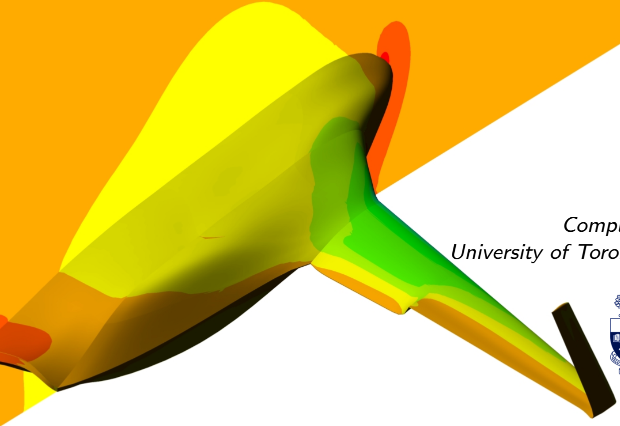
Estimating the Fuel-Burn Benefit of the Blended-Wing-Body Aircraft Configuration in the Regional Class Through Mixed-Fidelity Multidisciplinary Optimization



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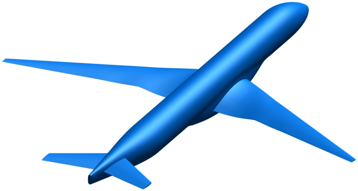
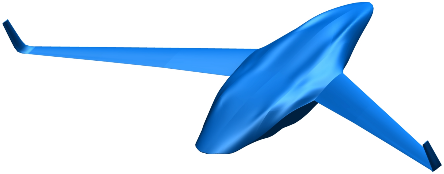
Introduction

Potential solution for significantly improved aircraft performance:

- **Unconventional aircraft**
  Risk must be reduced!



Conventional tube-and-wing (CTW) aircraft



Blended-wing-body (BWB) aircraft

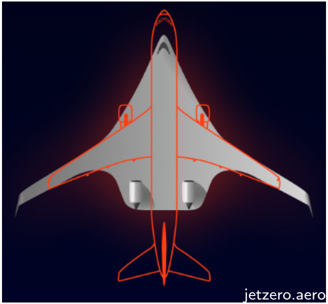
Preliminary work:

- One method of reducing risk is **high-credibility configuration assessment studies**
  (Optimization based on high-fidelity flow physics to gain accurate design insight)

Major Advantages of the BWB Configuration

Could achieve industry-wide environmental goals through **low drag and weight**:

- $\downarrow$ **Induced drag**: High span without the typical weight penalty
  - Wing root offset by structurally thick (efficient) centerbody
  - Centerbody carries some lift
  - Aligned lift and weight loads
- $\downarrow$ **Skin-friction drag**: Low wetted area (no empennage; centerbody masks part of wing)



Compunding effects (Ex. smaller engines) gives:

$\leftarrow$ **JetZero: 50%** $\downarrow$ specific fuel-burn

DZYNE Technologies' BWB specific fuel burn:

- **Regional: 43%** $\downarrow$ **vs. A220-100** [1]
- **Single-aisle: 39%** $\downarrow$ **vs. B737-MAX8**[1]

[1] Yang, S. et al., *2018 AIAA Aerospace Sciences Meeting*, Kissimmee, FL, USA.

BWB has high potential, but inherent challenges due to its highly integrated nature:

- **Design:** Possibly punitive stability and control requirements (already shown *feasible*)
- **Problem formulation:** Critical design requirements for efficient performance assessment ??

Numerical studies aimed at addressing these issues may expedite industry adoption

Motivating question:

- How to credibly assess BWB potential ?

Some project goals:

- Formulate, study, and solve optimization problems to accurately assess BWB fuel burn
- Compare BWB and CTW aircraft in the regional class

Previous Research on Regional-Class BWB Aircraft

GARDN-II UTIAS-Bombardier collaboration [2] **:**

Central question: Can regional-class BWBs satisfy typical S&C requirements? **YES!**

- One-engine-inoperative trim at very low speed ($V_{mcg} \approx$ Mach 0.15)
- Pitch acceleration of 3 deg/s^2 at initiation of rotation **(large fuel-burn penalty)**
- Cruise static margin ($K_n \geq -4\%$ MAC$_0$) and trim

Case studies:

- Wide 12-abreast vs. narrower 7-abreast cabin
  - Narrow-cabin BWBs have lower cruise-altitude, and MTOW and fuel-burn benefits
- Winglet- vs. centerbody-fin-mounted rudders
  - Both give similar optimal performance

[2] Reist, T.A. et al., *Multifidelity Optimization* ..., Journal of Aircraft, 2019.

Optimization Problem Definition

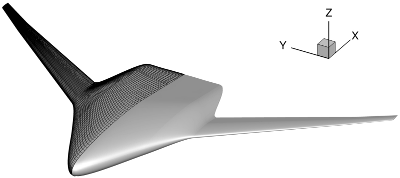
Aircraft Design VS. Configuration Assessment

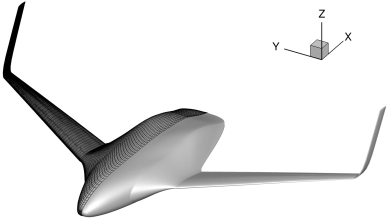
An example traditional approach to aircraft design:

- **Conceptual design:** System-level optimization based on low-fidelity models
- **Preliminary design:** Localized optimization and design improvements
- **Detailed design:** Wind-tunnel testing and iterative incremental improvements

Efficient high credibility configuration assessment:

- Mixed-fidelity optimization including RANS simulations
  (3 steps simultaneous; unconventional aircraft analyzable)
- **Approach**: Use high-fidelity where needed, but ONLY where needed, in order to accurately assess the potential of the BWB configuration





Initial geometry → Optimized geometry

One Subgoal and One Main Goal

Subgoal: Study of problem-definition elements

- Impact of typical aircraft-design requirements and geometric freedom on optimal performance and geometry

Main goal: Comparison of BWB and CTW aircraft

- Advantage of BWBs in the regional-class

Step 1: Objective Function Selection

Industrially relevant, system-level objective functions for aircraft configuration assessment

Target characteristics ↓	**Block fuel**	**Direct oper. costs**	**Climate-change impact**
Modeling uncertainty	↓	≈	↑
Comparability*	✓	≈	≈
Environmental focus	↑	≈	↑
Airline variability	↓	↑	↑
Selection:	✓		

* Comparability across different configurations, i.e. low configuration-dependent uncertainty

Step 2: Reference Configuration and Other Technology Level Selection

Options for reference CTW aircraft:

1. Existing, best-in-class CTW (performance estimated through optimization): E190-E2
2. CTW optimized with higher design freedom but current technologies
3. CTW optimized with possible higher design freedom and future technologies

Implications of using current technology levels:

- Lowering the barriers to entry of regional-class BWB by:
  - demonstrating that inherent benefits persist without future technologies
    $\Longrightarrow$ How advantageous is BWB with only the minimal necessary change from the current status quo ?
  - having low modeling uncertainty, so high credibility
- **Trade-off:**
  - Some future technologies disproportionately benefit the BWB
    (Ex: boundary-layer-ingesting engines)

Mission definition

- **Range** [nmi]:

  Analysis: 500

  Sizing: 2 150 (max. payload) and 3 400 (max. range)

  Diversion: 100

- **Passengers**:

  104

- **Altitude** [ft]:

  Analysis and sizing: 37 000 (CTW), 44 000 (BWB; main goal)

  Diversion: 15 000

- **Mach number**:

  Analysis and sizing: 0.78

  Diversion: 0.50

- **Mission profile**:

  Optimization (no diversion): T/O, climb, cruise, descend, land

  Sizing (with *diversion*): T/O, climb, cruise, descend, *climb, cruise, loiter, descend, land*

Step 4: Critical Problem-Definition Elements

Critical BWB problem-definition elements (confirmed to be critical during Subgoal work):

- Performance-based design requirements:
  - Cruise trim
  - One-engine-inoperative trim at on-ground minimum control speed (V_{mcg})
  - Takeoff field length and top-of-climb rate of climb
  - Low-speed (Mach 0.20) trim and static margin (aftmost CG, MTOW, 0 thrust)
  - Pitch acceleration of 3 deg/s^2 at initiation of takeoff rotation
    - Not imposed if variable-length landing gear (e.g. pivot-piston) is assumed
- Relevant geometric constraints:
  - Cabin shape inclusion within centerbody/blending-region
  - Tip-strike (9 deg pitch, 9.5 deg roll)
  - 3-ft ground clearance when on all wheels
  - Available wing volume $\geq$ fuel volume

*** High geometric freedom is key to satisfying many simultaneous constraints with this highly integrated aircraft configuration

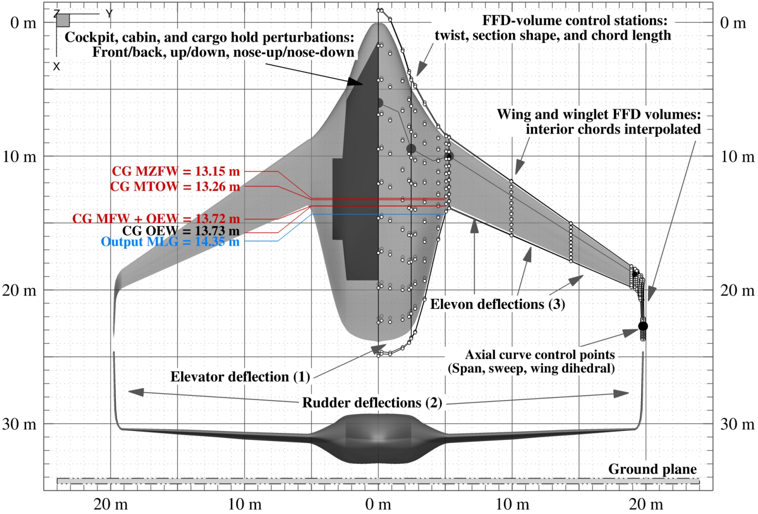
Step 5: Modeled Disciplines and Model Fidelity

Modeled disciplines and model fidelity:

- High fidelity
  (for physical quantities highly sensitive to fine model details):
  - Aerodynamics (RANS, not even Euler)
- Medium fidelity
  (if low fidelity is insufficient but high fidelity is not needed):
  - Mass properties
- Low-fidelity
  (if main effect is associated with high-level parameters (e.g. wing span, sweep, etc)):
  - Structures
  - Propulsion
- Mixed-fidelity
  - Flight mechanics (mixed high-, medium-, and low-fidelity models)
    - Takeoff field length
    - Rate of climb
    - Static margin
    - Trim

Step 6: Design Variables

418 design variables provide appropriate freedom for constraint satisfaction:



Also: Cruise and low-speed α, engine size and angle,
6 takeoff var.: V_{EF}, V_R, and V_{LO} and time to screen height (OEI and AEO),

Step 7: Problem Solution Strategy

Optimization problem solved using cost-efficient (possibly decoupled) mixed-fidelity strategy:

- **CTW**: 2-phase decoupled optimization solved sequentially (low-fi then high-fi) because:
  - High-fidelity models are not needed to determine the optimal value of many main (system-level) design variables
- **BWB:** 1-phase coupled optimization with all models solved simultaneously because:
  - Multidisciplinary and/or mixed-fidelity models that include the highest fidelity level are needed to determine the optimal value of many main (system-level) design variables

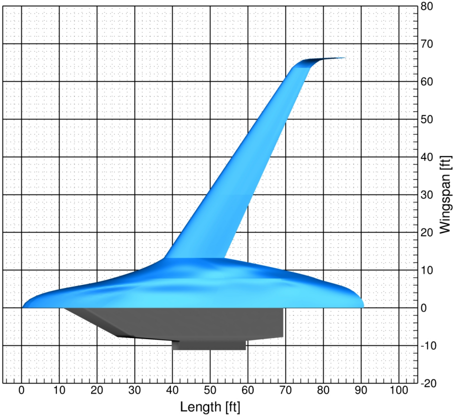
Subgoal Results:
Effect of Problem-Definition Elements

Reminder: Research Questions

? **What is the impact of each major problem-definition element on the block-fuel-burn objective function and the optimal design ?**

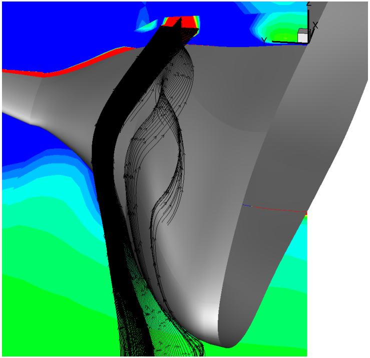
? **How does a regional-class BWB compare to an existing, best-in-class CTW ?**

Baseline Design (with Pivot-Piston Landing Gear)

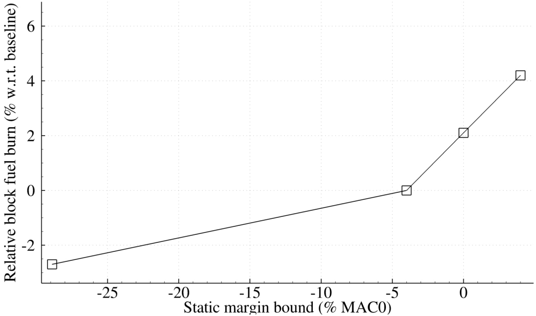


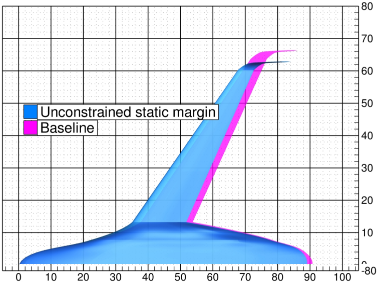
Notable design features:

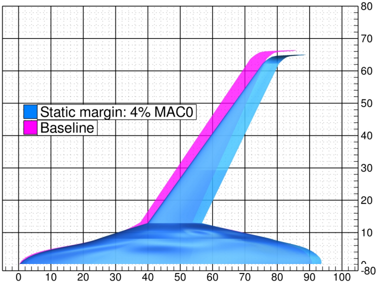
- High geometric freedom gives tight cabin contouring and good streamlining
- Inboard elevons used as flaps at low speed
- Relies on vortex lift at high AoA / low-speed flight



Low-Speed Static Margin Sensitivity: $\approx +0.52\%$ BFB per unit K_n bound





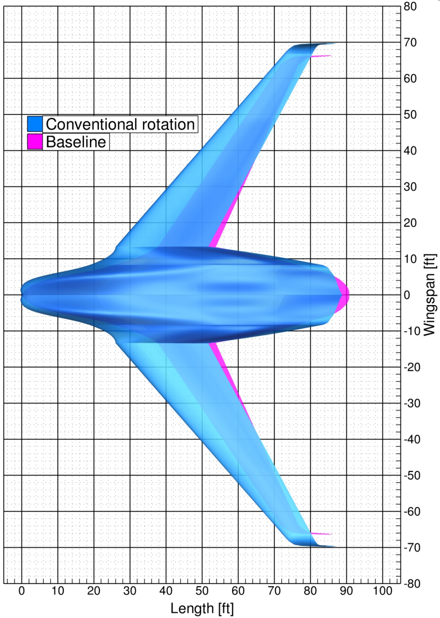


Adding a Conventional Rotation Constraint

Design features notably different from baseline, that help produce a positive pitching moment, or reduce the required pitching moment, at rotation:

- Wing moved forward to move center of pressure forward
- Transition-region leading-edge highly "carved" and twisted nose-up
- CGs moved forward to move main landing gear forward to increase pitch effector leverage (especially elevator)
- Thrust angle hit lower bound of -2 deg

Performance penalty: ≈ 23% block fuel burn
Weight penalty: 10% MTOW

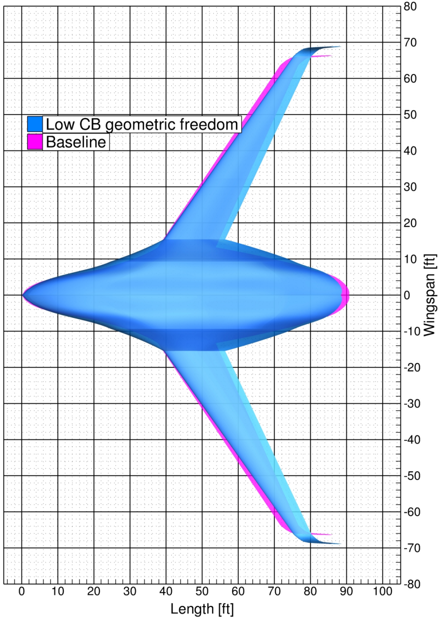


Low (Conceptual-Design-Like) Centerbody Geometric Freedom

Design features notably different from baseline:

- Bulkier centerbody
- Reinforces the importance of high geometric freedom for the efficient satisfaction of many competing constraints in this integrated aircraft configuration

Performance penalty: +6.0% block fuel burn
Weight penalty: +2.5% MTOW



Summary - Block-Fuel-Burn Variation

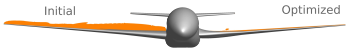
Block fuel burn (BFB) impact of individual problem-definition elements

Problem version	$\Delta BFB / BFB_{\text{baseline}}$
Low-speed static margin bound $= -\infty$	-2.7%
Low-speed static margin bound $= -4\%$ MAC_0	Baseline $=$ 20 481 lb
Low-speed static margin bound $=$ 0% MAC_0	+2.1%
Low-speed static margin bound $=$ 4% MAC_0	+4.2%
With conventional rotation mechanism	+23%
No OEI-trim constraint	-1.1%
No TOFL constraint	-0.99%
Low (conceptual-design-like) centerbody geometric freedom	+6.0%

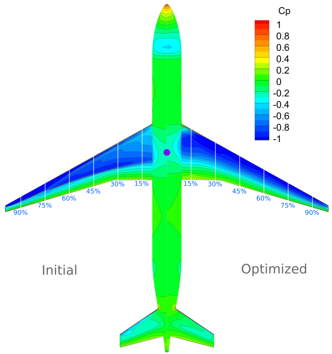
Main-Goal Results:
Comparative Study

- ? What is the impact of each major problem-definition element on the block-fuel-burn objective function and the optimal design ?
- ? **How does a regional-class BWB compare to an existing, best-in-class CTW ?**

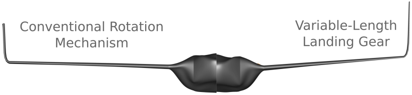
Comparative study of E190-E2-like CTW with regional-class BWB (500-nmi nominal mission)



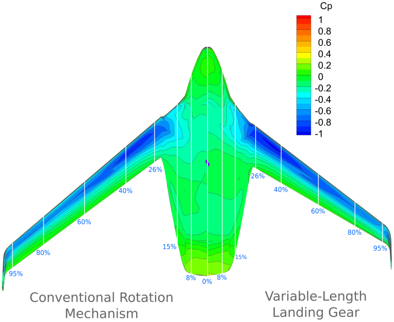
Shock surfaces



Surface pressure contours



Shock surfaces (absent)



Surface pressure contours

Relative block fuel burn: **-11.5%** (Thrust angle -9 deg) **-16.3%**

Other performance metrics

	Ref. CTW	Conv. rotation	Pivot-piston gear
Wing span	33.71 m	+27.8%	+16.7%
MTOW	56 400 kg	-8.0%	-12.9%
OEW	33 000 kg	-6.4%	-12.1%
Maximum takeoff thrust (per engine)	92.8 kN	+7.4%	-17.2%
Altitude *	37 000	44 000	44 000
Cruise L/D *	18.1	+22.1%	+23.8%
Block fuel burn	2 280 kg	-11.5%	-16.3%

Multifidelity multidisciplinary optimization results

* Cruise data are reported at the start of cruise for the nominal mission.

Conclusion

Conclusions

Subgoal: Effect of problem-definition elements on optimal design and performance

- Low-speed static margin sensitivity: $\approx 0.52\%$ block fuel burn per % MAC_0 K_n bound
- Added rotation constraint: $+23\%$ block fuel burn (with conventional thrust angle limit)
- Low (conceptual-design-like) centerbody geometric freedom: $+6.0\%$ block fuel burn

Main goal: Regional-class CTW and BWB comparison

- Rotation using only pitch-effector deflections is punitive (unconstrained thrust angle)
  - With conventional rotation constraint: BWB benefit = -11.5% block fuel burn
  - With pivot-piston landing gear: BWB benefit = -16.3% block fuel burn

Future work:

- Cabin shape & altitude relationship
- Multipoint at cruise for robustness to variations in cruise conditions
- Single-aisle-class BWB