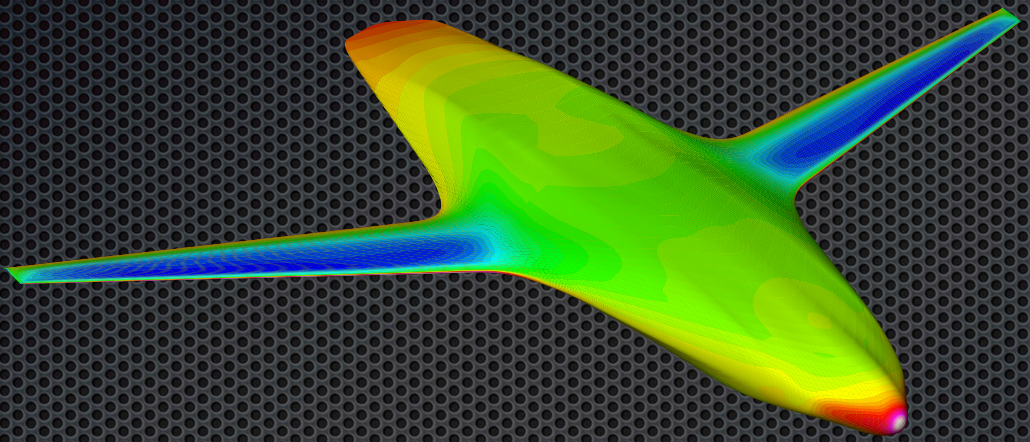
The Lifting-Fuselage Aircraft Configuration



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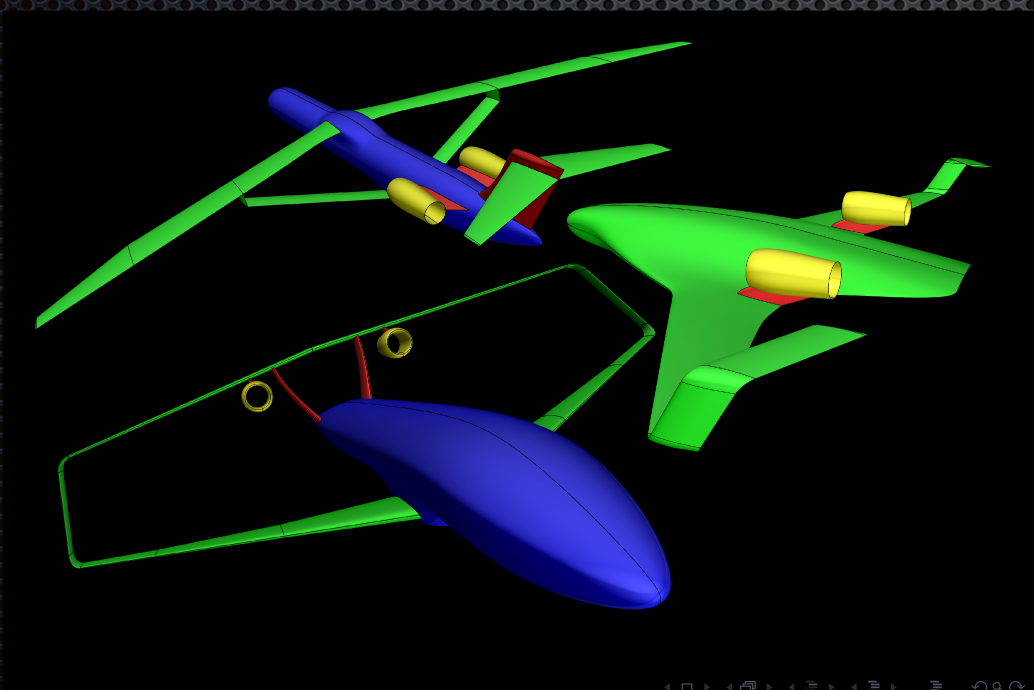
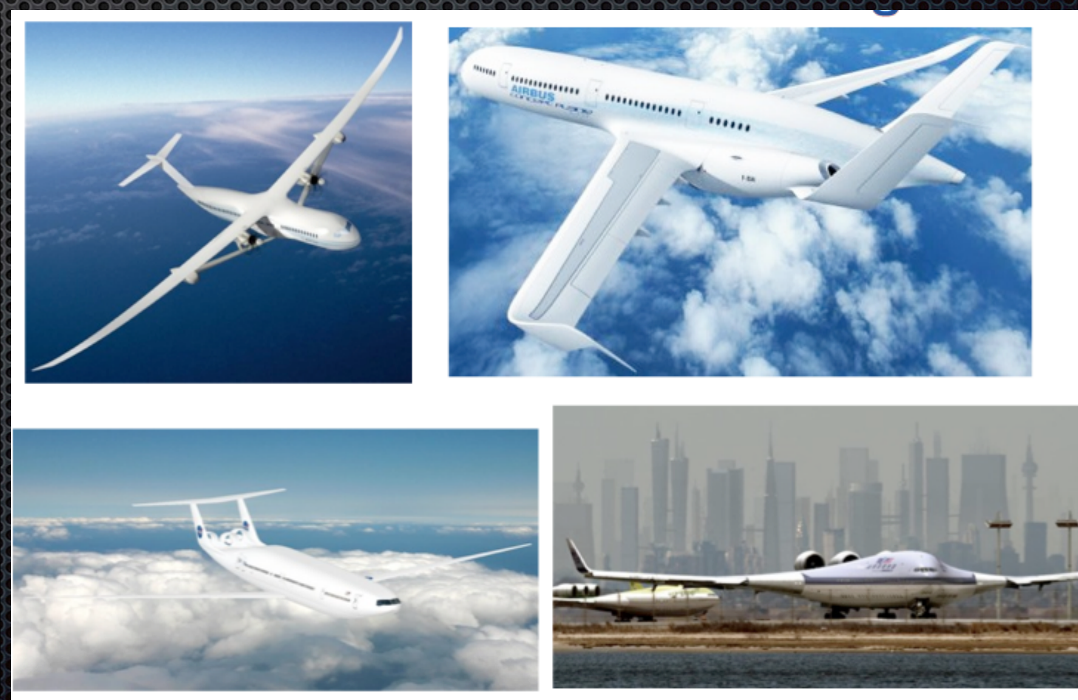
Background

- For both economic and environmental reasons, improving aircraft fuel efficiency is crucial
- This requires reductions in drag
  - ★ unconventional configurations
  - ★ advanced aerodynamic concepts
  - ★ flow control

Unconventional Aircraft Configurations

- Strut-braced wing
- Box wing (joined wing)
- “Double bubble” or D8
- Blended or hybrid wing-body (BWB or HWB)





The Blended Wing-Body (BWB)

Advantages:

- Aerodynamic
  - High wetted aspect ratio gives high lift-to-drag ratio
  - Natural ‘area-ruling’ improves high-speed performance
- Structural
  - Natural spanloading reduces bending loads
- Propulsive
  - Boundary-layer ingesting engines reduce fuel-burn
- Acoustic
  - Body-mounted engines are acoustically shielded
  - Low landing speed reduces airframe noise

Challenges:

- Aerodynamic
  - Shock-free airfoils with sufficient thickness
  - Maintaining stability and control without an empennage
- Structural
  - Design of non-cylindrical pressure vessel for the cabin
  - More complicated load-paths
- Propulsive
  - Robust boundary-layer ingesting engine technology
- Passenger comfort
  - Ride quality

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Blended Wing-Body Aircraft

- ★ usually considered for very large aircraft
- ★ scaling studies (Nickol 2012) indicate that they are not advantageous for smaller aircraft classes

Blended Wing-Body: Questions

- why is the BWB configuration less advantageous for smaller aircraft classes?
- can the concept be modified to achieve better performance for smaller aircraft?
- how does the optimal aerodynamic shape vary with aircraft size?

Aerodynamic Shape Optimization

- numerical optimization is a powerful tool that enables:
  - ★ optimization and assessment of novel configurations and advanced aerodynamic concepts
  - ★ optimization of parameters in flow control strategies
  - ★ possible invention of hitherto unknown configurations or concepts

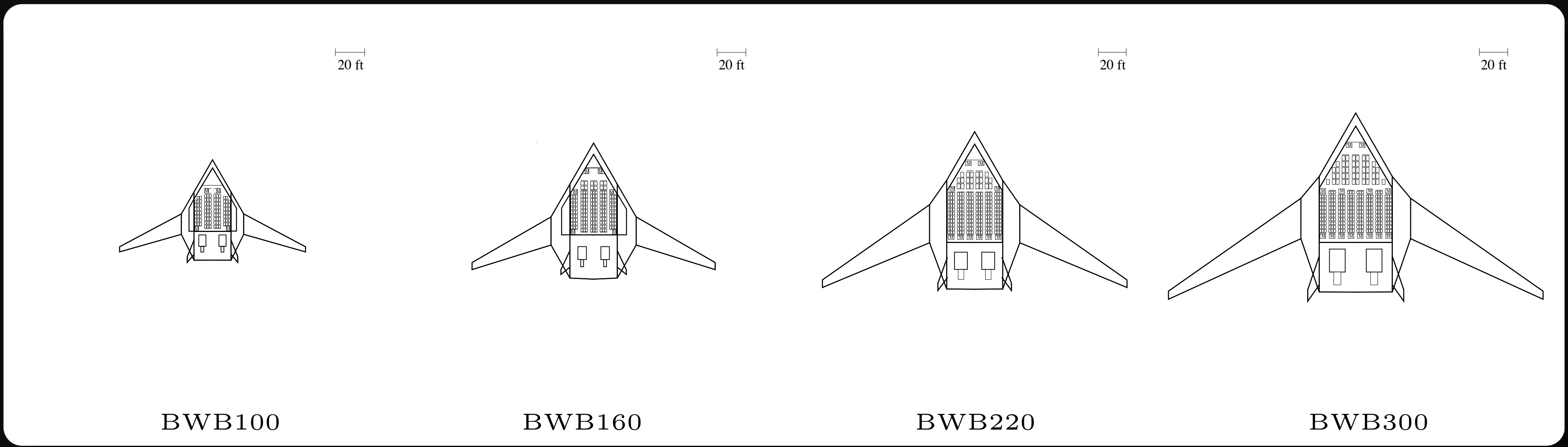
Components of Jetstream Aerodynamic Shape Optimization Methodology

- Efficient and robust flow solver for Euler and Reynolds-averaged Navier-Stokes equations: Diablo
  - ★ parallel implicit Newton-Krylov-Schur algorithm using summation-by-parts method for spatial discretization
- Adjoint method for gradient computation
- B-spline surface geometry parameterization
- Free form deformation or B-spline geometry control
- Integrated mesh movement technique based on B-spline volumes
- Sequential quadratic programming method for gradient-based optimization

Optimization Studies

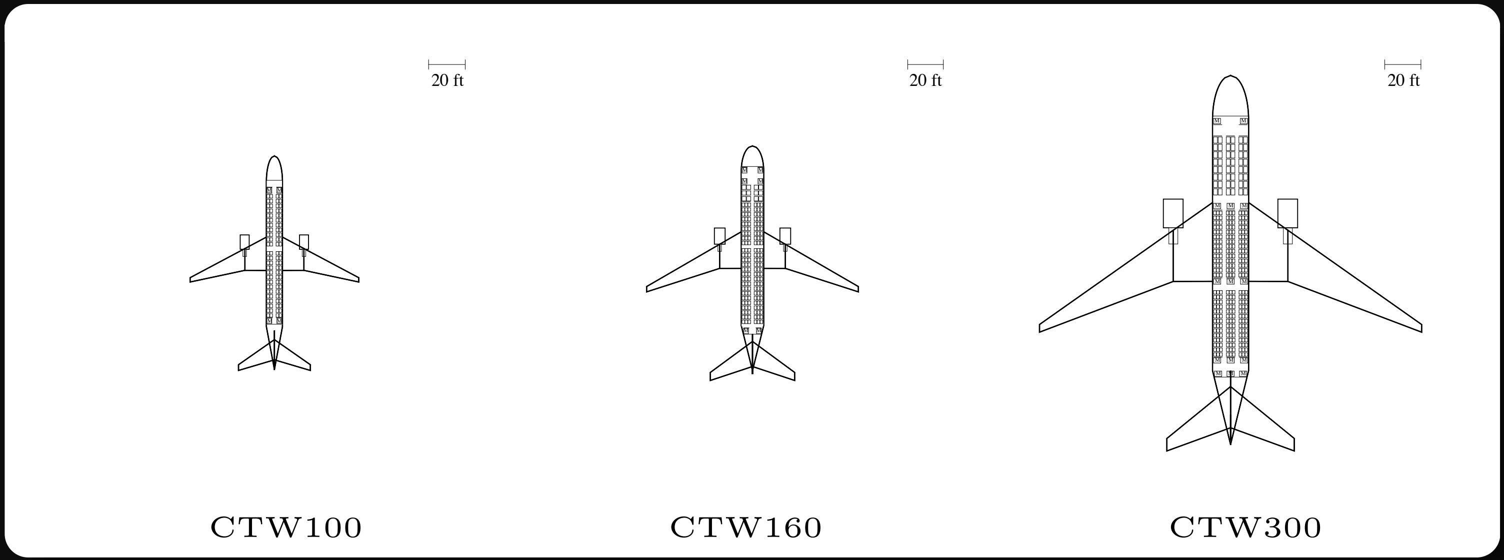
- Investigate the optimal aerodynamic performance of blended wing-body (BWB) transport aircraft
- Four classes of BWBs are considered:
  - A 100-passenger regional jet (similar to the Embraer E190)
  - A 160-passenger narrow-body (similar to the Boeing 737-800)
  - A 220-passenger mid-size transport (similar to the Boeing 767-200ER)
  - A 300-passenger wide-body (similar to the Boeing 777-200LR)
- Equivalent conventional tube-and-wing (CTW) designs are created for the regional, narrow-body, and wide-body classes, which serve as performance references
- Low-fidelity conceptual models are constructed for each design in order to obtain weight and balance estimates
- The span of each BWB is chosen so that its 'bending span' is similar to that of each CTW, and fits within a gate one size larger than each CTW
- Each design is optimized for a nominal mission

Blended Wing-Body Designs



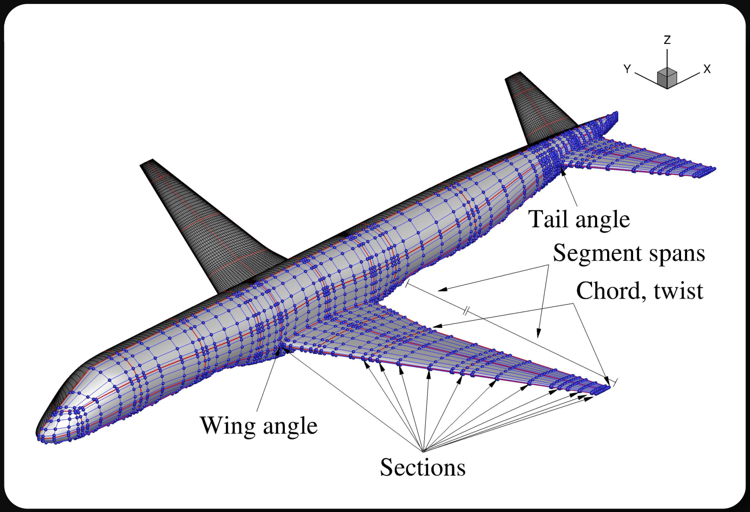
Design	PAX	Gate	Span [ft]	Bending span [ft]	Max range [nmi]	Max payload [lb]	MTOW [lb]
BWB100	100	D	130	88	2,900	28,400	121,200
BWB160	160	D	170	110	3,700	47,000	217,300
BWB220	220	E	213	150	8,000	78,400	432,600
BWB300	300	F	262	185	9,500	141,000	826,800

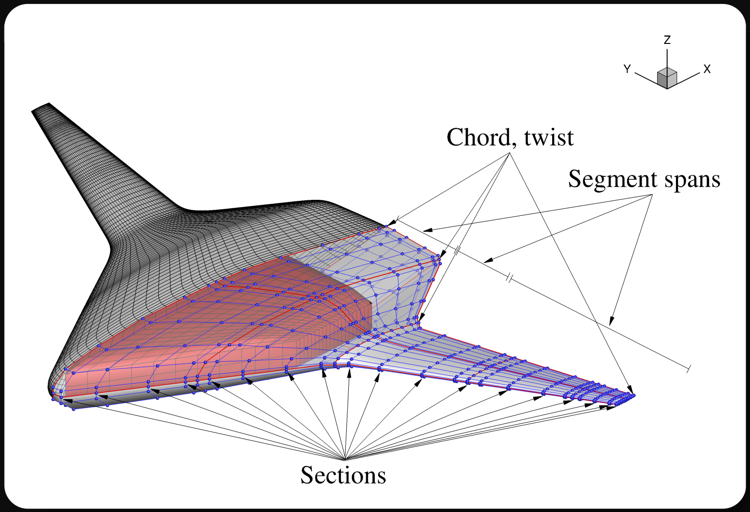
Conventional Tube-and-Wing Reference Designs



Design	PAX	Gate	Span [ft]	Bending span [ft]	Max range [nmi]	Max payload [lb]	MTOW [lb]
CTW100	100	C	94	85	2,900	28,400	105,800
CTW160	160	C	118	105	3,700	47,000	173,900
CTW300	300	E	213	193	9,500	141,000	775,500

Design Variables and Constraints





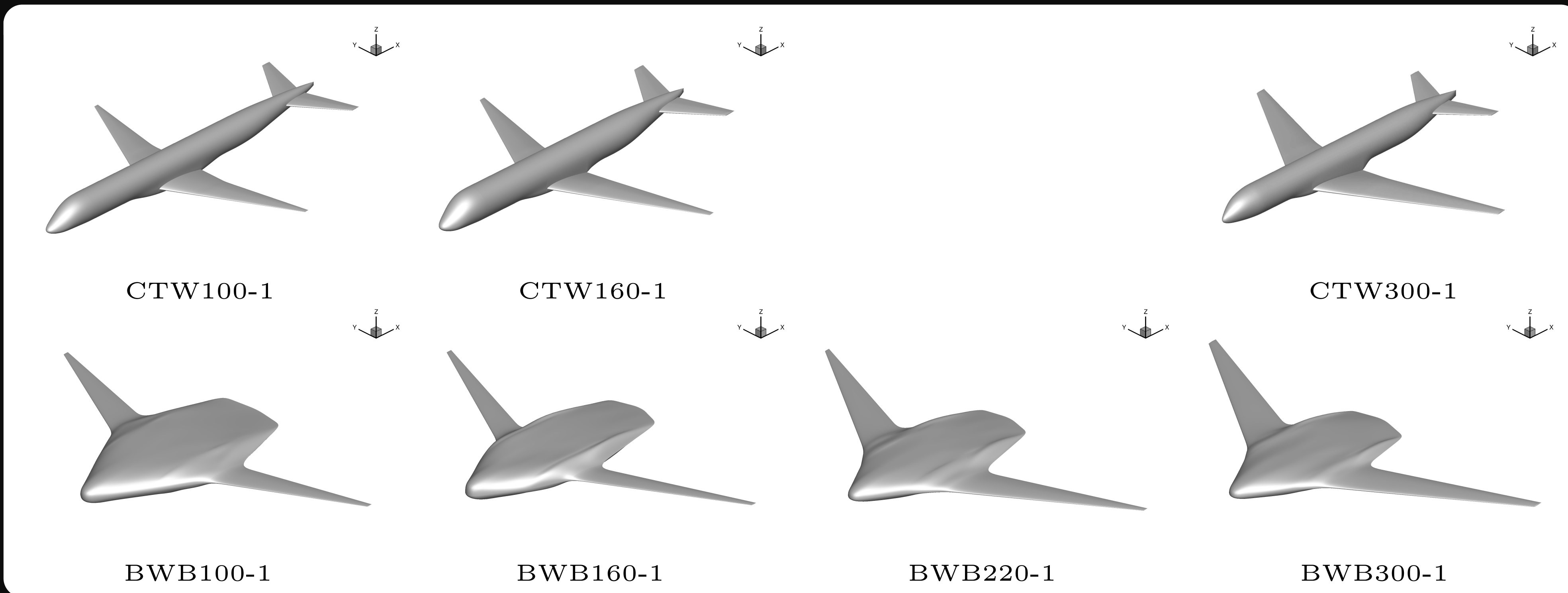
- Trim-constrained drag-minimization based on the RANS equations

- Angle-of-attack ($\pm 3°$)
- CTW wing and tail angles ($\pm 5°$)
- Segment spans
- Chord and twist
- Section shape with t/c constraints
- Wing volume constraint
- BWB cabin shape constraint

Class	Altitude [ft]	Mach [–]
Regional	36,000	0.78
Narrow-body	36,000	0.79
Mid-size	36,000	0.80
Wide-body	36,000	0.84

- Fins are not modelled, but their drag is accounted for post-optimization
- All final performance numbers are obtained through grid-refinement studies

Optimized Designs



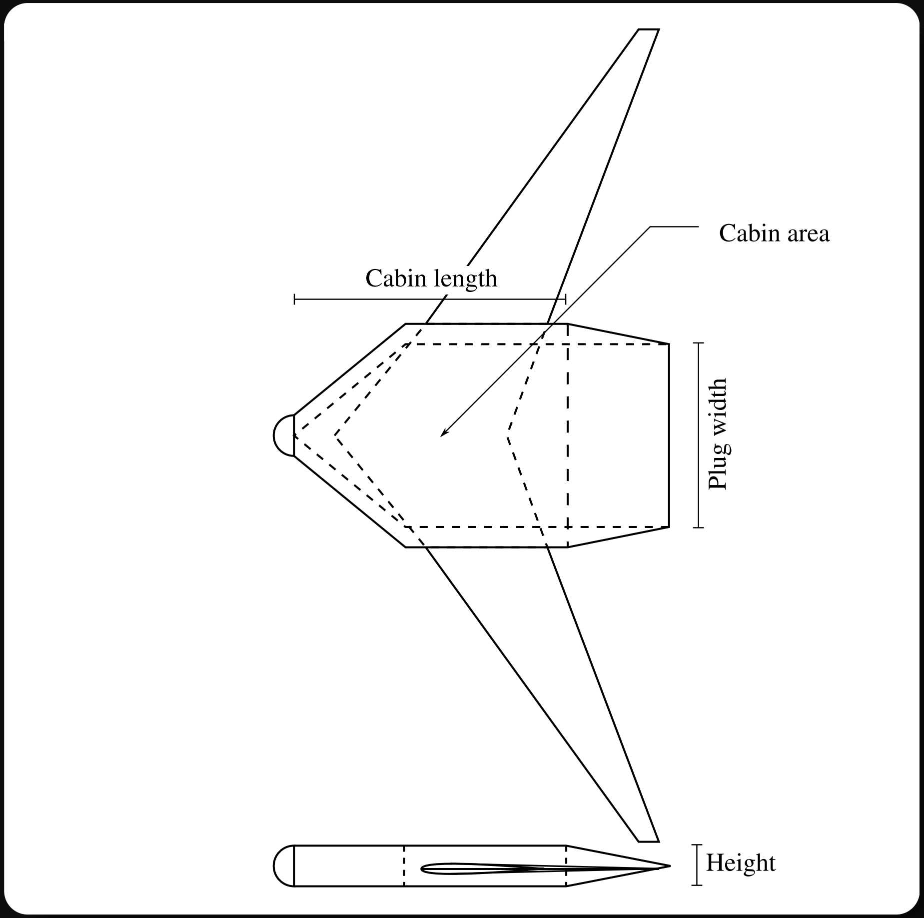
Class	Design	Center-body lift	L/D	Cruise fuel-burn
Regional	CTW100-1	13.0 %	19.8	–
	BWB100-1	40.3 %	23.0	+0.6 %
Narrow-body	CTW160-1	13.5 %	20.3	–
	BWB160-1	31.4 %	26.6	−1.4 %
Mid-size	BWB220-1	33.5 %	28.9	–
Wide-body	CTW300-1	11.8 %	23.4	–
	BWB300-1	32.2 %	30.0	−10.9 %

Importance of wetted area and span

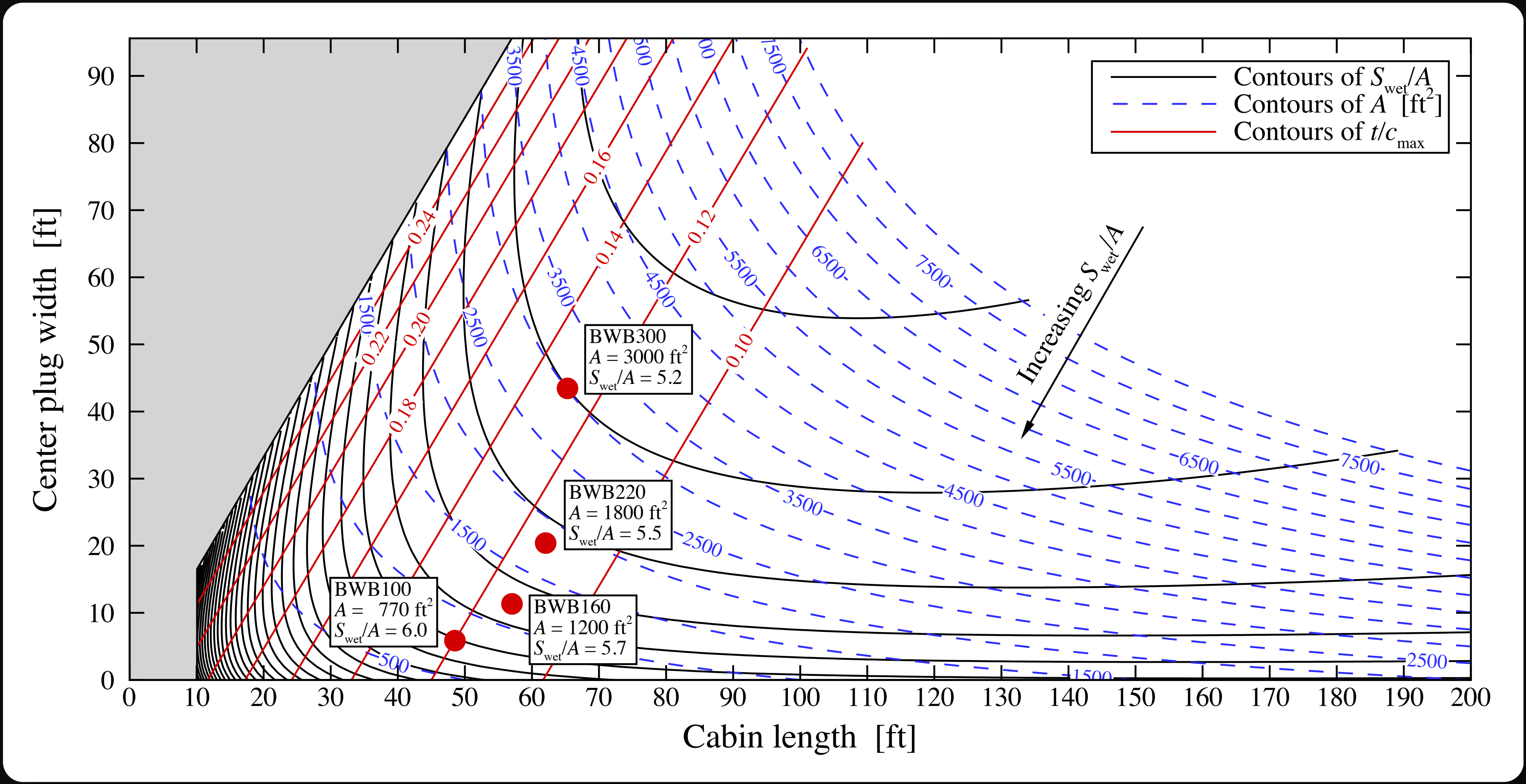
- Wetted area determines friction drag
- Induced drag is inversely proportional to span
- Hence a high wetted aspect ratio is desirable
- BWB configuration enables increased span
    - ★ wings carry reduced load
    - ★ wide center-body reduces bending span

A Geometric Model for Wetted Area

- Investigate the scaling of wetted area with BWB size and shape using a simple geometric model
- Wing span and area are related to cabin area based on existing aircraft
- For zero center plug width this model reduces to a conventional tube-and-wing (CTW)



BWB Geometric Scaling



- Regional-class:
  - 3% lower wetted area than a conventional design
- Wide-body-class:
  - 20% lower wetted area

Exploratory Aerodynamic Shape Optimization

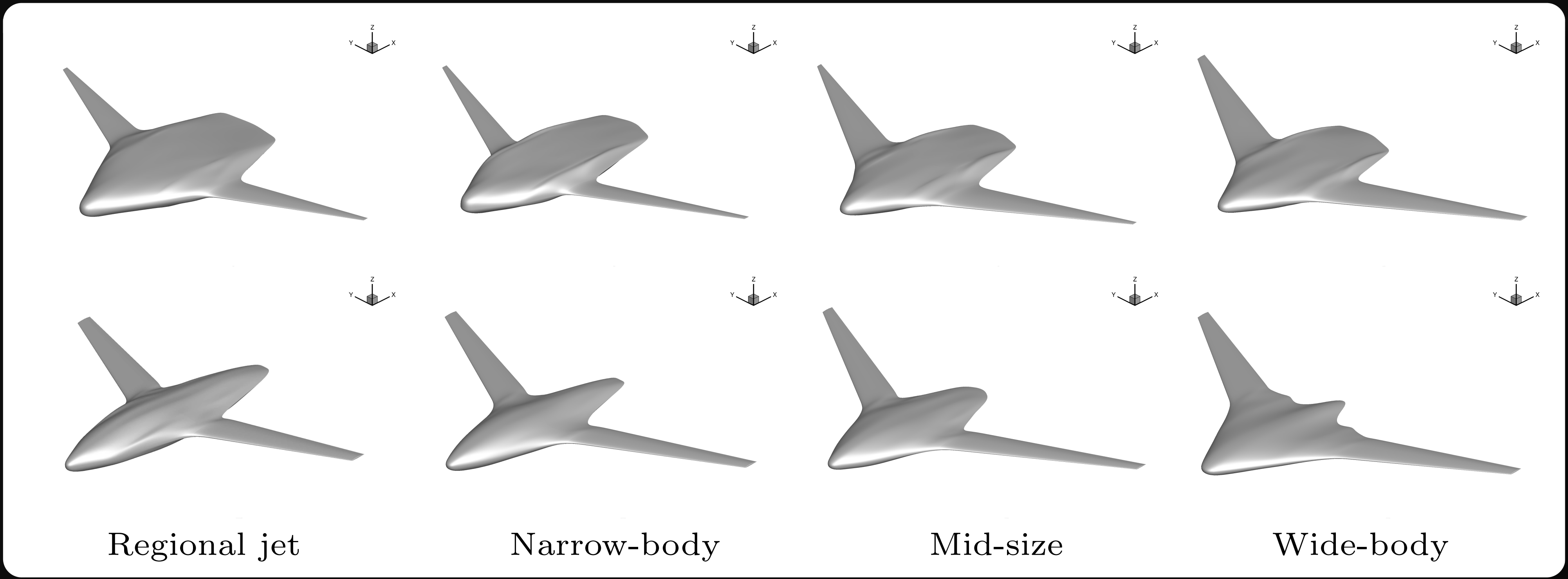
Motivation:

- The smaller BWBs do not reduce wetted area, and thus have little-to-no drag benefit
- Investigate alternative BWB configurations which may offer better aerodynamic performance
- Use RANS-based ASO to ‘discover’ novel shapes

Definition:

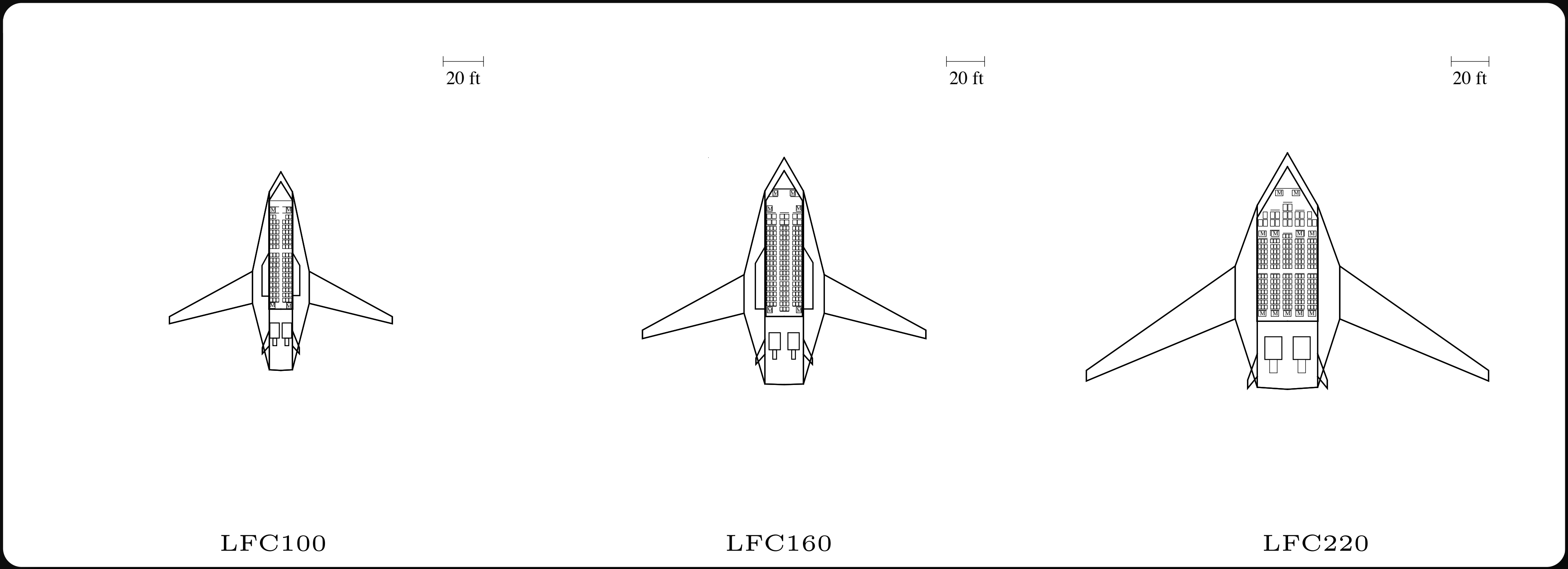
- Optimize each BWB with more geometric freedom and without the cabin shape constraint
- Instead, place bounds on the center-body floor area and volume
- Maximize the lift-to-drag ratio

Exploratory Results



- The exploratory optimizations result in a more slender lifting center-body with distinct wings
- The extent of these features is a function of aircraft size
- These exploratory results guide the design of a new configuration which can take into account additional considerations

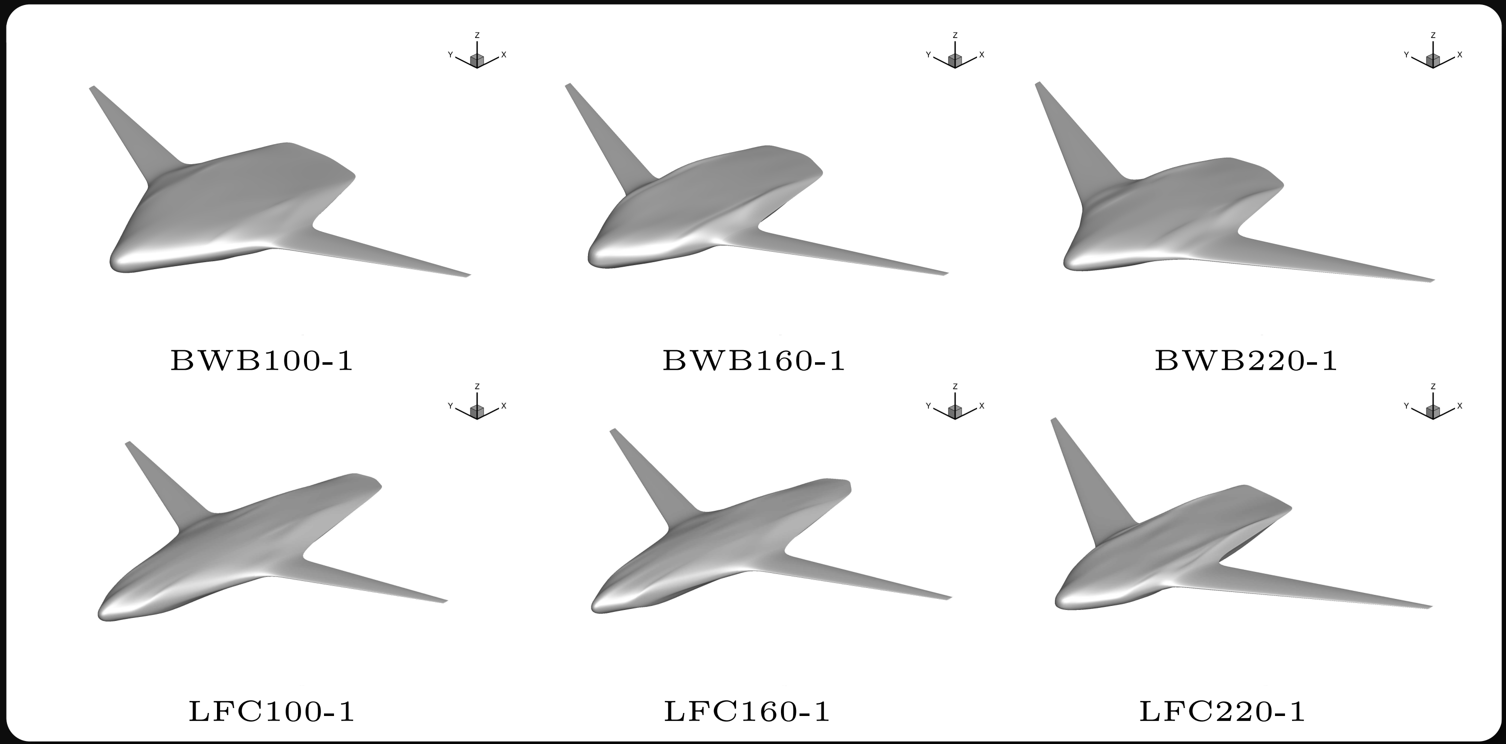
Lifting-Fuselage Configurations (LFCs)



Design	PAX	Gate	Span [ft]	Bending span [ft]	Max range [nmi]	Max payload [lb]	MTOW [lb]
LFC100	100	C	118	88	2,900	28,400	118,700
LFC160	160	D	150	108	3,700	47,000	209,600
LFC220	220	E	213	158	8,000	78,400	444,400

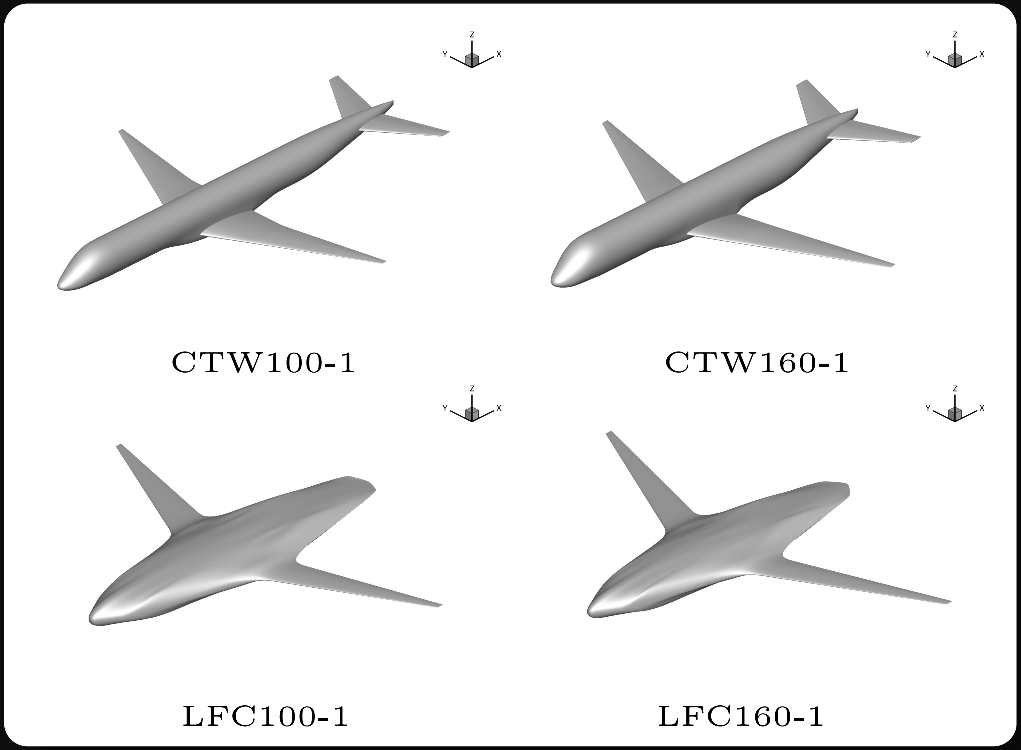
- Each design has a bending span close to that of the equivalent CTW
- With the exception of the LFC160, each LFC fits within the same gate limit as the corresponding CTW

Optimized LFC Designs Relative to the BWBs



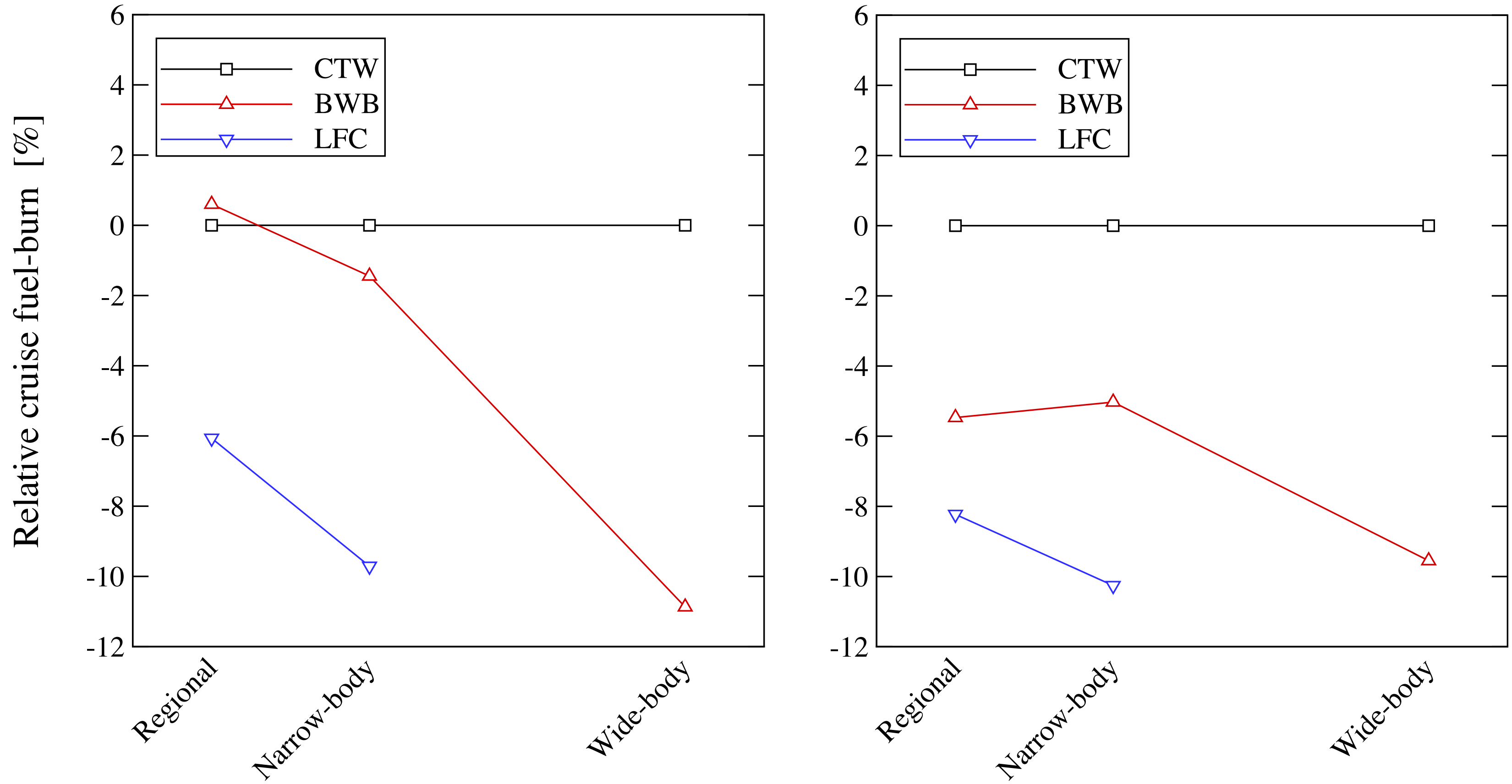
Class	Design	Center-body lift	L/D	Cruise fuel-burn
Regional	BWB100-1	40.3 %	23.0	–
	LFC100-1	31.5 %	24.0	−6.6 %
Narrow-body	BWB160-1	31.4 %	26.6	–
	LFC160-1	28.2 %	27.9	−8.4 %
Mid-size	BWB220-1	33.5 %	28.9	–
	LFC220-1	24.6 %	30.0	−2.1 %

Optimized LFC Designs Relative to the CTWs



Class	Design	Center-body lift	L/D	Cruise fuel-burn
Regional	CTW100-1	13.0	19.8	–
	LFC100-1	31.5	24.0	−6.1%
Narrow-body	CTW160-1	13.5	20.3	–
	LFC160-1	38.2	27.9	−9.7%

Relative Cruise Fuel-Burn



(a) At 36,000 ft

(b) At optimal altitude

CONCLUSIONS

- the lifting fuselage configuration is a promising option in the regional and single-aisle classes, with the potential to reduce fuel burn by up to 10%
- more refined studies that include additional disciplines are needed to confirm the potential efficiency benefits
- this configuration was “invented” by aerodynamic shape optimization!