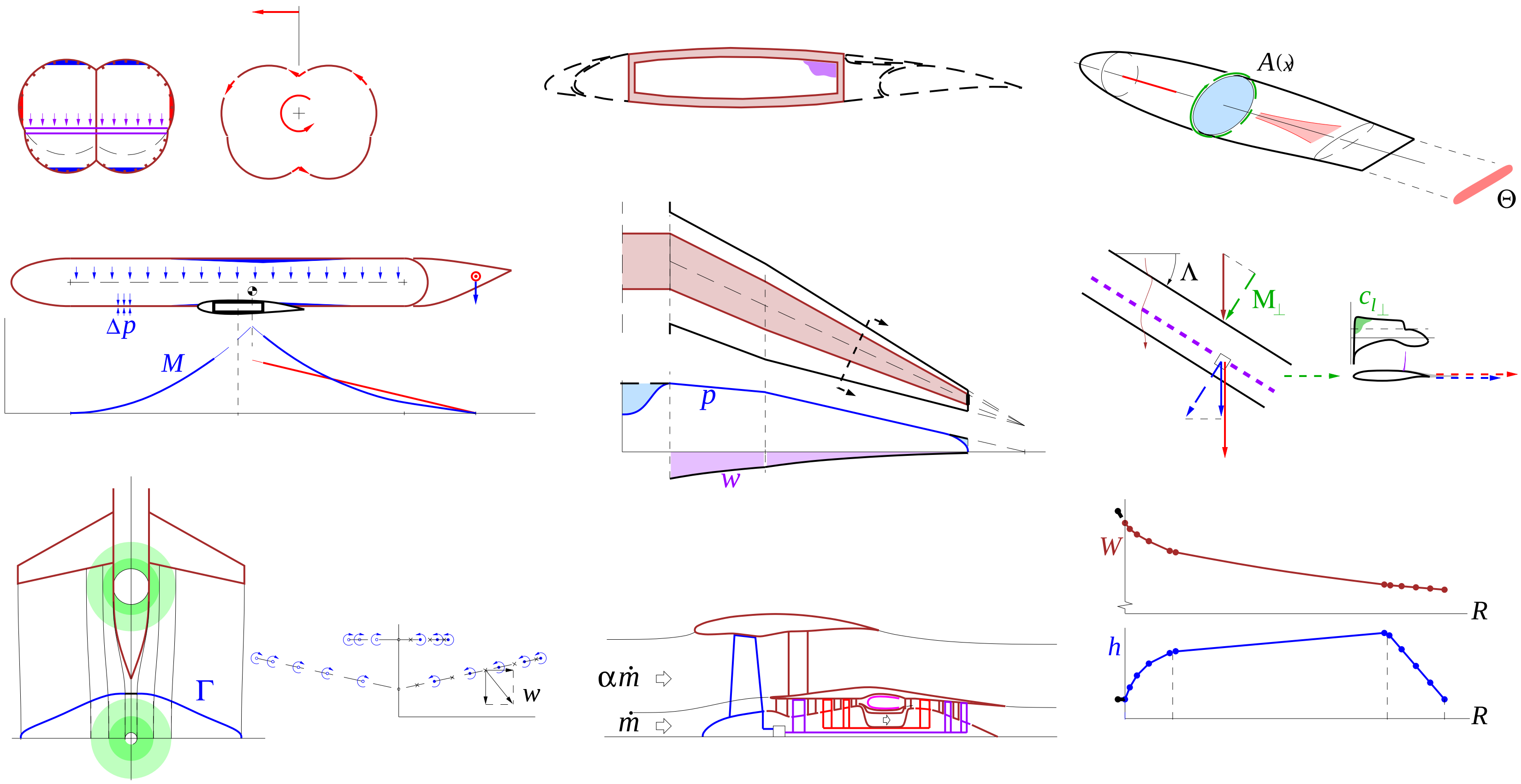
- Not useful as design guide, since factors strongly interact:
  - Larger $AR \rightarrow C_D/C_L$ decreases, W_{ZF} increases
  - Larger fan $\rightarrow \mathit{TSFC}$ decreases, C_D/C_L and W_{ZF} both increase
  - etc . . .

$\longrightarrow$ Tradeoffs are crucial. MDO required to minimize W_{fuel}

TASOPT MDO Code

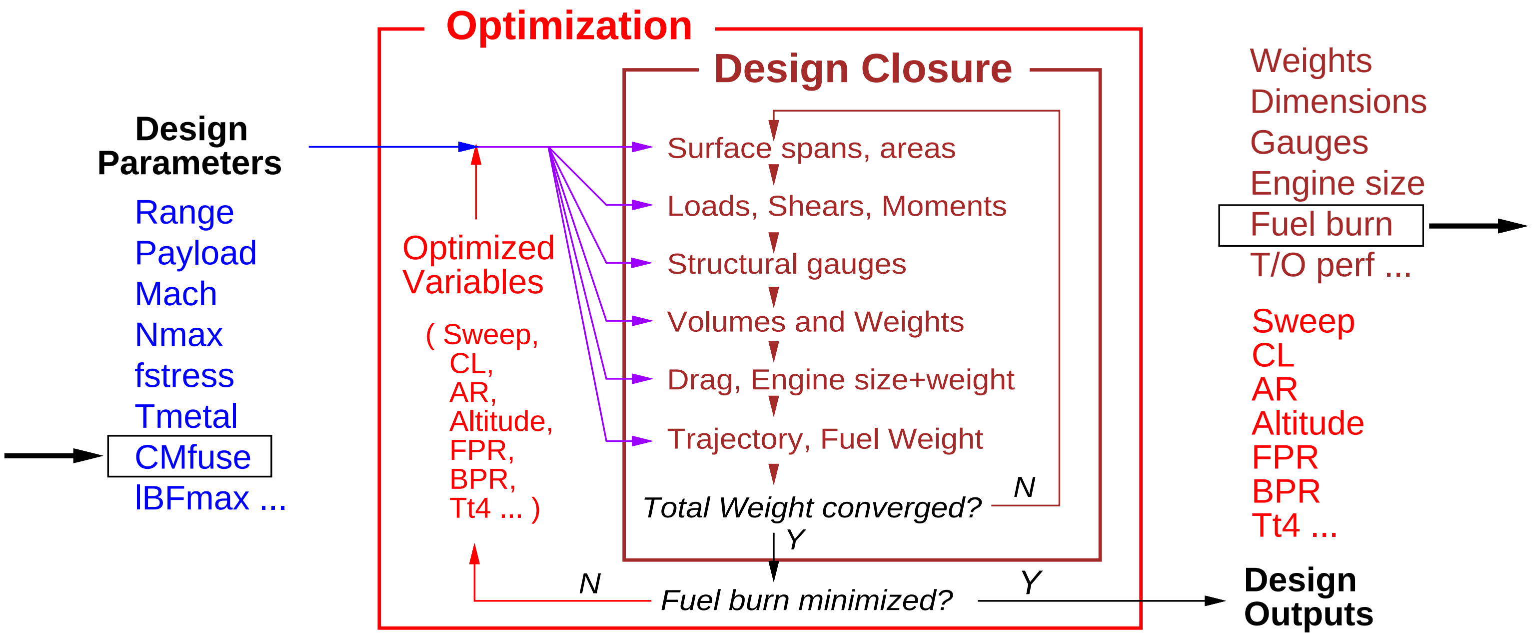
Collection of coupled low-order physical models:

- Primary structure
- Aero performance
- Engine performance
- Trim, Stability
- Takeoff performance
- Flight Trajectory



TASOPT Calculation Loops

- Closes design for specified Payload, Range
- Optimizes parameter subset (Design Variables) to minimize fuel burn



Optimization

Design Closure

Design Parameters

Range
Payload
Mach
Nmax
fstress
Tmetal
CMfuse
lBFmax ...

Optimized Variables

(Sweep,
CL,
AR,
Altitude,
FPR,
BPR,
Tt4 ...)

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

Total Weight converged? *N* *Y*

N *Fuel burn minimized?* *Y*

Weights
Dimensions
Gauges
Engine size
Fuel burn
T/O perf ...

Sweep
CL
AR
Altitude
FPR
BPR
Tt4 ...

Design Outputs

⟶ Fuel burn *of re-sized and re-optimized airplane* is the figure of merit for design change evaluation

Specifications for TASOPT

Same for Baseline and D8.x:

- Payload: $W_{\mathrm{pay}} = 38700\,\mathrm{lb}$
- Range: $R = 3000\,\mathrm{nmi}$
- Field: $l_{\mathrm{BF}} \leq 7500\,\mathrm{ft}$
- Span: $b \leq 118\,\mathrm{ft}$
- 2D airfoil characteristics
- Engine component efficiencies
- Material properties
- Misc. weight fractions (attendants, seats, APU, LG . . .)

Different between Baseline and D8.x:

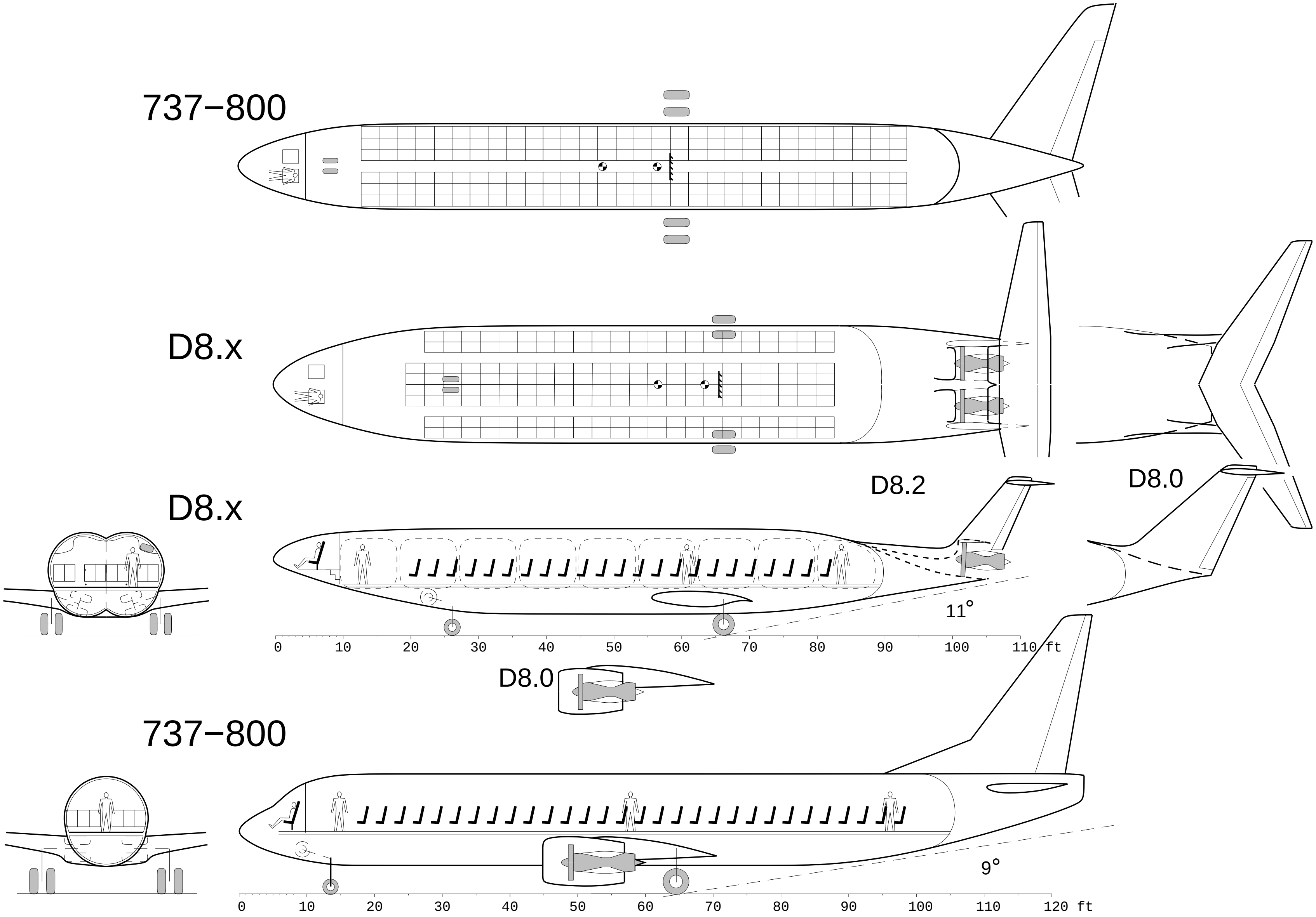
- Fuselage layout
- Fuselage lift, moment properties
- Airplane topology (tail type, engine placement)
- Cruise Mach for D8.2

$\longrightarrow$ Objective is to evaluate D8 fuselage, airplane topology

Design Variables Selected for Optimization

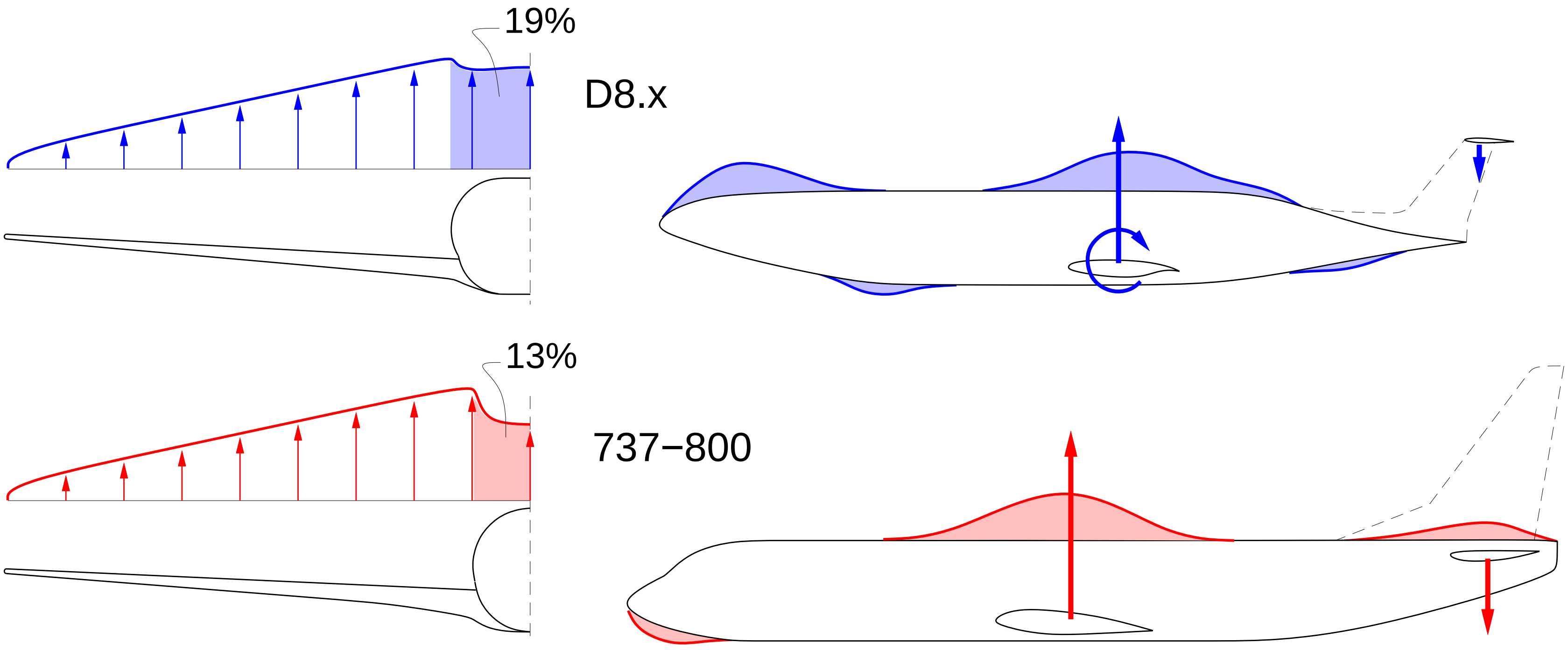
$C_{L_{\mathrm{CR}}}$	cruise lift coefficient
AR	aspect ratio
Λ	wing sweep angle
$(t/c)_o$	root airfoil thickness ratio
$(t/c)_s$	panel-break and tip airfoil thickness
λ_o	inner-panel taper ratio
λ_s	outer-panel taper ratio
$r_{c_{\ell_s}}$	local/root c_ℓ ratio at panel break
$r_{c_{\ell_t}}$	local/root c_ℓ ratio at tip
FPR_{D}	design fan pressure ratio
BPR_{D}	design bypass ratio
$T_{t4_{\mathrm{TO}}}$	turbine inlet temperature at takeoff
$T_{t4_{\mathrm{CR}}}$	turbine inlet temperature in cruise
h_{CR}	start-of cruise altitude

737/D8 Fuselage Comparison



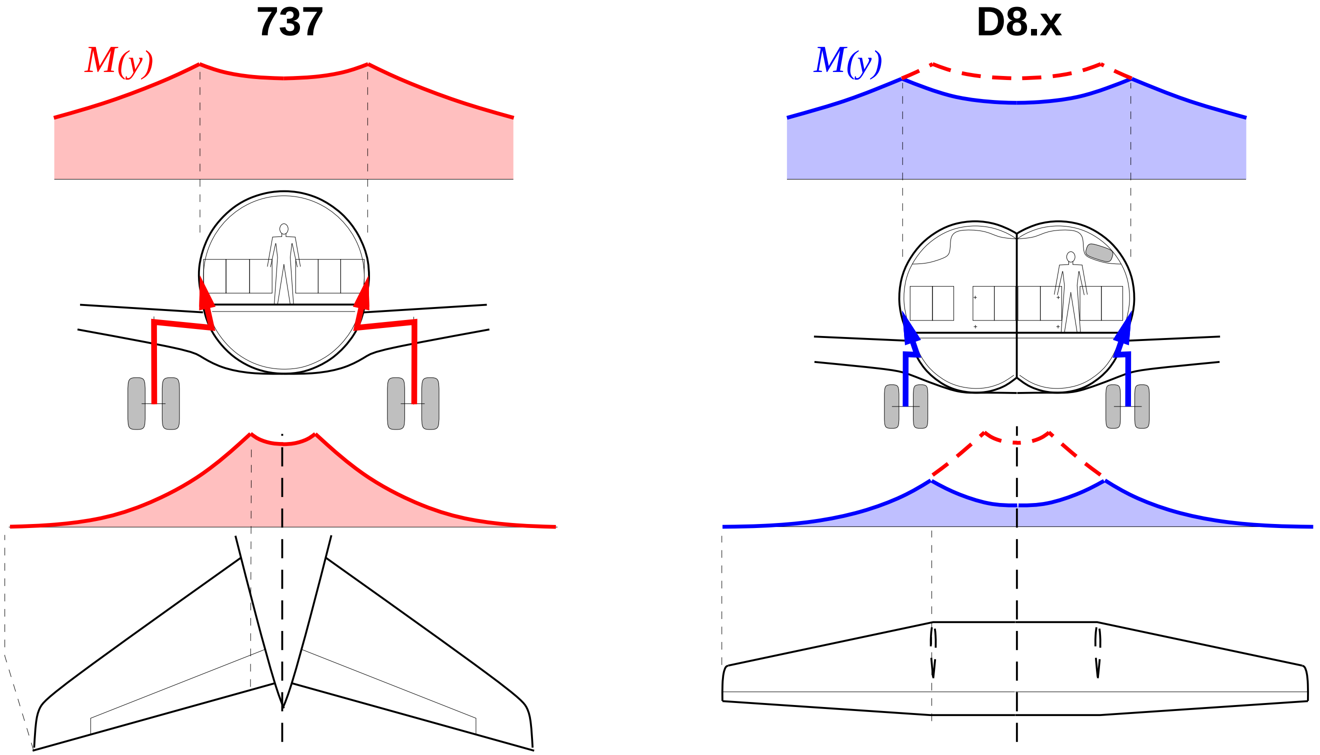
D8 Fuselage

- More carryover lift → shrinks exposed wing
- Nose-up trimming moment → shrinks tail, tail download, wing

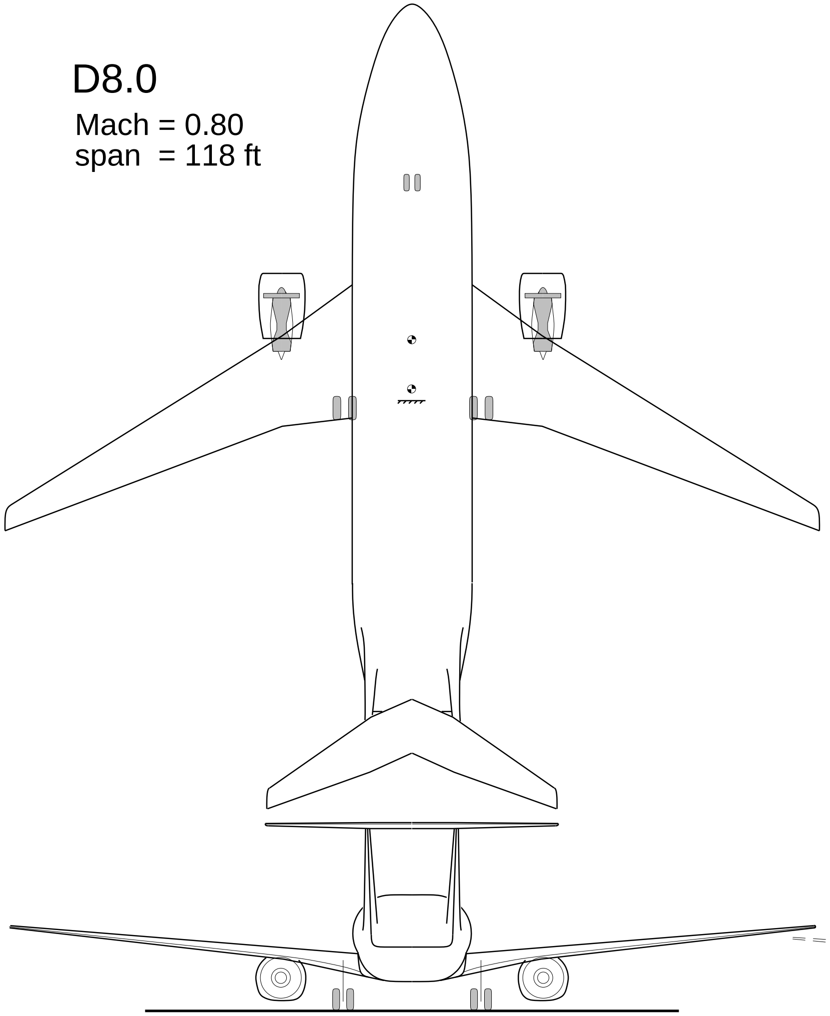


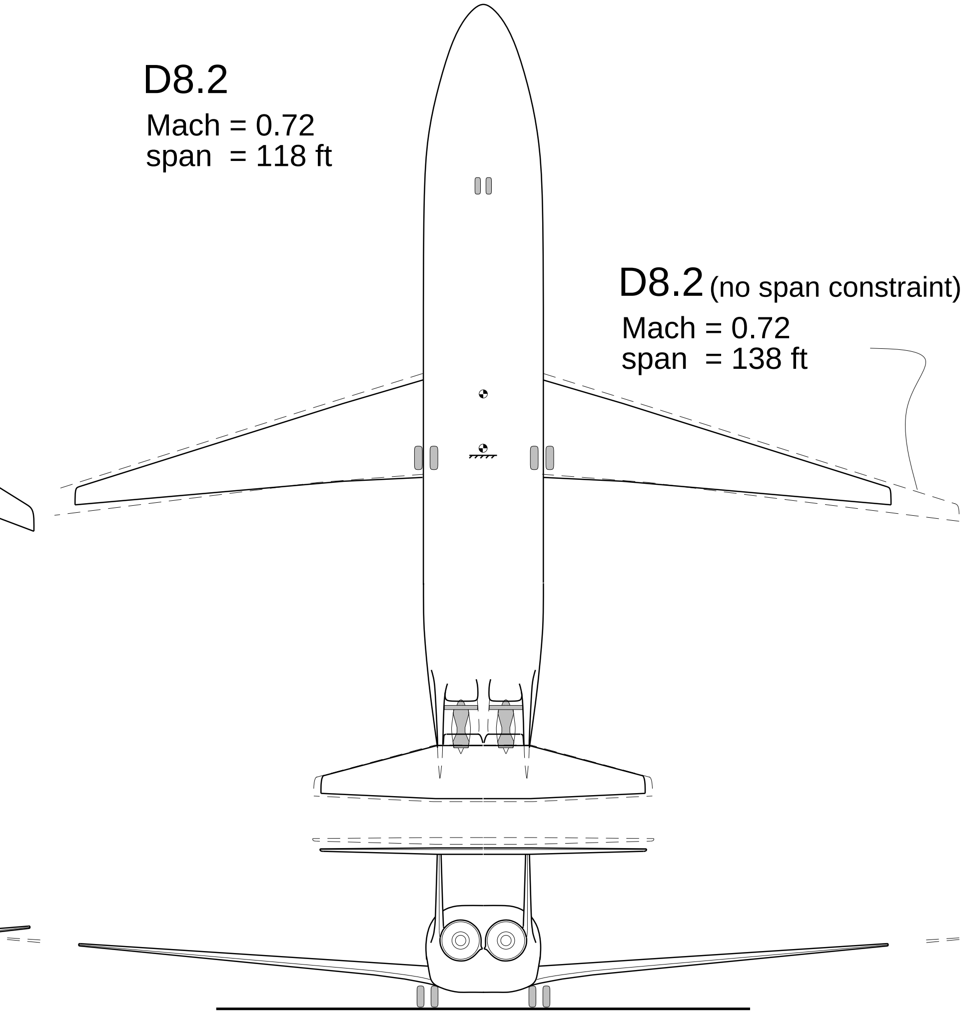
D8 Fuselage

- Wider sidebody load points → partial spanloading, lighter LG
- Shorter cabin → less window weight, less CG travel
- Center floor support → lighter floor
- Twin-fin “Pi-tail” → lighter horizontal tail



D8.0 and D8.2 Configurations



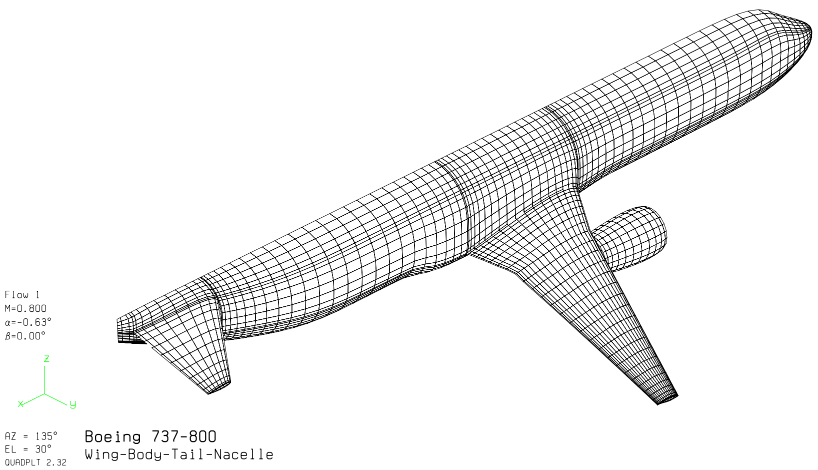


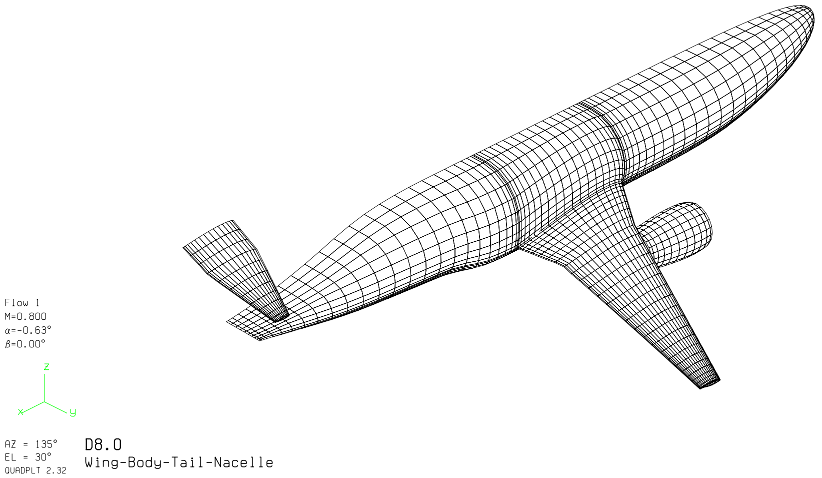
Configuration Parameter Summary from TASOPT

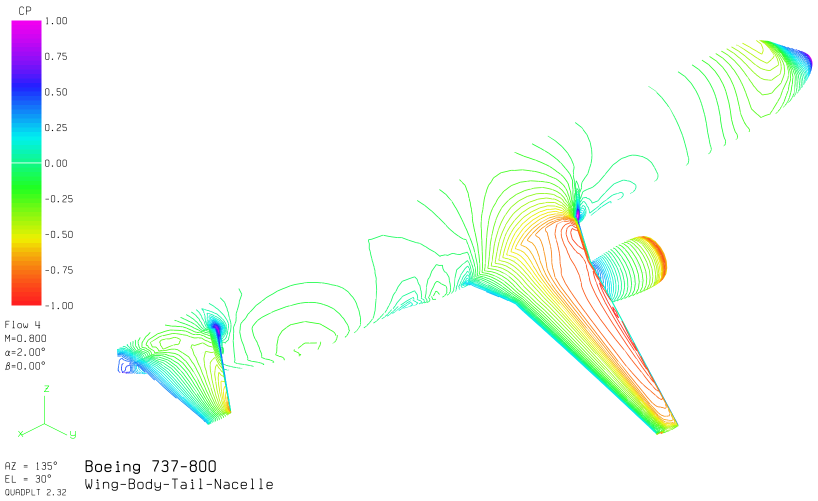
	M	Λ deg	AR	C_L	L/D	span con?	b ft	W_{MTO} frac	W_{fuel} frac	eng. opt?	BPR	FPR	$TSFC$ 1/hr	h_{CR} Kft
737-800	0.80	25	10.2	0.55	15.9	N	112	1.031	1.052	N	5.10	1.650	0.565	33.5
737-OPT	0.80	27	10.6	0.56	16.3	N	118	1.000	$\boxed{1.000}$	N	5.10	1.650	0.559	35.8
D8.0	0.80	28	10.9	0.57	16.4	Y	118	0.898	0.894	N	5.10	1.650	0.555	38.1
D8.0	0.80	28	10.3	0.57	16.4	Y	118	0.894	$\boxed{0.882}$	Y	6.65	1.765	0.547	39.3
D8.2	0.72	13	13.3	0.70	18.3	Y	118	0.775	$\boxed{0.671}$	Y	6.91	1.626	0.477	36.6
D8.2	0.72	14	15.7	0.69	19.8	N	138	0.815	0.658	Y	7.31	1.652	0.475	38.3

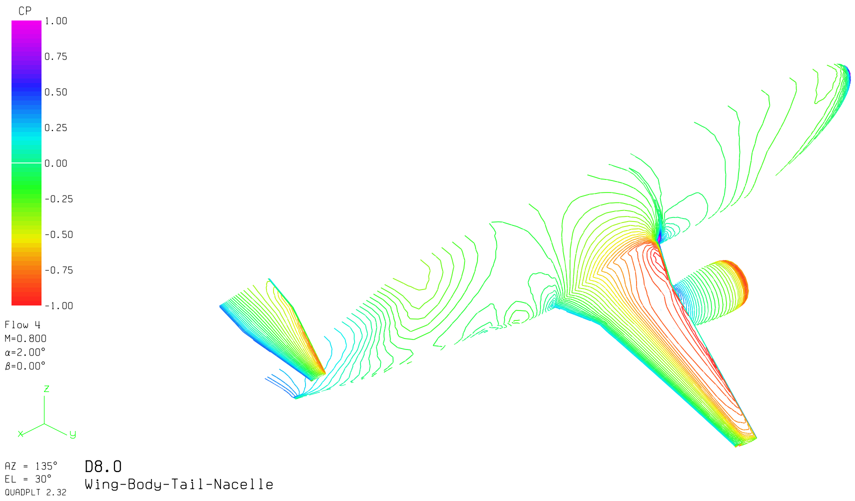
- D8.0 uses -12% less fuel than baseline
- D8.2 uses -33% less fuel than baseline

QUADPAN Models for TASOPT Calibration and Diagnosis



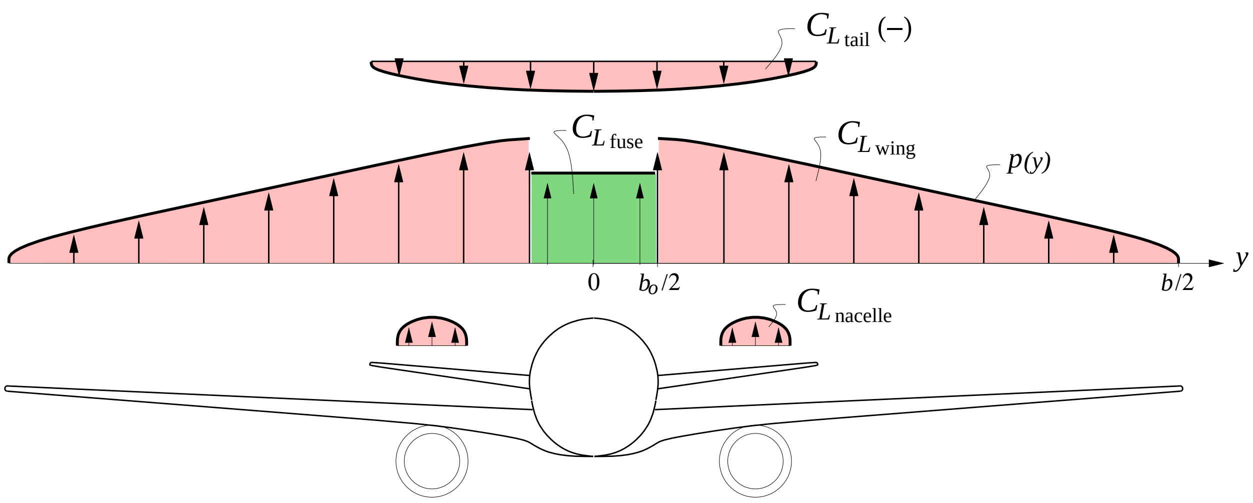


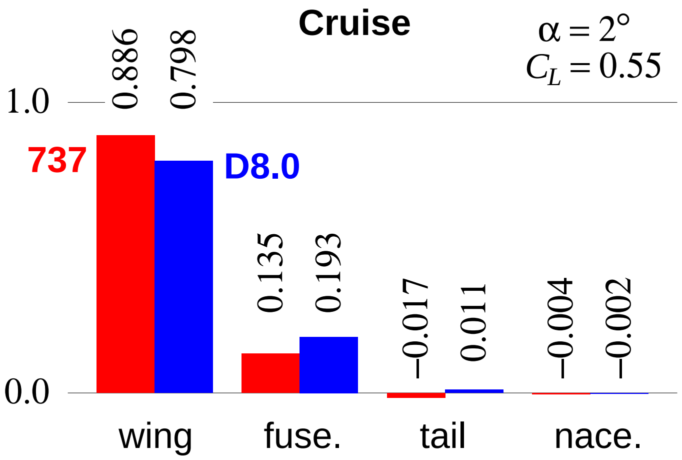


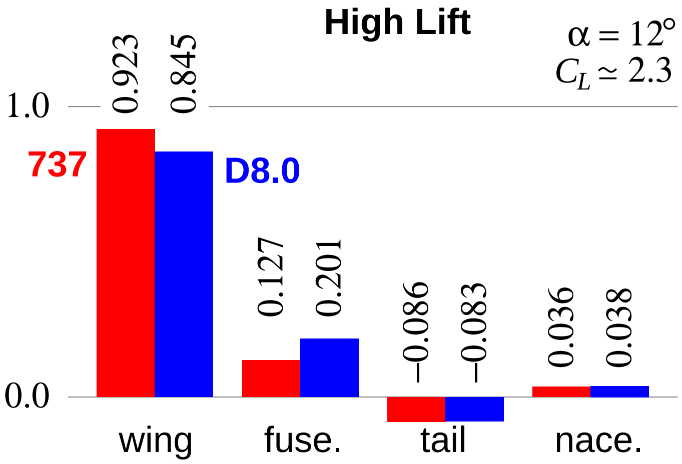


Component Lift Breakdown

$$C_L \;=\; C_{L_{\mathrm{wing}}} + C_{L_{\mathrm{fuse}}} + C_{L_{\mathrm{tail}}} + C_{L_{\mathrm{nacelle}}}$$







Tail Size

Horizontal Tail area, set from stability + trim requirements:

$$\mathcal{V}_{\mathrm{h}} \equiv \frac{S_{\mathrm{h}}}{S}\frac{\ell_{\mathrm{h}}}{\bar{c}} = \left(SM_{\min} - \frac{C_{M_{\mathrm{ac}}}}{C_{L_{\max}}} + \frac{\Delta x_{\mathrm{cg}}}{\bar{c}}\right)\left(\frac{(-c_{\ell_{\mathrm{h}}})_{\max}}{C_{L_{\max}}} + \frac{\partial c_{\ell_{\mathrm{h}}}}{\partial C_L}\right)^{-1}$$

Depends on:

$SM_{\min}$	minimum static margin at the aft-CG limit
$C_{M_{\mathrm{ac}}}$	pitching moment of tailless configuration
Δx_{cg}	CG travel range
$\partial c_{\ell_{\mathrm{h}}}/\partial C_L$	HT lift-curve efficiency

	$C_{M_{\mathrm{ac}}}$	$\Delta x_{\mathrm{cg}}/\bar{c}$	$\partial c_{\ell_{\mathrm{h}}}/\partial C_L$
737-800	-0.1665	0.586	0.36
D8.0	-0.0825	0.507	0.41

$\longrightarrow$ D8 fuselage reduces $C_{M_{\mathrm{ac}}}$ and Δx_{cg}

$\longrightarrow$ Pi-tail increases $\partial c_{\ell_{\mathrm{h}}}/\partial C_L$

Allows smaller HT

Cruise Tail Load

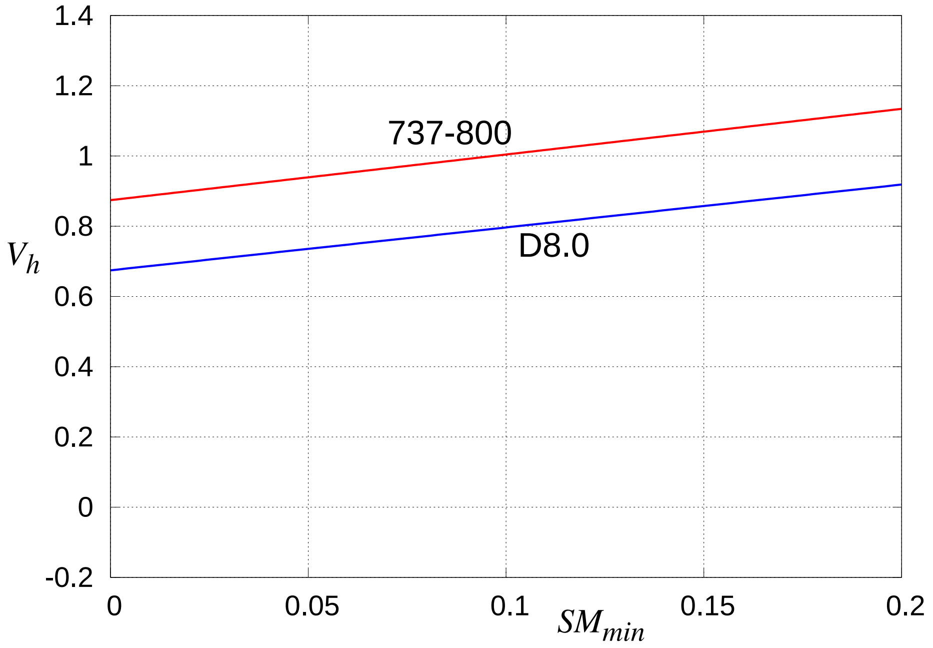
Tail load fraction of given HT, from pitch trim requirement:

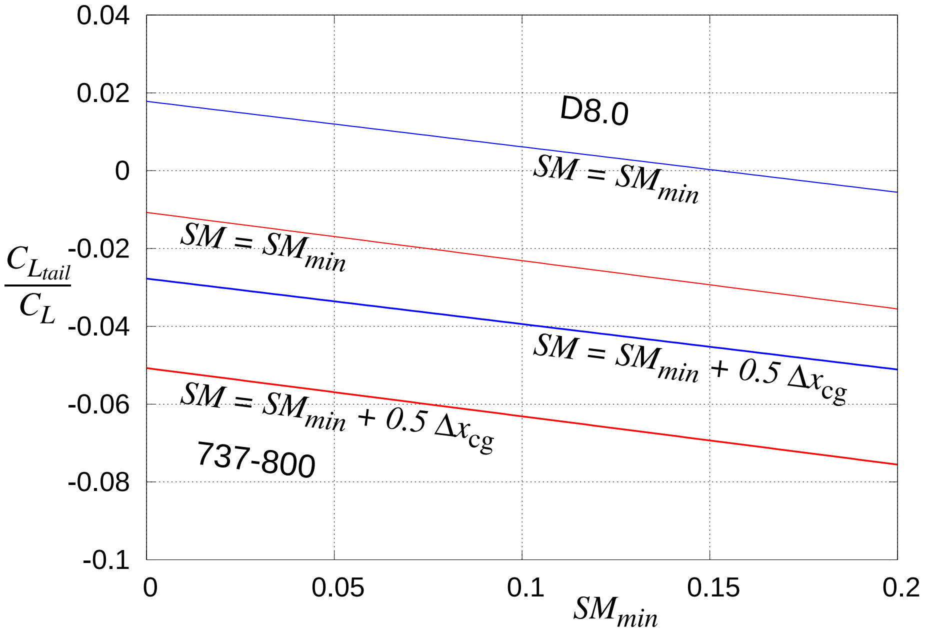
$$\frac{C_{L_{\rm tail}}}{C_L} \;=\; \frac{1}{\ell_{\rm h}/\bar{c}}\left(\frac{C_{M_{\rm ac}}}{C_L} \,-\, SM \,+\, \frac{\partial c_{\ell_{\rm h}}}{\partial C_L}\mathcal{V}_{\rm h}\right)$$

$\longrightarrow$ D8 + Pi-tail has less-negative $C_{M_{\rm ac}}$ and larger $\partial c_{\ell_{\rm h}}/\partial C_L$

Gives smaller cruise HT download for given SM

Tail Sizing and Cruise Tail Load



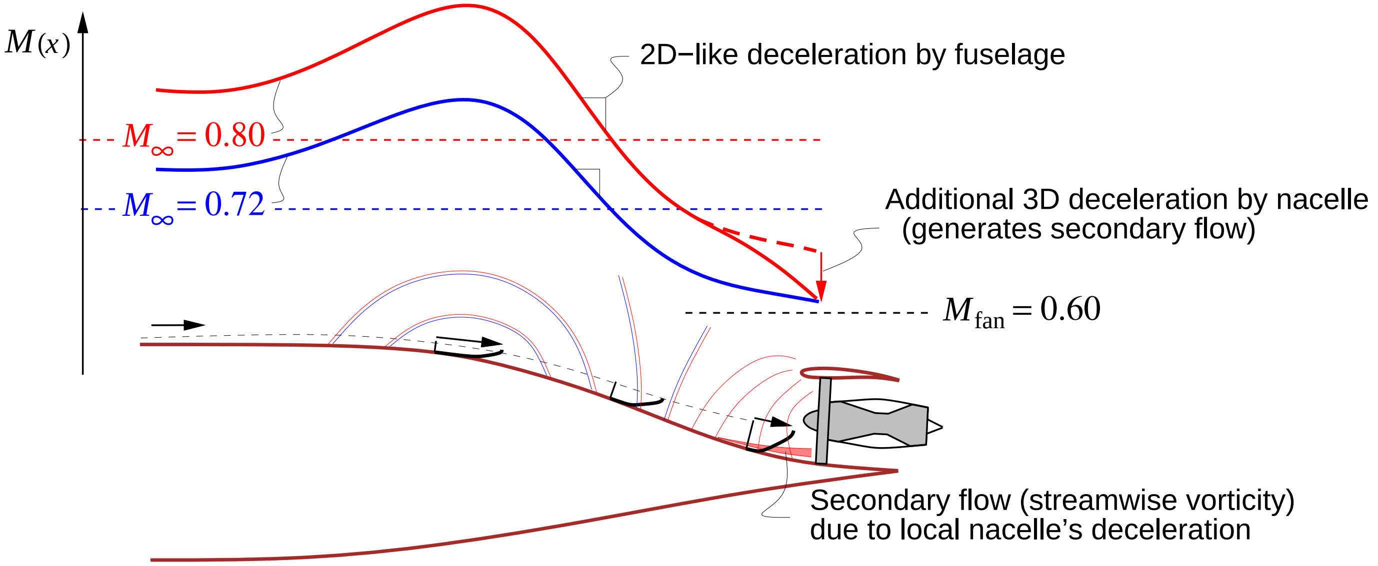


D8 fuselage allows

- Horizontal Tail smaller by 20%
- Cruise tail load more positive by 2-3% of total weight

D8.2 Configuration Features

1. Rear flush-mounted engines:
   - Boundary Layer Ingestion (BLI): Decreases net $TSFC$
   - Rear fuselage aligns engine flow: Allows minimal nacelles
   - Tiny engine-out yaw moments: Shrinks vertical tail
   - Provides fan-face shielding: Low noise
   - Fin strakes act as pylons: Structural synergy
   - Invisible head-on, esp. at T/O: Immune to bird strike
2. Mach number reduced from 0.80 to 0.72
   - Allows low-sweep wing: Less weight, greater cruise C_L, $C_{L_{\max}}$
   - Engine-flow diffusion by fuselage: No secondary flow, enables BLI



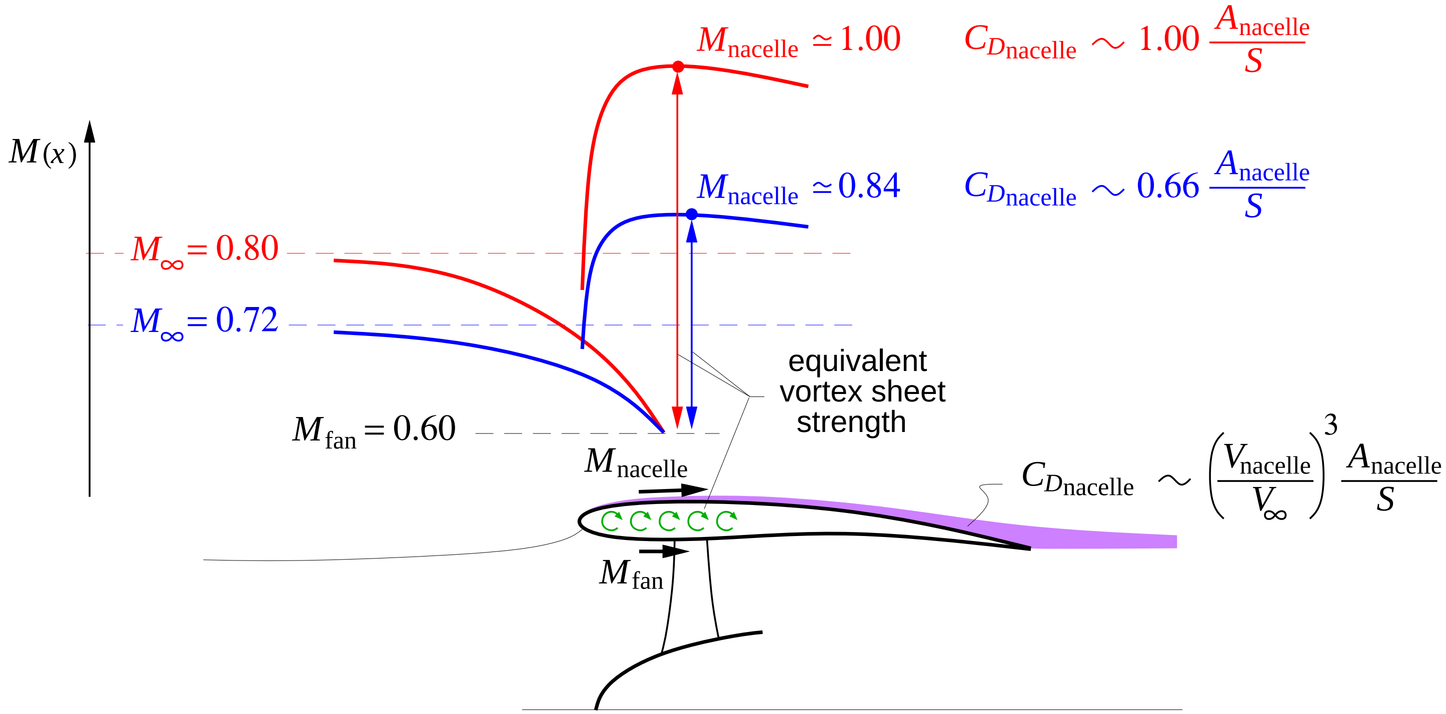
2D−like deceleration by fuselage

Additional 3D deceleration by nacelle
(generates secondary flow)

Secondary flow (streamwise vorticity)
due to local nacelle’s deceleration

Nacelle Drag Reduction

- Flush-engine nacelle is smaller
- Reduced Mach reduces nacelle surface supervelocity

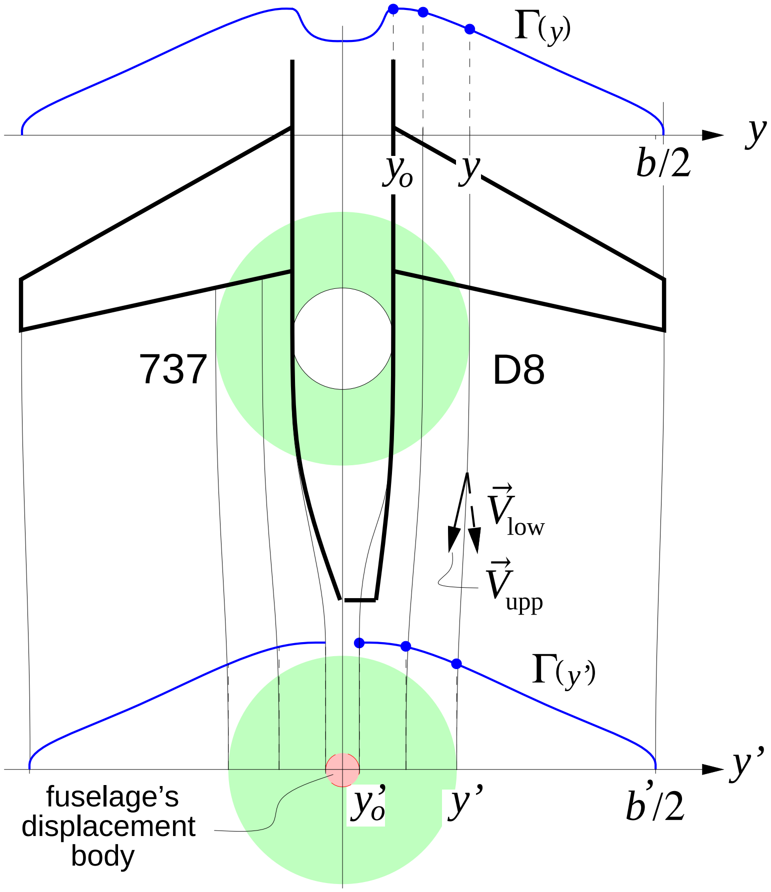


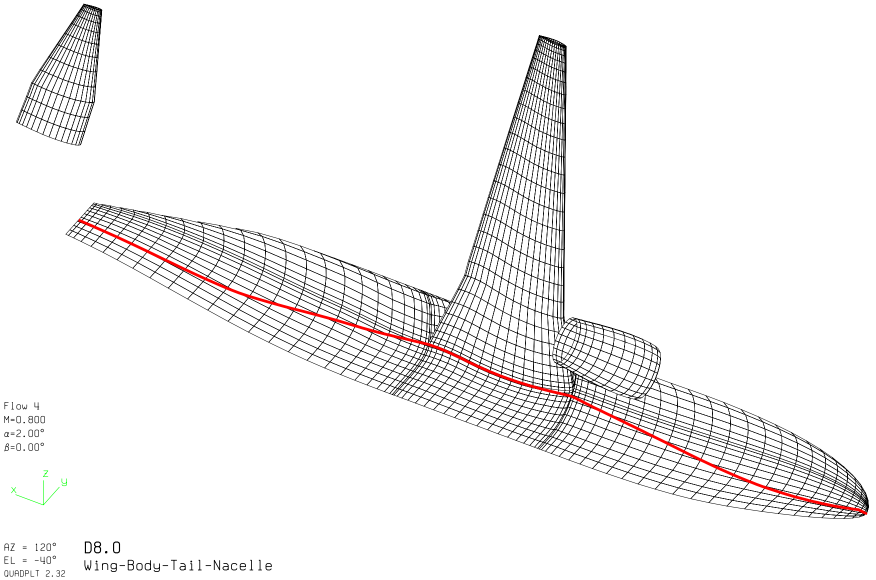
$\longrightarrow$ D8.2 has -85% less nacelle drag than D8.0 or Baseline

Induced Drag Issues

Concern of large C_{D_i} from lifting fuselage is unjustified:

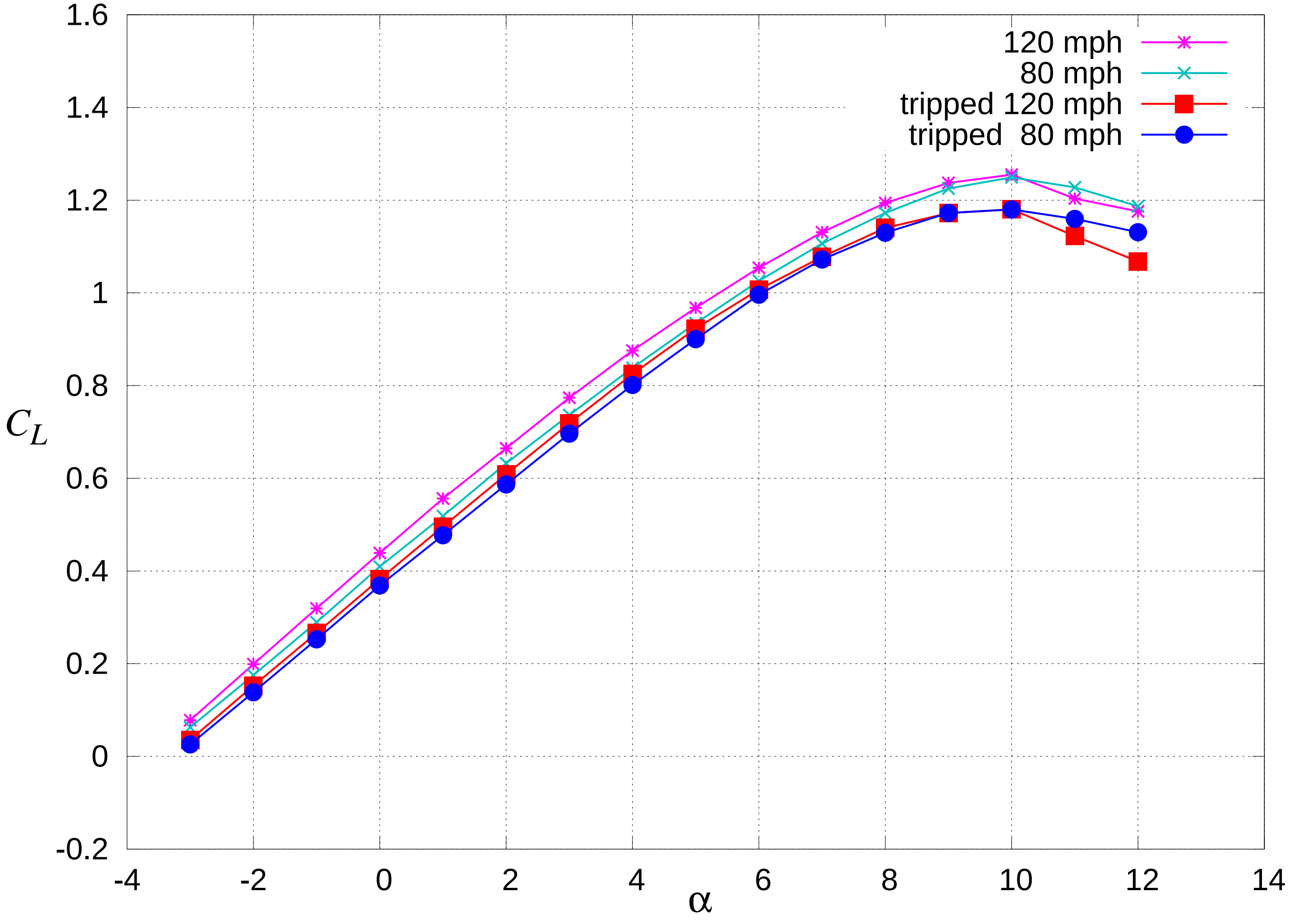
- Wing vortex sheet carrying Γ contracts behind unseparated fuselage
- Produces smooth $\Gamma(y')$ into the Trefftz Plane
- Loss of effective span from b to b' accounted for in TASOPT





20:1 Low-Speed D8.1 Tunnel Model

20:1 Low-Speed D8.1 Tunnel Model Data



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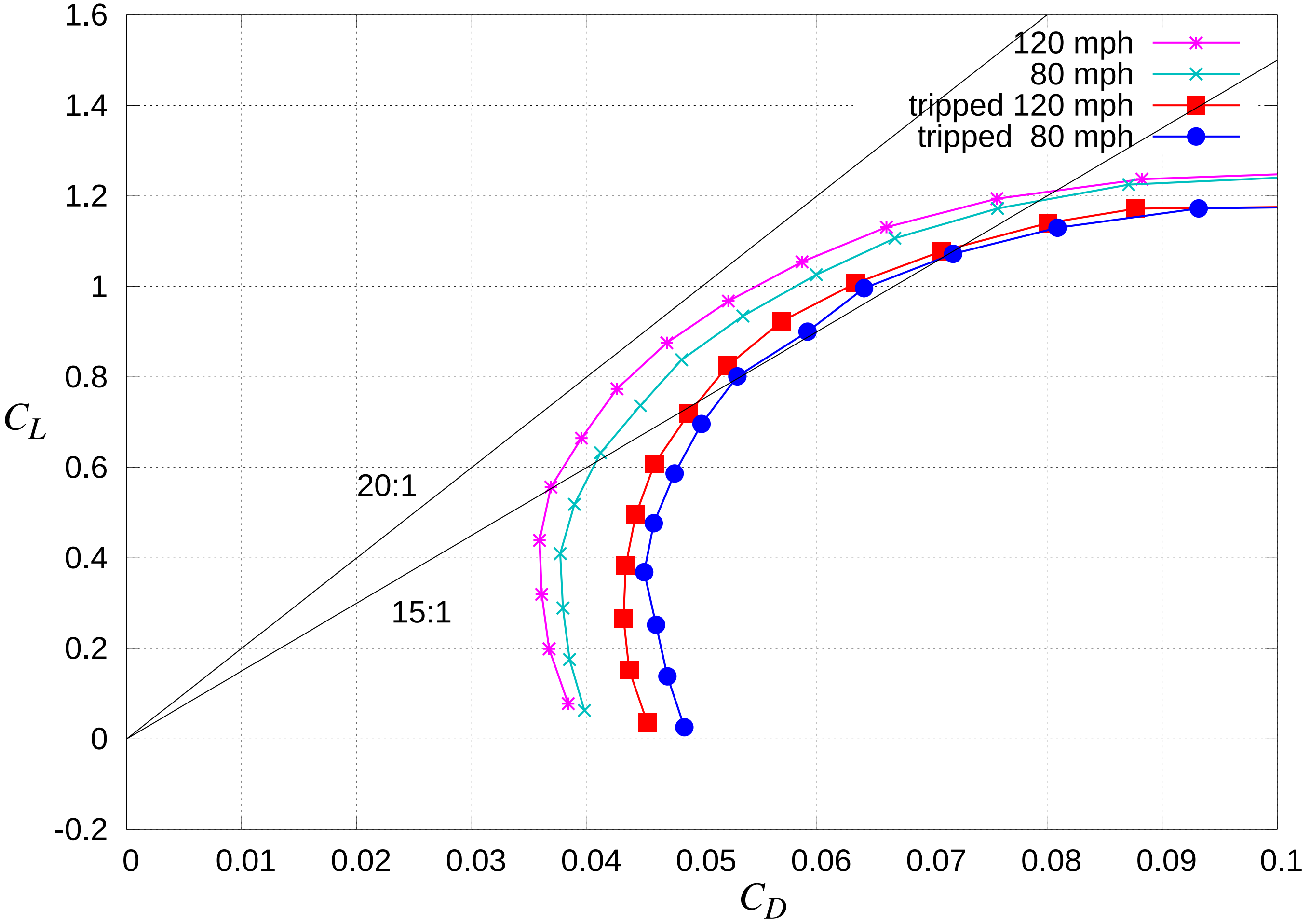


$L/D = 16.1$ max for tripped case

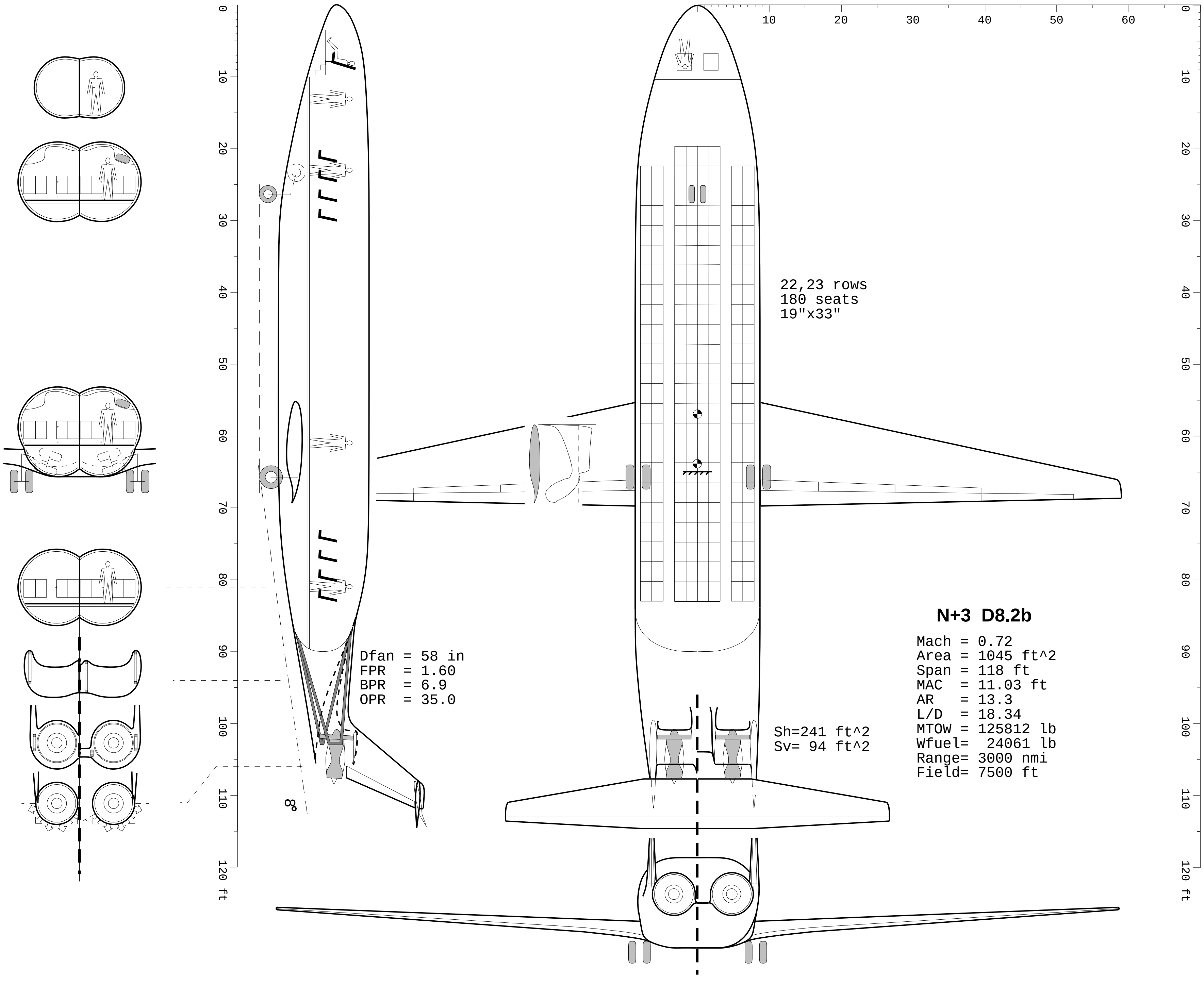
$L/D = 22.8$ with C_{D_p} correction to full-scale Re

$L/D = 21.0$ predicted by TASOPT for transonic D8.1 $\surd$

Summary

- D8.x configuration a promising transport concept
- Two variants examined, compared to 737-800 baseline:
  - D8.0 has minimal risk, gives -12% fuel burn reduction
  - D8.2 has moderate risk, gives -33% fuel burn reduction
- Physical origins of benefits analyzed and identified
- Test data supports aerodynamic performance estimates

Backup Slides

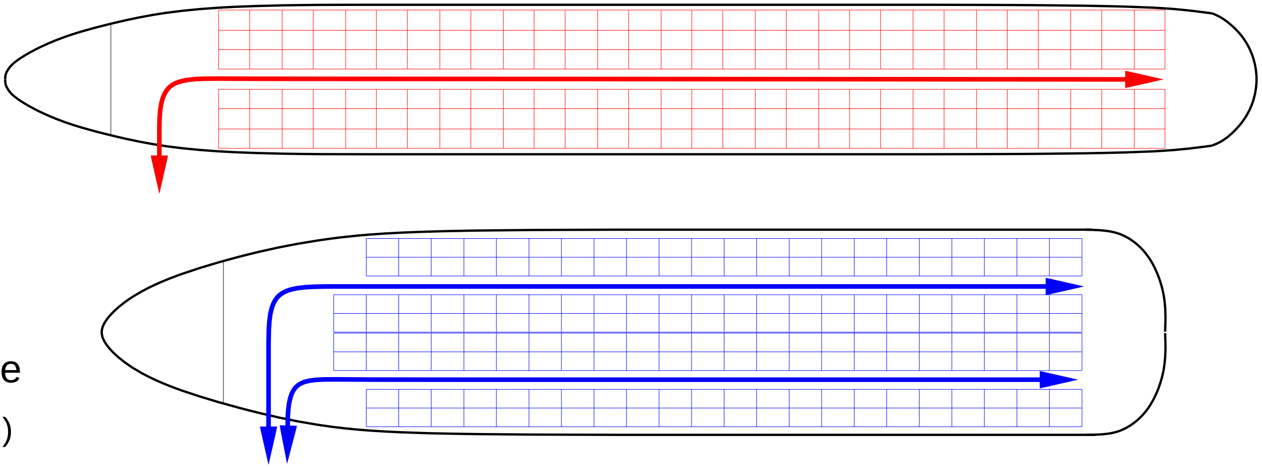


Dfan = 58 in
FPR = 1.60
BPR = 6.9
OPR = 35.0

N+3 D8.2b

Mach = 0.72
Area = 1045 ft^2
Span = 118 ft
MAC = 11.03 ft
AR = 13.3
L/D = 18.34
MTOW = 125812 lb
Wfuel= 24061 lb
Range= 3000 nmi
Field= 7500 ft

Load/Unload Time Comparison



B737−800

30 x 6 per aisle

(30 minutes load,unload)

D8.x

23 x 4 per aisle

(15 minutes load,unload)

⟶ Gate to gate time is comparable for NY-LAX, despite slower cruise