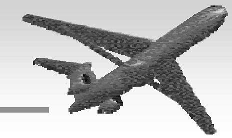
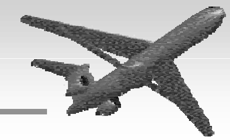


Multidisciplinary Design Optimization of a Strut-Braced Wing Transonic Transport

John F. Gundlach IV

Masters Thesis Defense

June 7,1999



Acknowledgements

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  - Dr. Rakesh Kapania
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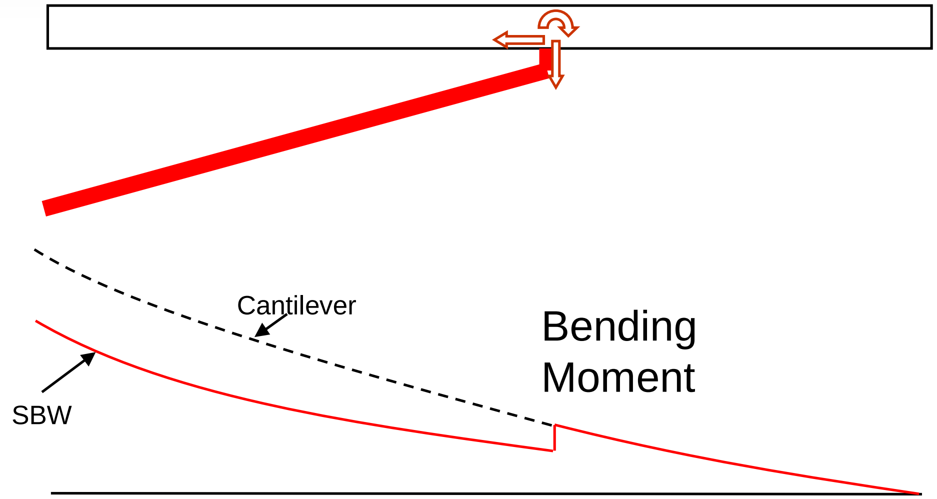
Why a Strut-Braced Wing?



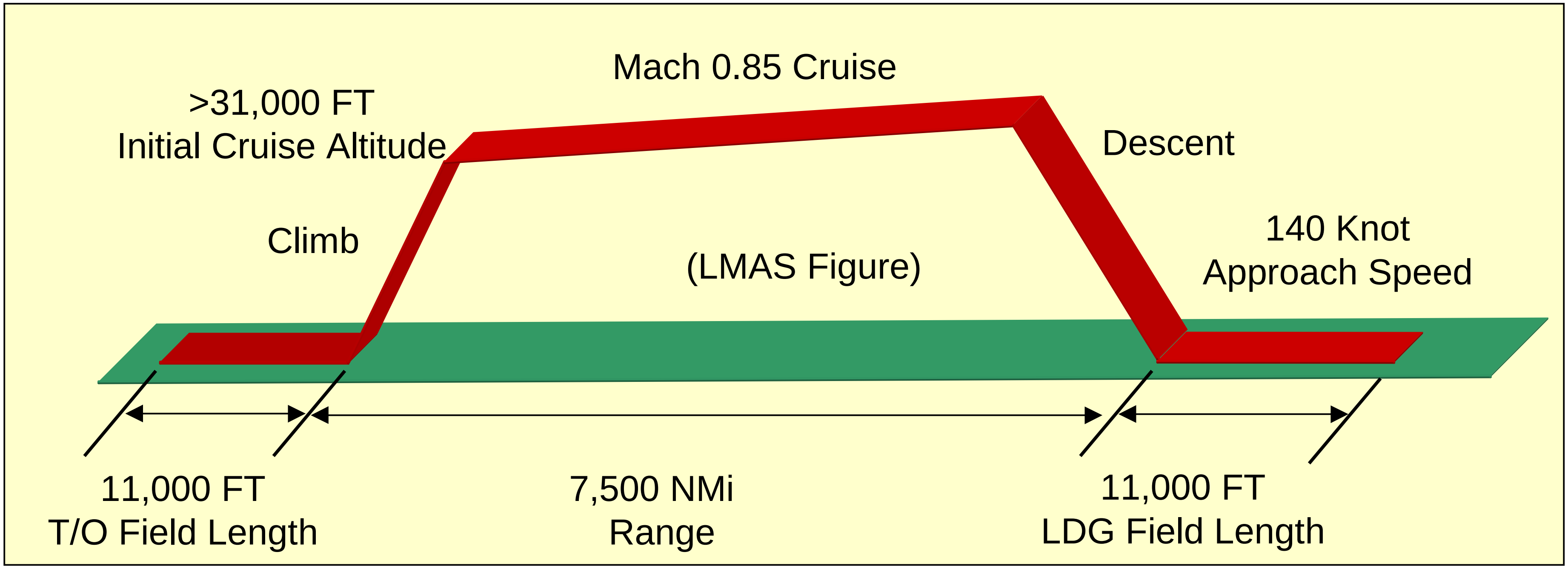
- Strut Allows Span Increase, t/c Reduction and/or Wing Bending Material Weight Reduction
- Small t/c Allows Wing to Unsweep for Same Transonic Wave Drag
- Reduced Sweep Permits More Natural Laminar Flow
  - Fuel Savings
  - Causes Additional Weight Savings

History

Pfenninger Concept
(NASA Photo)

- Werner Pfenninger at Northrop (1950's)
- Boeing (1960's) and Lockheed (Late 1970's) Design Studies
- NASA High Altitude Research Aircraft Design Study (Early 1980's)
- NASA Subsonic Business Jet Design Study (Early 1980's)
- Numerous Subsonic SBW Examples Flying Today

Problem Statement

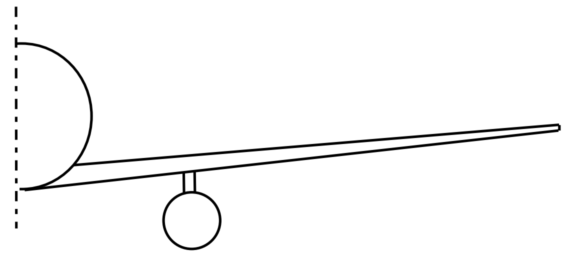


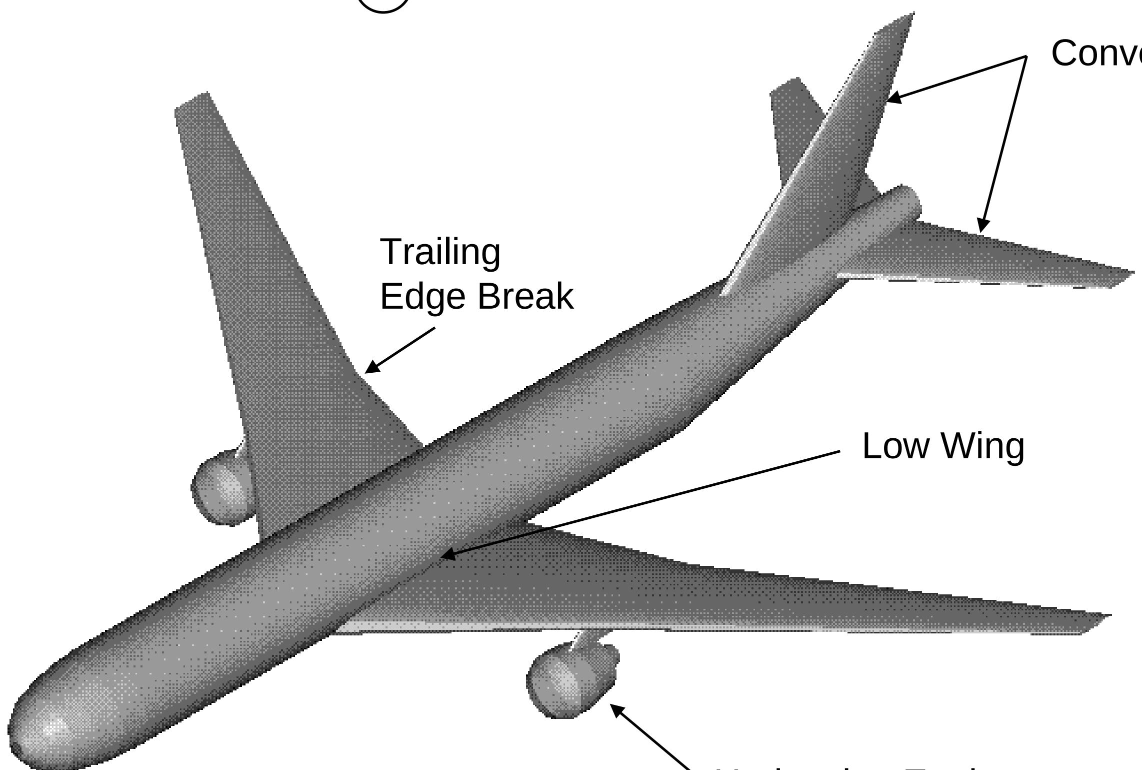
- Use a Multidisciplinary Design Optimization Approach to Design 325-Passenger, 7500 nmi Range Mach 0.85 Transports of Cantilever and Strut-Braced Wing (SBW) Configurations.

Problem Statement, Cont.

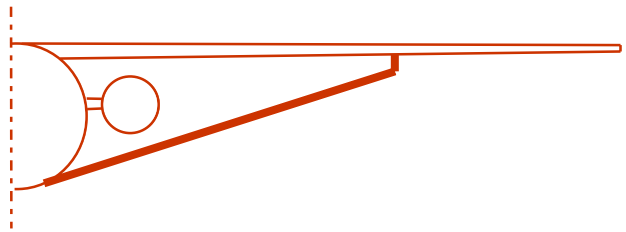
- Minimize Take-Off Gross Weight (TOGW) and Fuel Weight.
- Evaluate Sensitivity of TOGW to Advanced Technologies
- Determine the Effect of Range on TOGW
- Perform Cost Analysis
- Perform Economic Mission Analysis

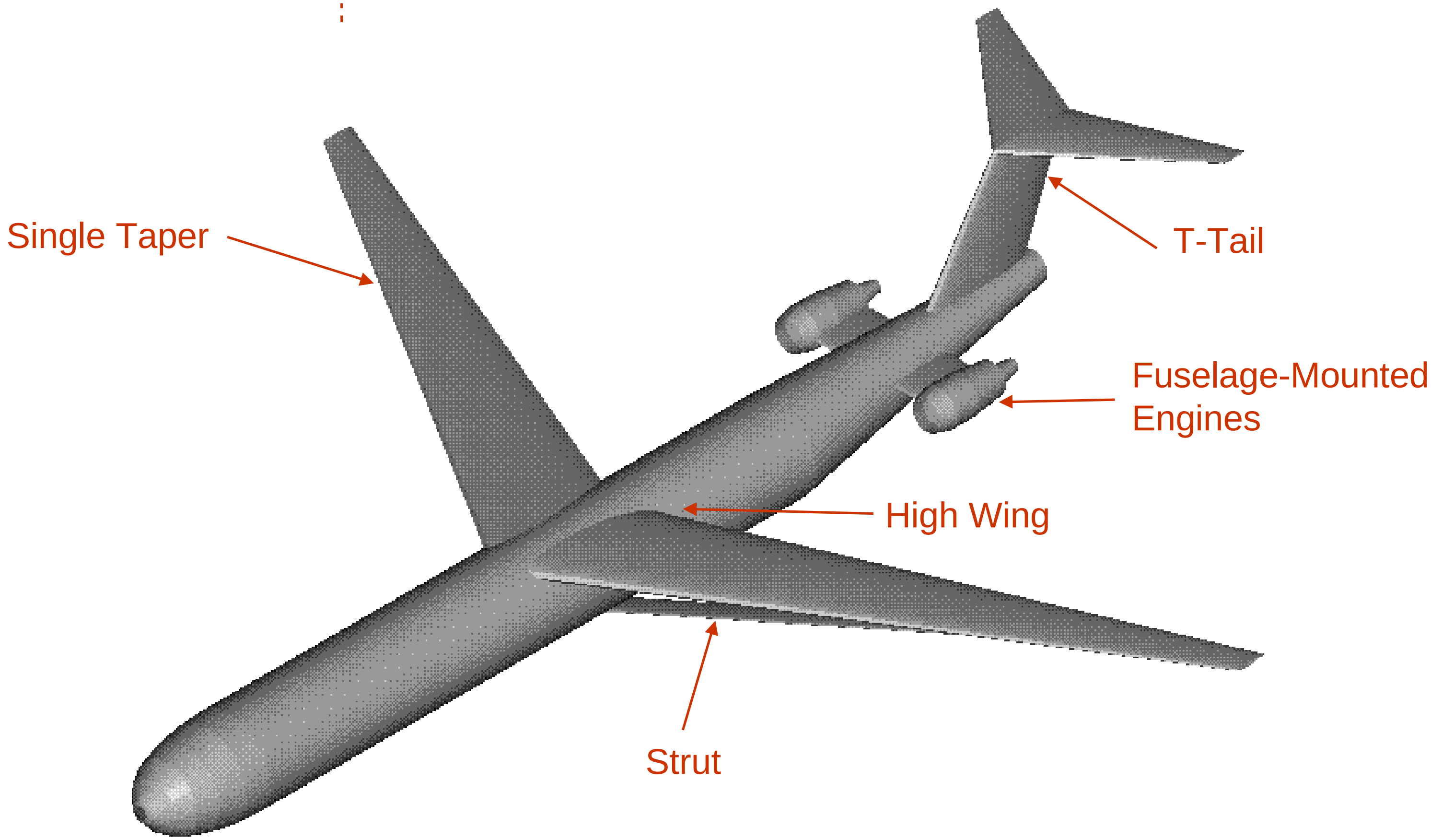
Configurations - Cantilever



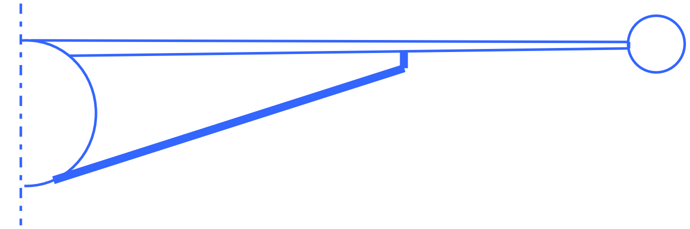


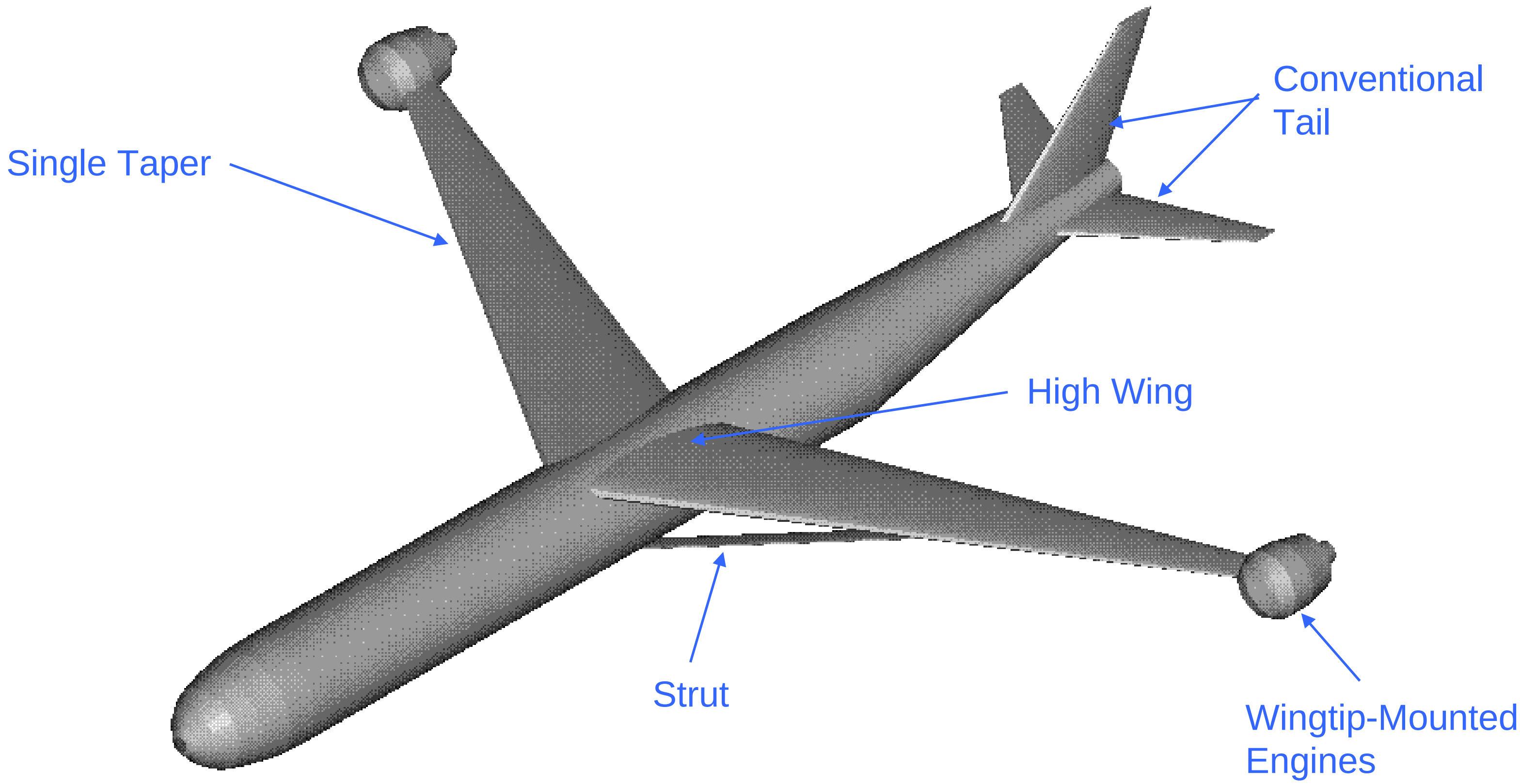
T-Tail Fuselage-Mounted Engine SBW



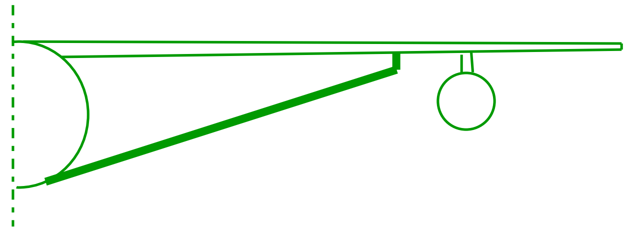


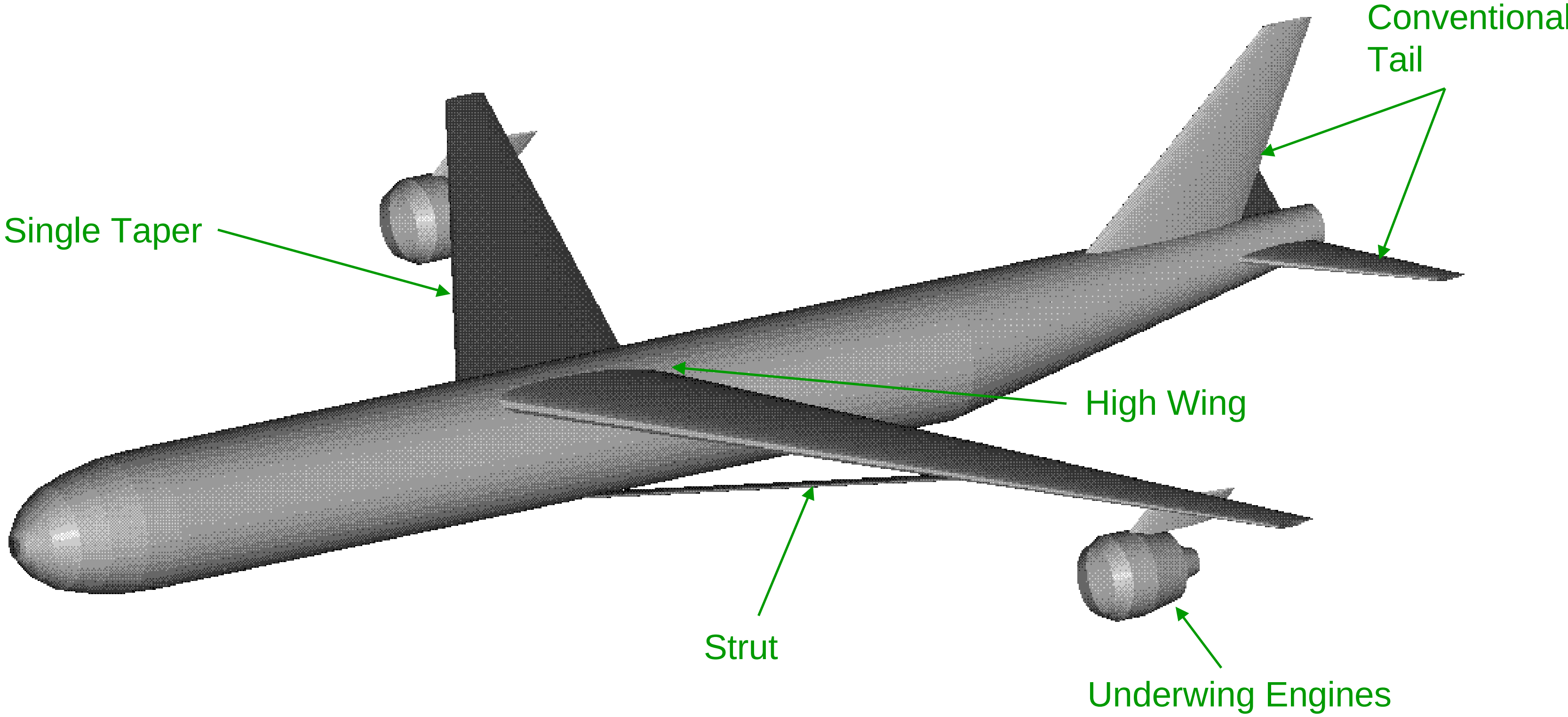
Wingtip-Mounted Engine SBW

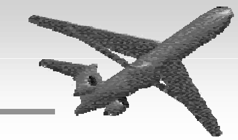




Underwing Engine SBW



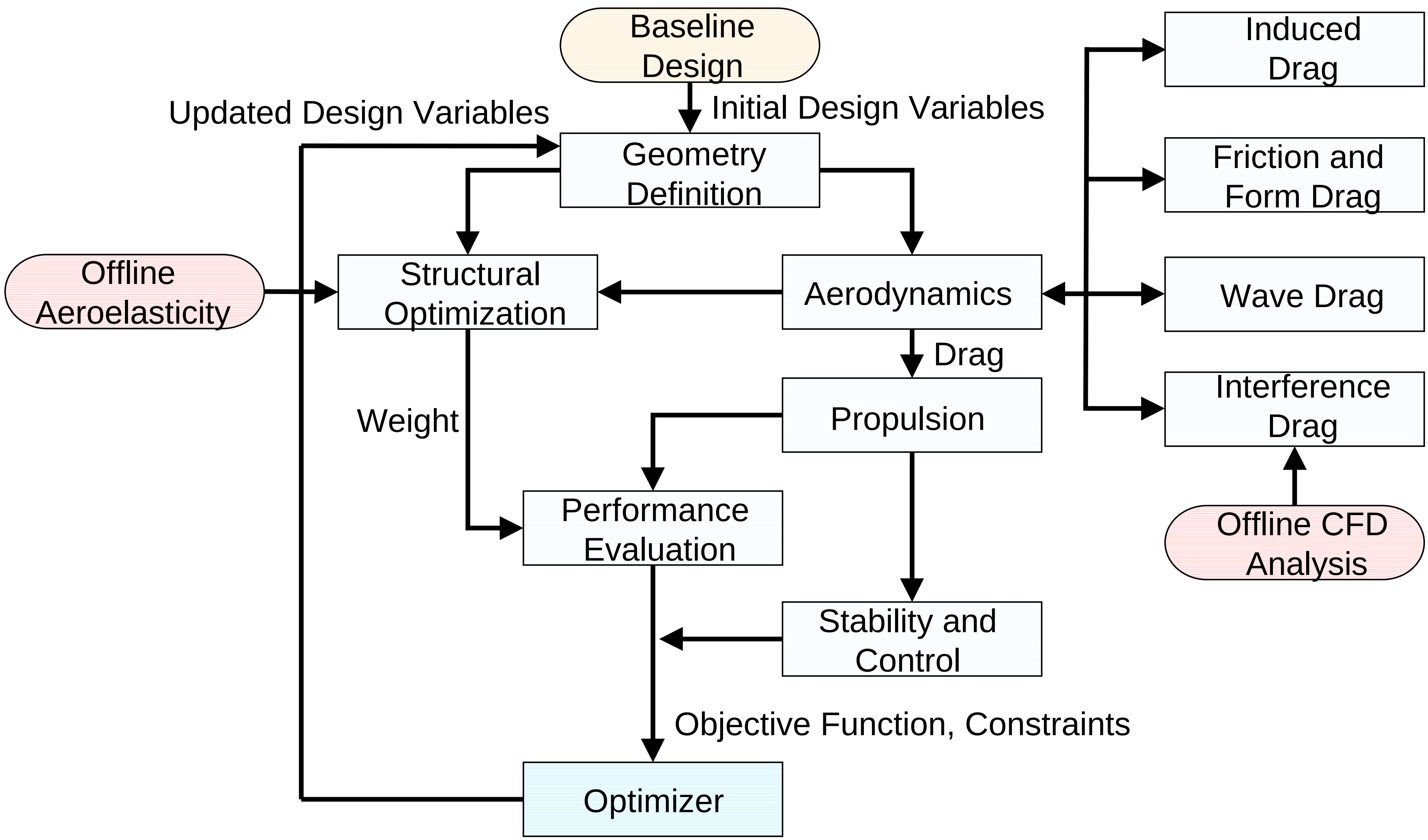




VPI/LMAS Interactions

- Add Realism to Design Study
- Experience of a Major Airframe Manufacturer
- Interpretation of FARs
- Validations Accelerated Code Development
  - Calibration of 1995 and 2010 Cantilever Baseline Aircraft
  - LMAS Review of Virginia Tech T-Tail Fuselage Mounted Engine SBW
- General Design Tool Modifications
  - Code Changes by VPI and LMAS

MDO Tool Architecture



Design Variables and Constraints

Design Variables

1.	Semi-Span of Wing/Strut Intersection
2.	Wing Span
3.	Wing Inboard ¼ Chord Sweep
4.	Wing Outboard ¼ Chord Sweep
5.	Wing Dihedral
6.	Strut ¼ Chord Sweep
7.	Strut Chordwise Offset
8.	Strut Vertical Aerodynamic Offset
9.	Wing Centerline Chord
10.	Wing Break Chord
11.	Wing Tip Chord
12.	Strut Chord
13.	Wing t/c at Centerline
14.	Wing t/c at Break
15.	Wing t/c at Tip
16.	Strut t/c
17.	Wing Skin Thickness at Centerline
18.	Strut Tension Force
19.	Vertical Tail Scaling Factor
20.	Fuel Weight
21.	Zero Fuel Weight
22.	Required Thrust
23.	Semispan Location of Engine
24.	Average Cruise Altitude
25.	Econ. Mission Fuel Weight
26.	Econ. Mission Average Cruise Altitude

Constraints

1.	Zero Fuel Weight Convergence
2.	Range Calculated > Reference Range
3.	Initial Cruise Rate of Climb > 500 ft/min
4.	Cruise Section C_l < 0.7
5.	Fuel Weight < Fuel Capacity
6.	C_n Available > C_n Required
7.	Wing Tip Deflection < Max Wing Tip Deflection at Taxi Bump Conditions
8.	Wing Weight Convergence
9.	Max. Body and Contents Weight Convergence
10.	Second Segment Climb Gradient > 2.4%
11.	Balanced Field Length < 11,000 ft
12.	Approach Velocity < 140 kts.
13.	Missed Approach Climb Gradient > 2.1%
14.	Landing Distance < 11,000 ft
15.	Econ. Mission Range Calculated > 4000 nmi
16.	Econ. Mission Section C_{lmax} < 0.7
17.	Thrust at Altitude > Drag at Altitude

2 Side Constraints for Each Design Variable

*Red Text Indicates New Additions

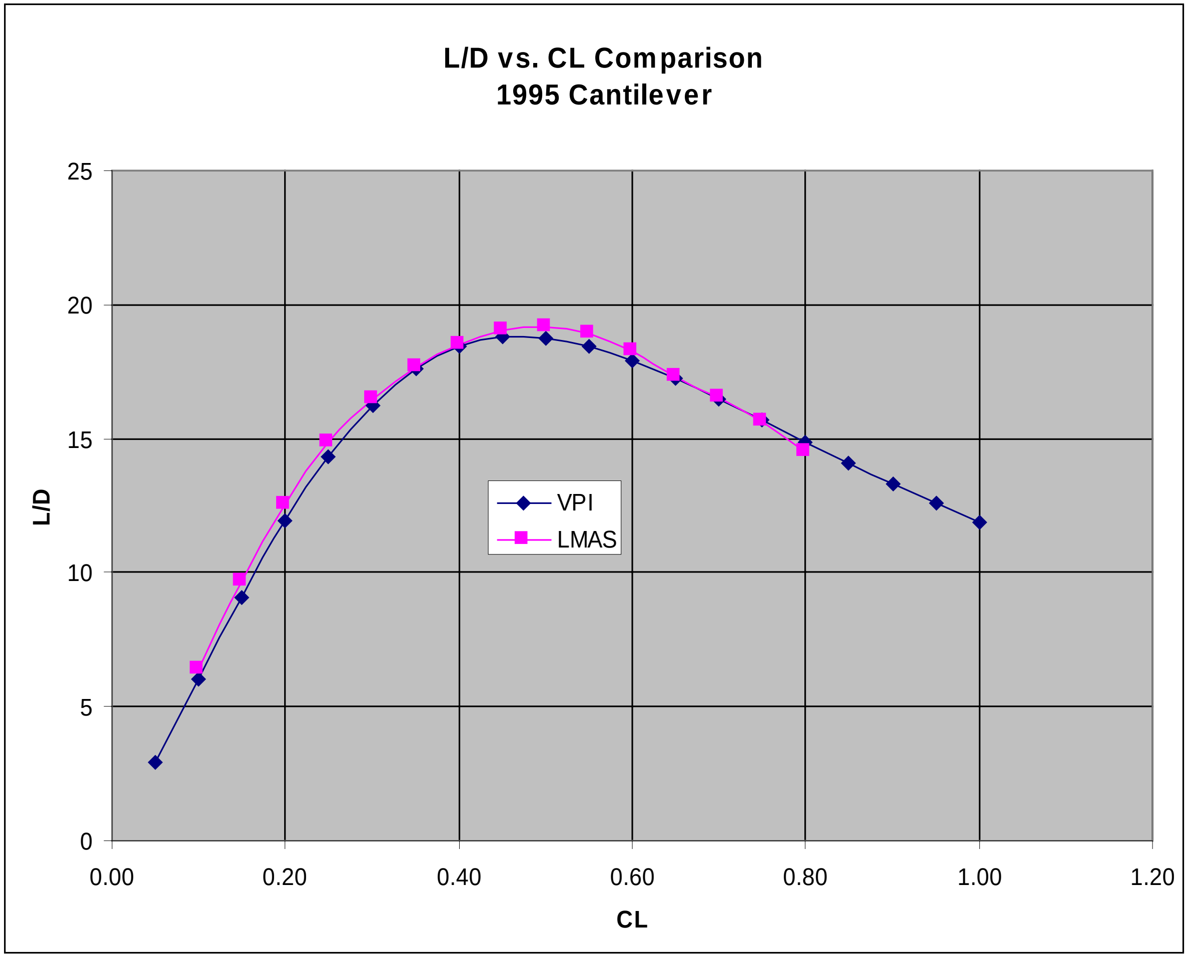
MDO Tool Development

- Modifications and Improvements to VPI MDO Code
  - Aerodynamics
  - Structures
  - Tail Geometry
  - Propulsion
  - Field Performance
- LMAS Dictates Fuselage Mounted Engine SBW
  - Circulation Control Considered Not Mature by 2010 Timeframe
- Continued Research
  - Optimum Cantilever Aircraft
  - Wingtip-Mounted Engine SBW
  - Underwing Engine SBW Cases

Aerodynamics

- Differing LMAS/VPI Drag Accounting Conventions
- Wave Drag
  - LMAS now Uses VPI Wave Drag Code
    - Korn Equation and Lock’s Drag Rise Fit
- Friction Drag
  - LMAS Form Factors and C_F Equations Used in FRICTION.F
- Additional Profile Drag Term
  - Accounts for Lift Dependent Profile Drag
  - Improves Drag Polar Fit at Off-Design Conditions

New Drag Polar

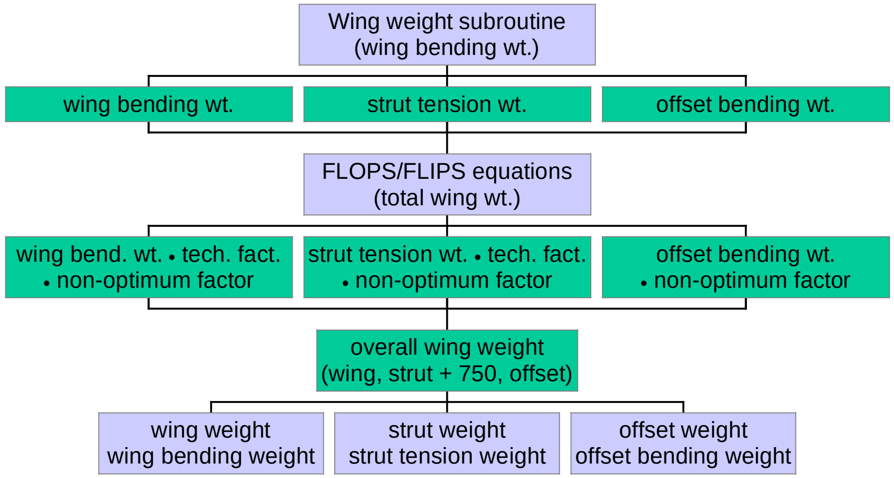


Structures

- FLOPS Weight Build-Up Modified to Use LMAS Equations and Factors
  - Wing Weight
  - Fuselage Weight
  - Tail Surfaces (and T-Tail Factors)
  - Landing Gear Weight
  - Nacelle Weight
  - Passenger Service Weight
- LMAS and FLOPS Equations Used Everywhere Except Wing Bending Material Weight

Wing Weight

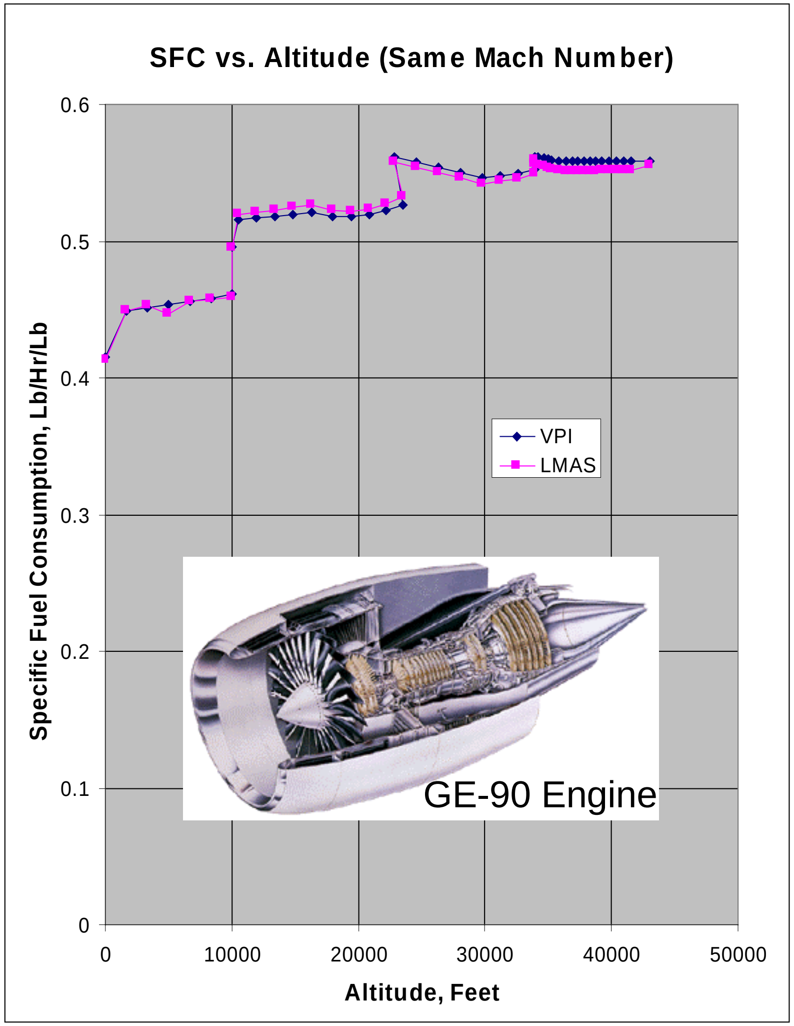
- Structural Benefits of the Strut Appear in Wing Bending Material Term
- Subroutine WING Uses Piecewise Linear Beam Model (Double Plate)
- LMAS Equations Make Additional Corrections

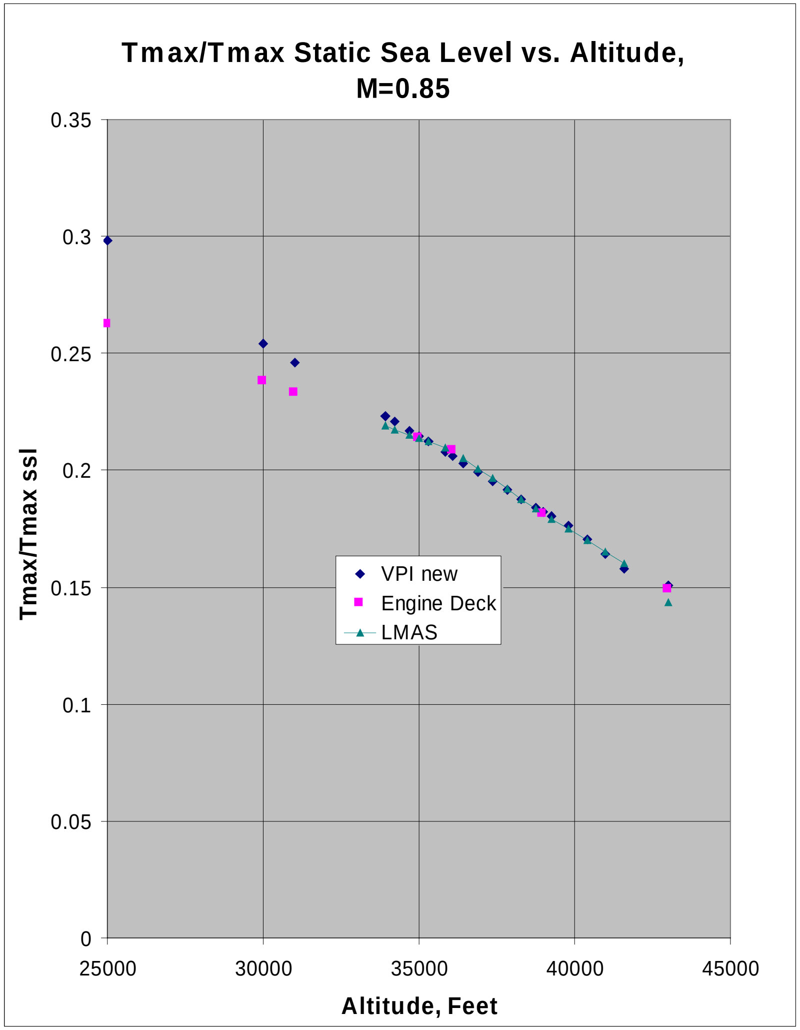


Tail Sizing

- Tail Volume Coefficient Method
  - Dependent on Wing Geometry and Tail Moment Arm
  - Previously: Fixed Tail Area Except for Vertical Tail
    - Vertical Tail Multiplying Factor for C_N Constraint
- Tail Geometry Parameterized
- Option Exists for Fixed Tail Area
- Circulation Control

Engine Model

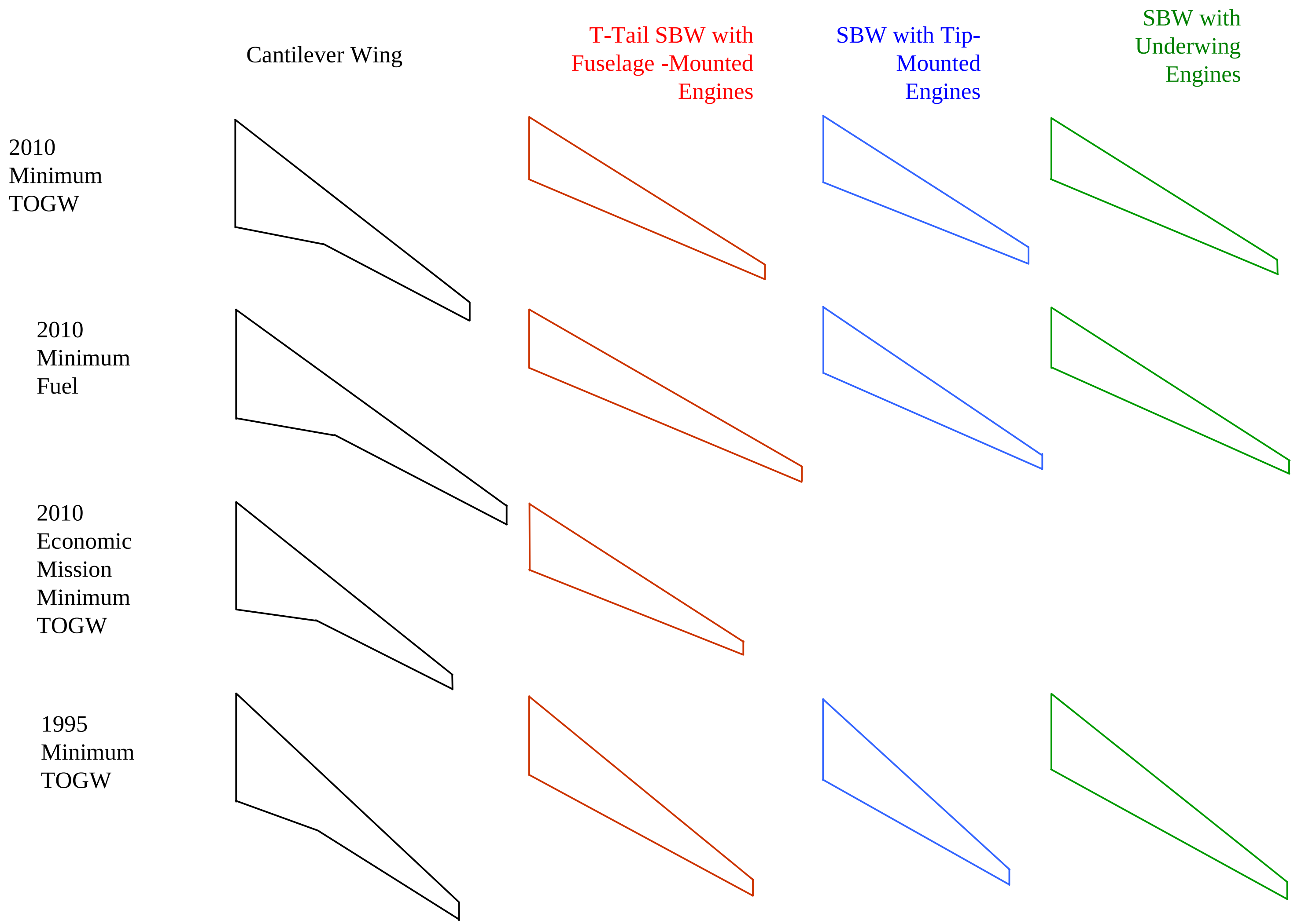




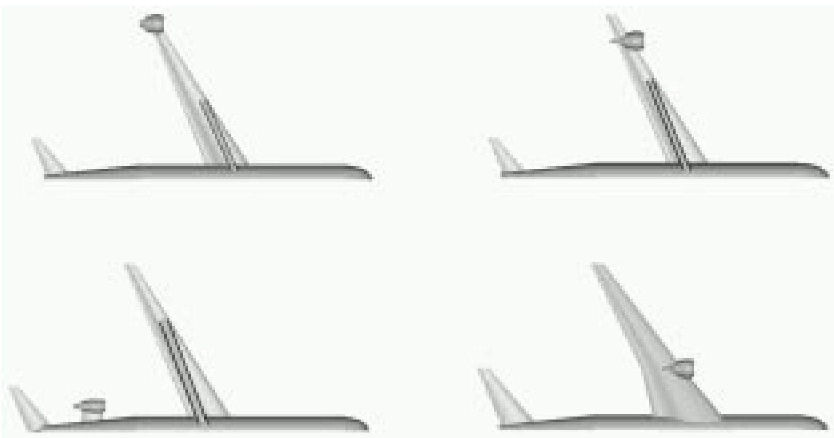
Field Performance

- LMAS - Field Performance is Critical
- Uses LMAS Drag Polars
  - Corrected for Wetted Area and Aspect Ratio
- Components
  - Balanced Field Length
  - Second Segment Climb
  - Landing Field Length
  - Missed Approach Climb
  - Approach Velocity
- Added 4 New Constraints

Primary Case Matrix



2010 Minimum-TOGW Optima

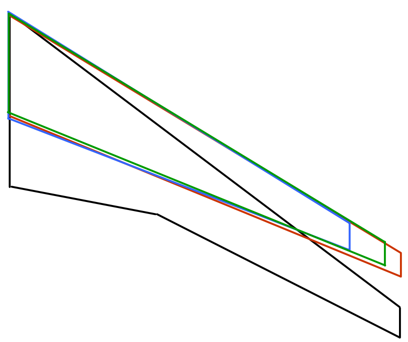


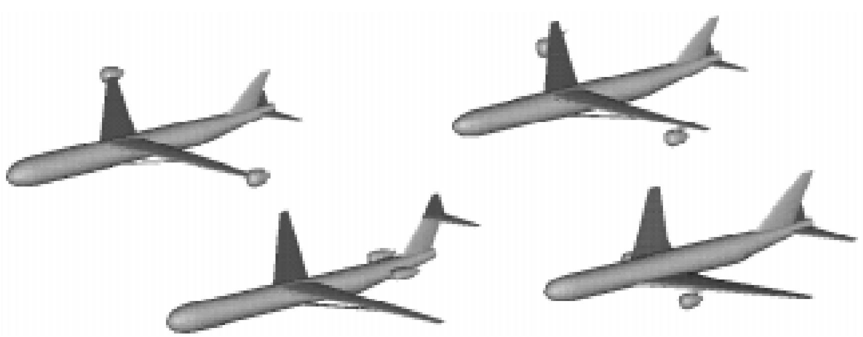
2010 Conv Wing-Eng.	SBW T-Tail	SBW Tip Engines	SBW Underwing	SBW Inboard Eng.	
225.3	226.0	198.6	220.1	220.6	Span (ft)
52.0	30.2	31.8	29.4	30.0	Root Chord (ft)
5307	4205	3907	3970	4065	S_w (ft^2)
9.57	12.15	10.10	12.20	11.98	AR
15.14%	14.28%	14.36%	14.00%	14.06%	Root t/c
10.55%	6.58%	7.56%	7.15%	7.19%	Break t/c
7.40%	6.56%	6.85%	7.37%	7.38%	Tip t/c
34.2	29.9	30.2	29.8	30.4	Wing $\Lambda_{1/4}$ (deg)
	20.5	23.5	21.6	21.2	Strut $\Lambda_{1/4}$ (deg)
	68.8%	56.8%	62.4%	67.4%	η Strut
37.0%		100.0%	83.8%	37.0%	η Engine
75793	59463	51851	56562	58859	T_{max} (lbs)
42052	40429	40736	40097	39994	Cruise Altitude (ft)
23.38	25.33	25.25	25.30	24.99	L/D
63706	59581	41854	50287	55742	Wing Wt. (lbs)
47266	42473	25213	33335	39364	Bending Matl (lbs)
186295	159629	145618	151342	157587	Fuel Wt. (lbs)
540230	**490312**	**446294**	**464556**	**479526**	TOGW (lbs)
	9.2%	17.4%	14.0%	11.2%	% TOGW Improvement
	14.3%	21.8%	18.8%	15.4%	% Fuel Improvement
	21.5%	31.6%	25.4%	22.3%	% Thrust Reduction
87.49	82.69	76.70	79.01	80.72	Acquisition Cost ($M)
583.68	538.49	504.86	518.75	530.72	DOC ($M)
892.07	885.88	880.41	882.68	884.54	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE	ACTIVE		ACTIVE	ACTIVE	2nd Segment Climb
	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
					Initial Cruise ROC
		ACTIVE	ACTIVE		Wingtip Deflection
ACTIVE					Engine Out
					Approach Velocity
					Fuel Volume

2010 Minimum-TOGW Optima

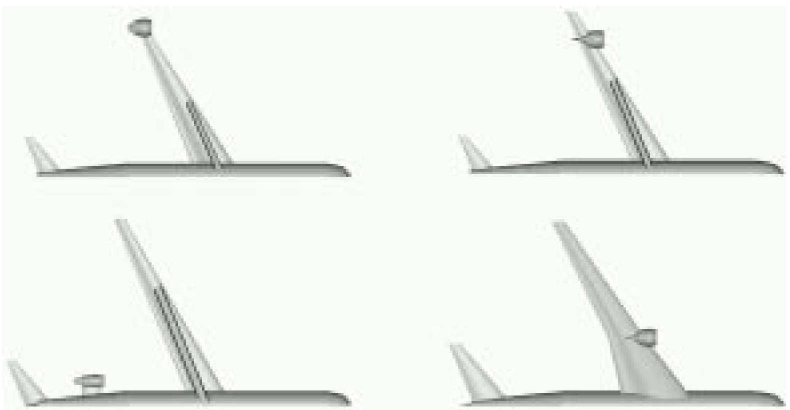
- Thrust Reduction of 21.5-31.6%
  - Lower Noise Pollution at Urban Airports
- Large SBW Sweep Reduction
- Less Wing Area

- SBW %TOGW Improvement = 9.2-17.4%
- SBW %Fuel Improvement = 14.3-21.8%
- Similar Wingspans Except for Wingtip-Engine Case
- Wingtip Deflection Constraint





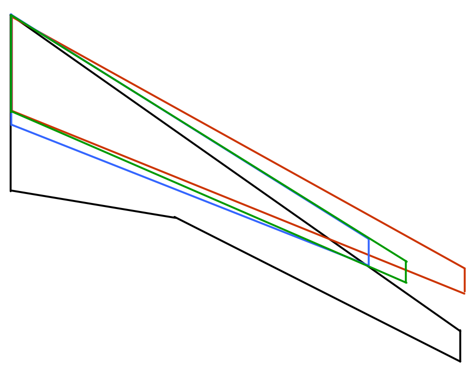
2010 Minimum-Fuel Optima



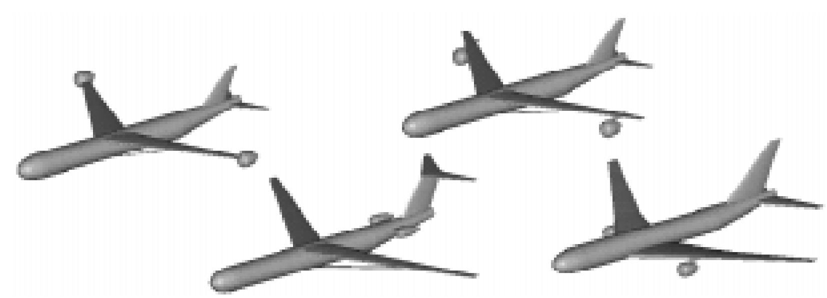
2010 Conv Min Fuel	SBW T-Tail Min F	SBW Tip Eng Min F	SBW Wing Eng	
260.9	262.1	204.3	230.6	Span (ft)
52.0	28.4	32.0	29.1	Root Chord (ft)
5793	4723	3933	4113	S_w (ft^2)
11.75	14.54	10.61	12.92	AR
12.97%	12.20%	14.07%	13.78%	Root t/c
9.27E-02	6.22%	7.52%	7.12%	Outboard t/c
5.21E-02	5.95%	6.88%	7.52%	Outboard t/c
32.5	28.3	31.7	30.5	Wing $\Lambda_{1/4}$ (deg)
	22.0	24.3	22.3	Strut $\Lambda_{1/4}$ (deg)
	65.9%	53.8%	60.2%	η Strut
37.0%		100.0%	82.9%	η Engine
71032	56304	52285	54973	T_{max} (lbs)
43783	42723	40765	40518	Cruise Altitude (ft)
26.37	29.23	26.08	26.34	L/D
92991	85558	47120	56488	Wing Wt. (lbs)
78456	68276	30914	39593	Bending Matl (lbs)
177692	**148838**	**143425**	**147695**	Fuel Wt. (lbs)
561893	507227	449926	466858	TOGW (lbs)
	9.7%	19.9%	16.9%	% TOGW Improvement
	16.2%	19.3%	16.9%	% Fuel Improvement
92.66	87.54	77.76	80.12	Acquisition Cost ($M)
590.96	543.02	506.22	518.41	DOC ($M)
894.76	887.98	880.87	882.96	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE				2nd Segment Climb
	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
	ACTIVE			Initial Cruise ROC
		ACTIVE	ACTIVE	Wingtip Deflection
				Engine Out
				Approach Velocity
				Fuel Volume

2010 Minimum-Fuel Optima

- SBW TOGW Reduction Over Cantilever for Min-Fuel Optima Greater than TOGW Reduction for Minimum-TOGW Optima
- L/D Change from Min-TOGW to Min-Fuel Objective Function
  - Cantilever: 23.4-26.4
  - T-Tail SBW: 25.3-29.2
  - Wingtip Engine SBW: 25.3-26.1
  - Underwing Engine SBW: 25.3-26.3



- Greater Wingspan to Fly at Higher Altitude with High L/D
- SBW Fuel Reductions
  - 16.2-19.3%
- Fuel Reduction over Min TOGW
  - antilever: 4.62%
  - -T-Tail SBW: 6.76%
  - Wingtip Engine SBW: 5.23%
  - Underwing Engine SBW: 2.41%



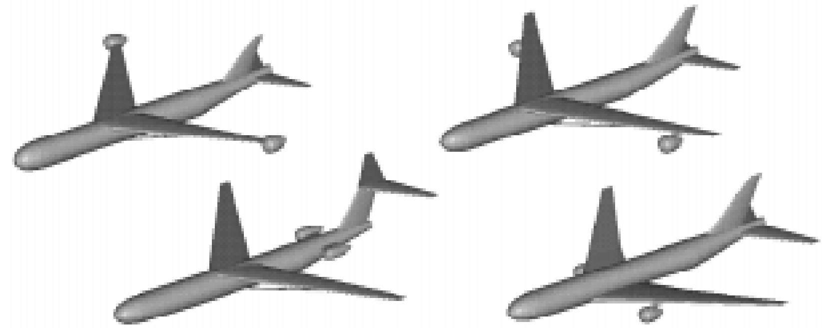
Sensitivity Analysis

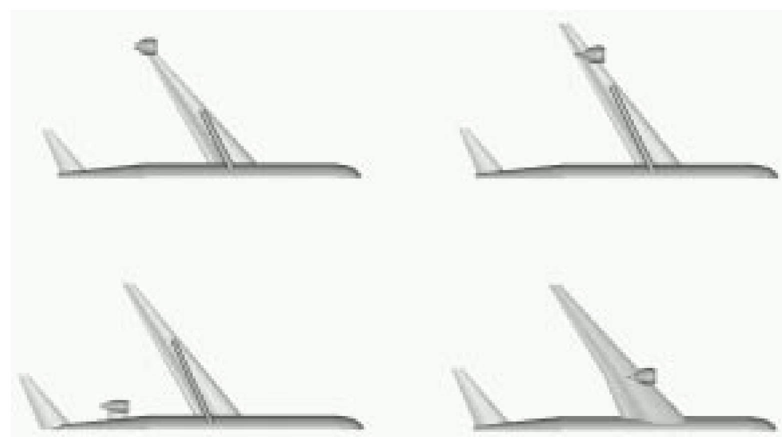
- Determines Sensitivity of a Configuration to Technology Groupings
- Procedure:
  - 1. Find 1995 and 2010 Technology Level Baseline Aircraft
  - 2. Individually Apply LMAS Technology Groups to 1995 Baseline
  - 3. Sum ΔTOGW for Each Technology Group
  - 4. If the Overall ΔTOGW Between 1995 and 2010 Baselines is Greater than the Sum of Each Technology Group: Design Synergism

Sensitivity Analysis Technology Groups

- Natural Laminar Flow
  - Wing, Strut, Tails, Fuselage and Nacelles
- Other Aerodynamics
  - Riblets on Fuselage and Nacelles
  - Active Load Management for Induced Drag Reduction
  - All Moving Control Surfaces
  - Supercritical Airfoils
- Airframe
  - Composite Wings and Tails
  - Integrally Stiffened Fuselage Skins
- Propulsion
  - Reduced Specific Fuel Consumption
- Systems
  - Integrated Modular Flight Controls
  - Fly-by-Light and Power-by-Light
  - Simple High Lift Devices
  - Advanced Flight Management Systems

1995 Minimum-TOGW Designs

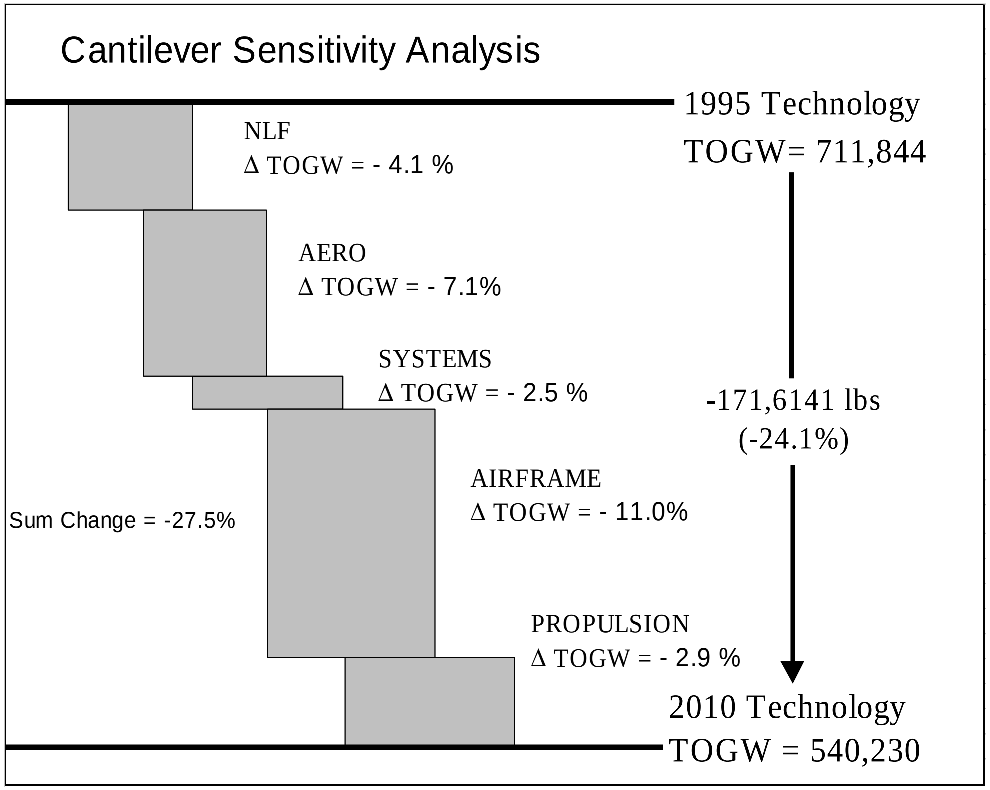




- Large Sweep Increase
  - 6-7 Degrees SBW
  - 5.5 Degrees Cantilever
  - No Laminar Flow Benefit to Low Sweep, but Lower Wave Drag
- Large Wing Area Increase

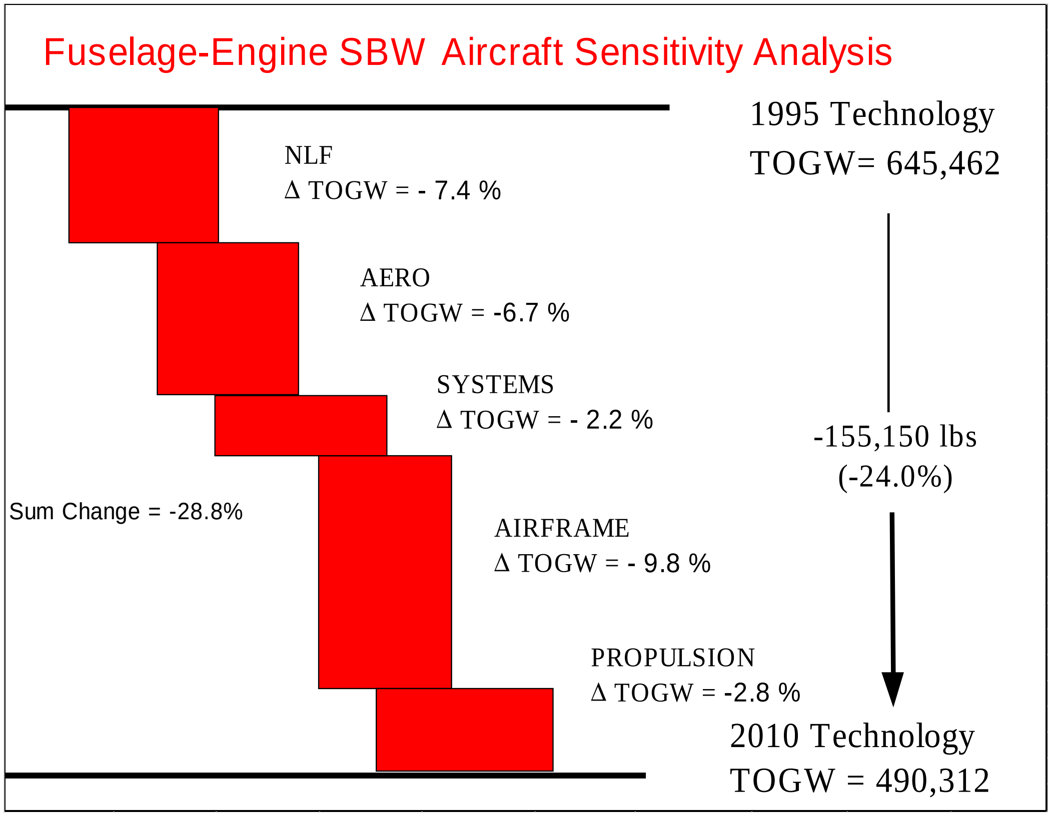
Cantilever Wing Sensitivity Analysis

- Airframe Weight Factors have Greatest Effect
- No Overall Synergism



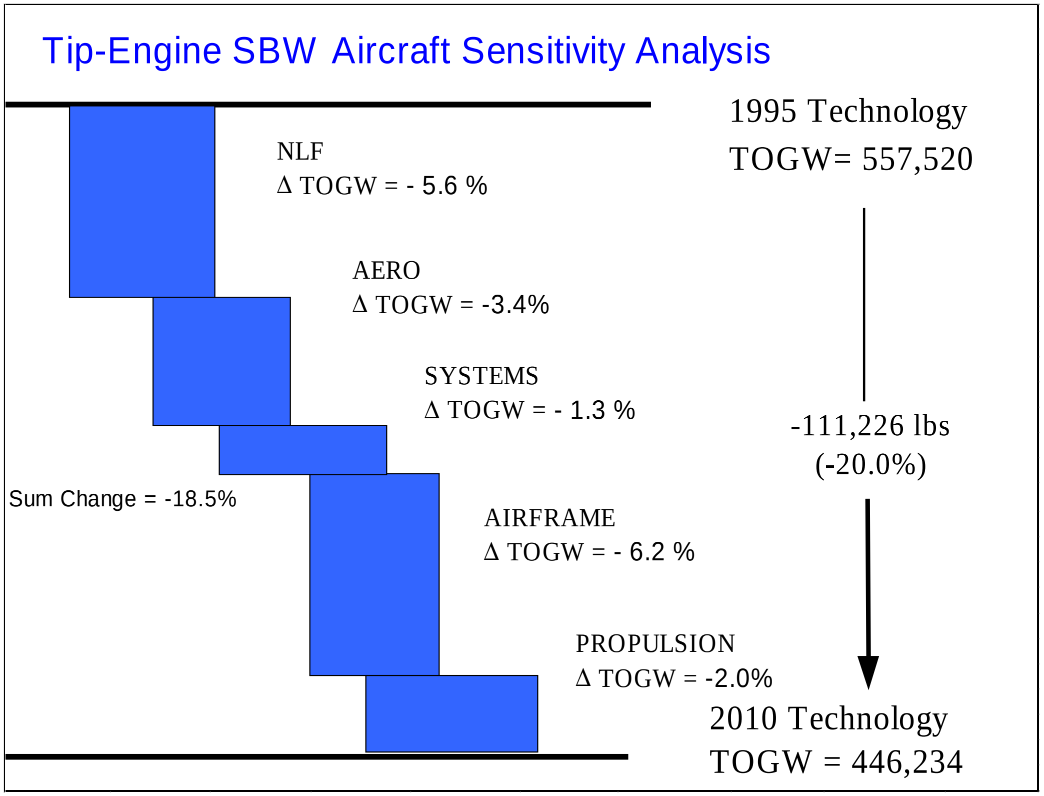
T-Tail Fuselage-Mounted Engine SBW Sensitivity Analysis

- Airframe Technologies have Greatest Impact
- NLF Becomes Very Important
- Improvements of Other Groups is Smaller Compared to Cantilever Wing
- Overall % Improvement is Nearly Same as Cantilever Wing
- No Synergy



Wingtip-Mounted Engine SBW Sensitivity Analysis

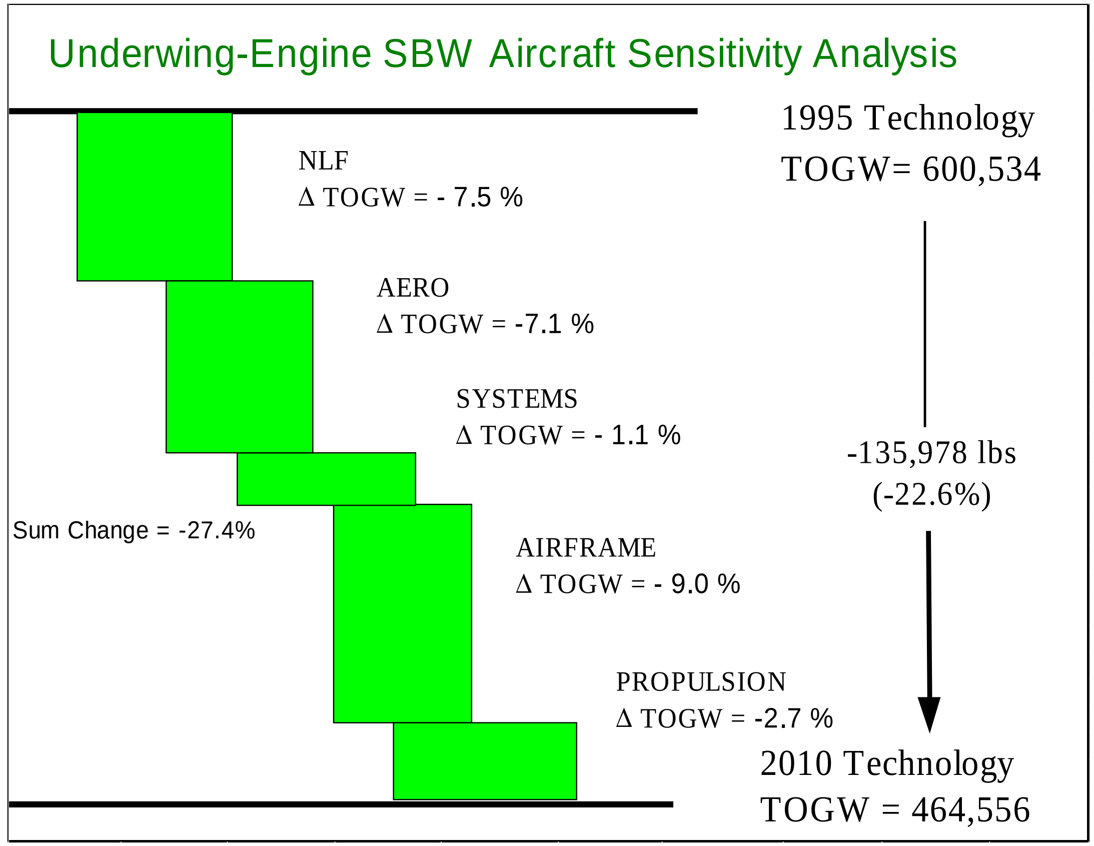
- Less NLF Improvements
- Low Sensitivity to All Groups Relative to Other Cases
- Some Synergy
- 1995 Span Reduction Over 2010 Case
  - 2010 to 1995: 199 to 182 feet
  - Wingtip Deflection Constraint



Underwing Engine SBW Sensitivity Analysis

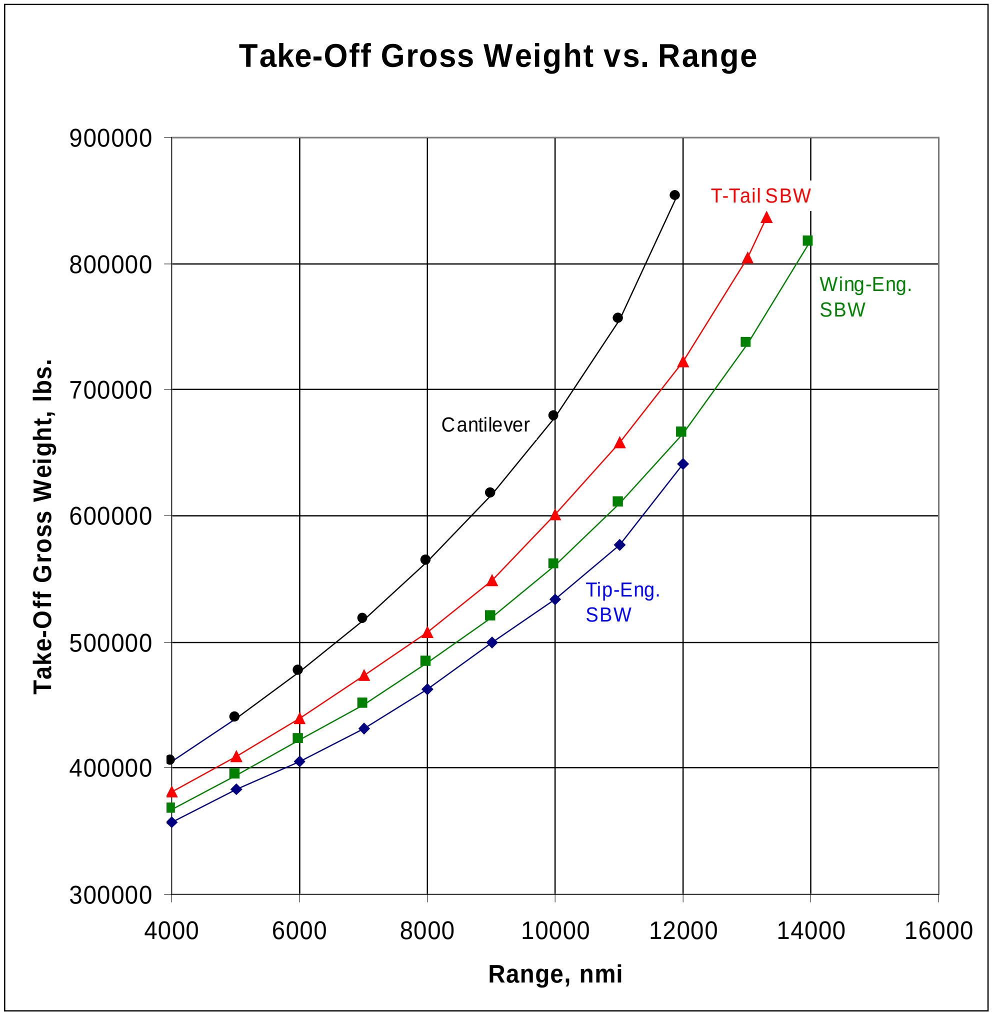
- Similar Trends as T-Tail SBW
- Less Sensitive to Airframe Technologies
- No Synergy

- General:
- SBW is More Sensitive to NLF Technolgies
- SBW is Less Sensitive to All Other Technology Groups
- SBW is Lighter for Every Case



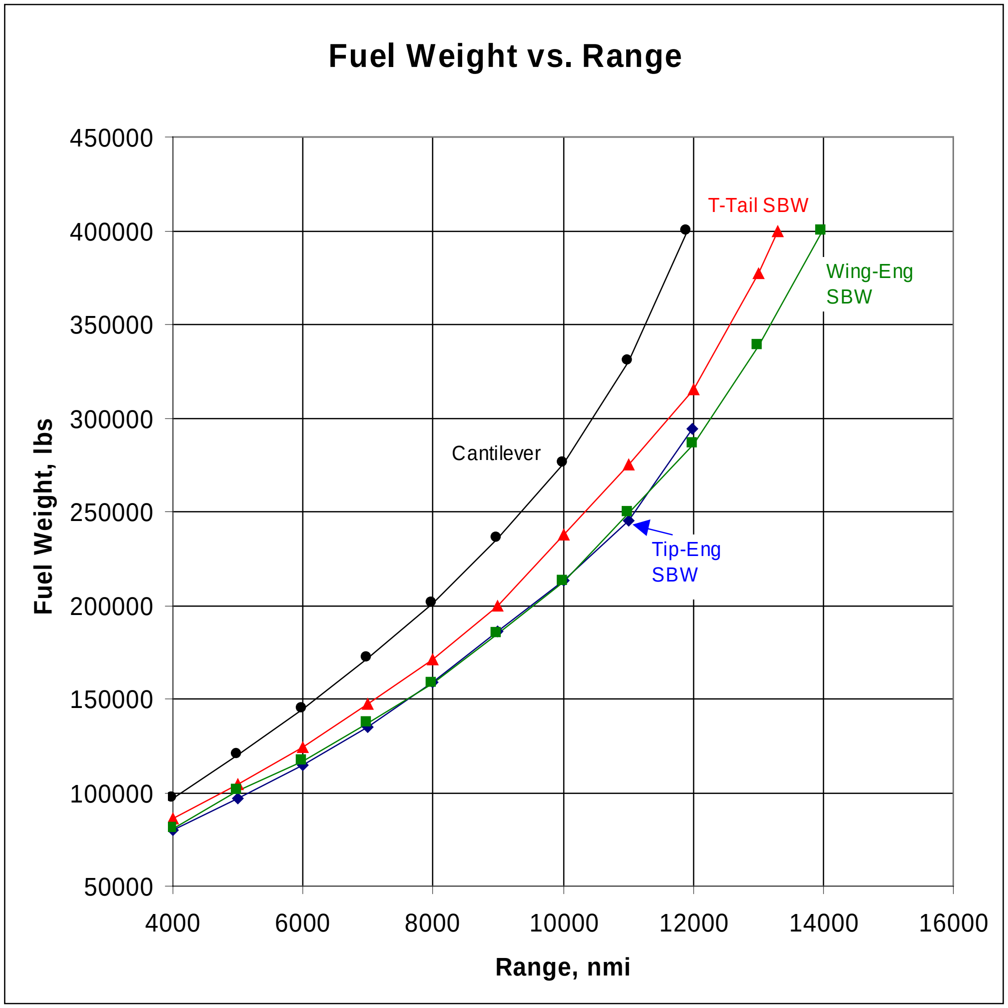
Minimum TOGW Range Effects - TOGW

- SBW TOGW Improves with Range
  - T-Tail: 6.0-12.9% Reduction
  - Wingtip Engine: 11.8-23.7%
  - Underwing Engine: 9.5-19.2%



Minimum TOGW Range Effects - Fuel Weight

- SBW Fuel Weight Generally Improves with Range
  - T-Tail: 11.3-16.8% Reduction
  - Wingtip Engine: 17.6-25.8%
  - Underwing Engine: 16.0-24.6%
- Wingtip-Mounted Engine Case not Always Superior in Fuel Weight
  - Modest Span Limits L/D (222 ft versus 263 ft)
  - As Span Increases, AR Decreases
  - Most TOGW Reduction Due to Zero-Fuel Weight
- Range Comparisons



Cost Analysis Results

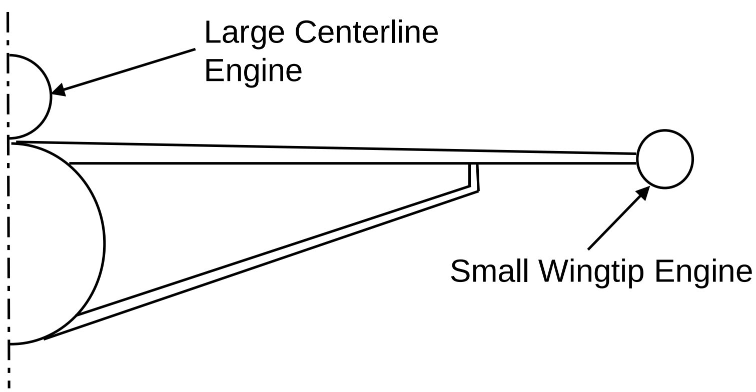
- Total Cost = Acquisition Cost+DOC+IOC
- SBW Acquisition Cost Reductions = 5.5-16.1% (Min Fuel)
  - Strong Function of Zero-Fuel Weight
- SBW DOC Reductions = 8.1-14.3% (Min Fuel)
  - Strong Function of Fuel Weight
- SBW IOC Reductions = 0.8-1.3% (Min TOGW)
  - Weak Function of TOGW, Strong Function of Passenger Load

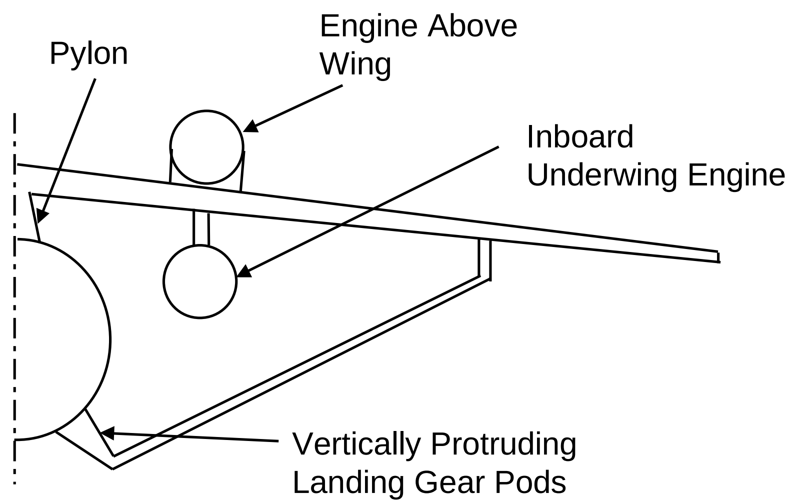
Conclusions

- SBW TOGW Reduction for All Cases
- SBW Fuel Reduction
  - Less Pollutant Discharge
- SBW Thrust Reduction
  - Less Noise Pollution at Urban Airports
- SBW Cost Reduction
- SBW is More Sensitive to NLF Technologies
- Greater Range for Given Fuel Load and Weighs Less for a Given Range
- Implications
- Passenger Acceptance

Recommendations

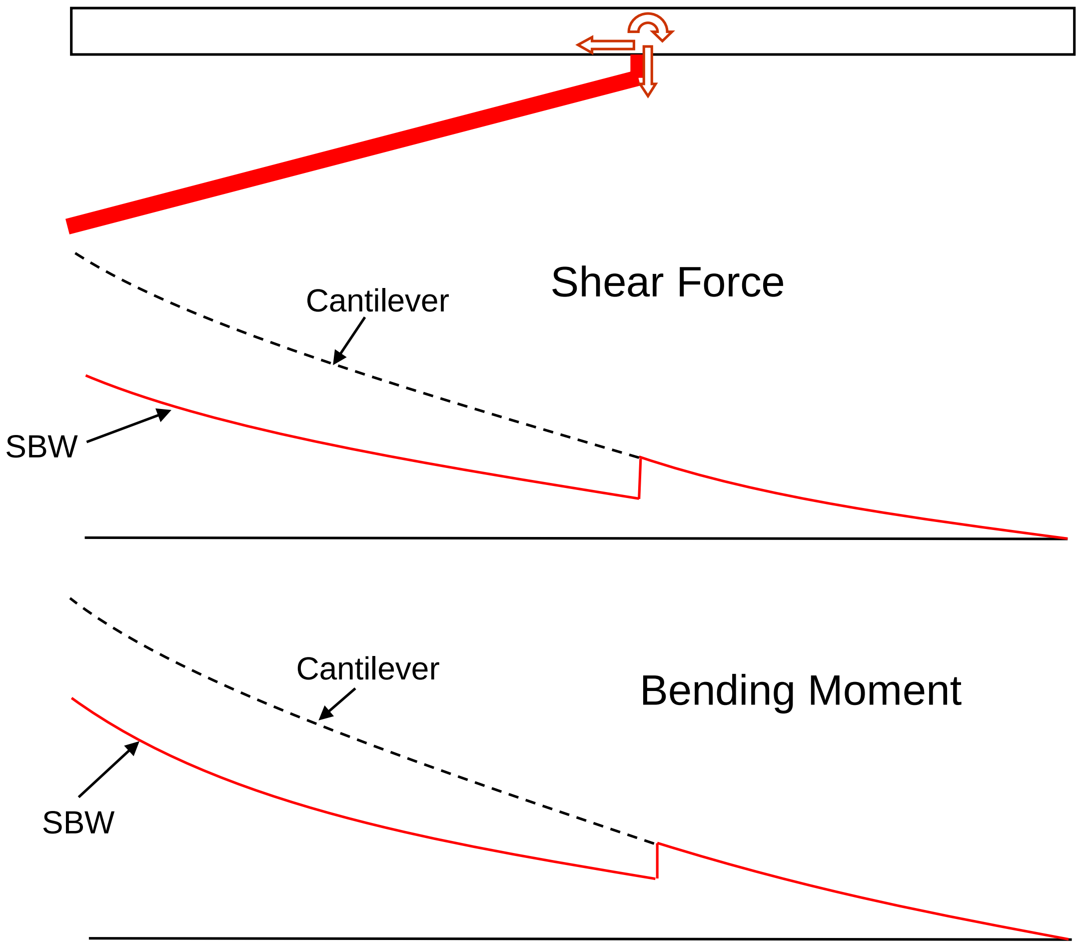
- Use More Design Variables for Strut Vertical Offset
- Increase Wing/Strut Vertical Separation
  - Pylon
  - Vertically Protruding Landing Gear Pods
  - Double Deck Fuselage
- 3 Engine Configuration for Wingtip-Mounted Engine Case





Backup Slides

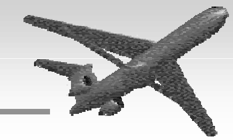
Role of the Strut



Economic Mission Analysis and Results

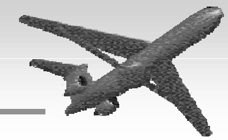
- Economic Mission:
  - 4000 nmi
  - Reduced Passenger and Bag Load
- Economic Mission Aircraft Must be Capable of Full Mission
- 2 Scenarios:
  - 1. Full Mission Aircraft Analyzed at Economic Mission Case
  - 2. Economic Mission Optimum
- Results
  - TOGW Optima for Economic and Full Mission have similar TOGW at a given Flight Profile
  - Wingspan Reduction

Cantilever Wing Sensitivity Analysis



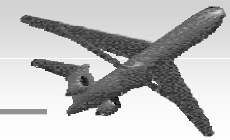
1995 Conv Wing Eng.	1995 Conv NLF	1995 Conv Aero	1995 Conv Strutctures	1995 Conv Propulsion	1995 Conv Systems	2010 Conv Wing-Eng.	Tot Change **-171614** Sum Change **-27.5%**
7500.1	7496.5	7500.1	7500.1	7500.0	7500.1	7499.8	Range
214.9	211.5	217.9	215.2	210.4	213.9	225.3	Span (ft)
52.0	52.0	52.0	52.0	52.0	52.0	52.0	Root Chord (ft)
5413	5213	5198	4959	5254	5415	5307	S_w (ft^2)
8.53	8.58	9.13	9.34	8.43	8.45	9.57	AR
15.61%	15.27%	16.36%	15.26%	15.39%	15.65%	15.14%	Root t/c
10.65%	10.32%	11.73%	10.83%	10.28%	10.61%	10.55%	Outboard t/c
6.20%	5.78%	6.66%	5.52%	5.75%	5.25%	7.40%	Outboard t/c
39.8	39.0	36.7	40.4	39.3	39.8	34.2	Wing $\Lambda_{1/4}$ (deg)
37.0%	37.0%	37.0%	37.0%	37.0%	37.0%	37.0%	η Engine
108861	104599	98437	94274	106772	105789	75793	T_{max} (lbs)
35640	35598	37253	36112	35519	35943	42052	Cruise Altitude (ft)
19.94	20.68	20.83	20.39	19.79	20.15	23.38	L/D
98791	93734	87267	75388	94109	96260	63706	Wing Wt. (lbs)
60253	56940	51513	58395	57001	58325	47266	Bending Matl (lbs)
280900	262535	253180	246252	268265	271935	186295	Fuel Wt. (lbs)
711844	**682770**	**661501**	**633848**	**691004**	**694142**	**540230**	TOGW (lbs)
0	-4.1%	-7.1%	-11.0%	-2.9%	-2.5%	-24.1%	% TOGW Change
102.51	100.54	98.56	94.81	101.02	99.55	87.49	Acquisition Cost ($M)
729.68	704.50	687.65	667.66	712.13	712.26	583.68	DOC ($M)
913.37	909.74	907.12	903.69	910.78	911.17	892.07	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	2nd Segment Climb
							Balanced Field Length
							Wingtip Deflection
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Engine Out
ACTIVE	ACTIVE			ACTIVE			Approach Velocity
							Fuel Volume

Fuselage Eng. T-Tail SBW Sensitivity Analysis



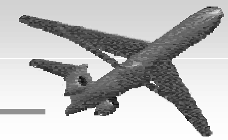
T-Tail SBW 1995	T-Tail SBW NLF	T-Tail SBW AERO	T-Tail SBW Structures	T-Tail SBW Propulsion	T-Tail SBW Systems	T-Tail SBW 2010	Tot Change **-155150** Sum Change **-28.8%**
7499.6	7499.5	7499.2	7499.5	7498.9	7497.8	7499.9	Range
214.4	210.9	208.4	212.7	211.8	212.2	226.0	Span (ft)
37.7	36.3	35.9	35.1	37.1	37.5	30.2	Root Chord (ft)
4908	4598	4581	4541	4770	4805	4205	S_w (ft^2)
9.37	9.68	9.48	9.96	9.41	9.37	12.15	AR
13.68%	13.36%	14.19%	13.65%	13.74%	13.64%	14.28%	Root t/c
7.07%	6.61%	7.13%	6.72%	6.82%	6.85%	6.58%	Outboard t/c
7.48%	6.93%	7.55%	7.43%	7.39%	7.33%	6.56%	Outboard t/c
36.9	35.6	32.9	37.1	36.4	36.6	29.9	Wing $\Lambda_{1/4}$ (deg)
23.7	24.5	21.6	26.4	24.6	24.4	20.5	Strut $\Lambda_{1/4}$ (deg)
65.5%	67.6%	67.5%	66.1%	64.5%	68.8%	68.8%	η Strut
89515	81836	83553	78461	86991	87404	59463	T_{max} (lbs)
36655	36576	37851	37046	36628	36648	40429	Cruise Altitude (ft)
20.11	21.89	20.88	20.48	20.07	20.10	25.33	L/D
88244	81346	75472	67152	85143	84196	59581	Wing Wt. (lbs)
13484	12871	11937	10650	12700	14087	9994	Strut Wt. (lbs)
5071	3875	4180	4367	4534	4304	2844	Offset Wt. (lbs)
50794	46012	41735	48129	48876	47679	42473	Bending Matl (lbs)
253141	220879	230181	225527	241120	247624	159629	Fuel Wt. (lbs)
645462	**597922**	**602480**	**582378**	**627268**	**631176**	**490312**	TOGW (lbs)
0	-7.4%	-6.7%	-9.8%	-2.8%	-2.2%	-24.0%	% TOGW Change
95.26	92.39	91.66	88.94	94.11	92.33	82.69	Acquisition Cost ($M)
675.12	632.86	639.84	625.26	659.21	661.22	538.49	DOC ($M)
905.13	899.23	899.80	897.30	902.87	903.36	885.88	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	2nd Segment Climb
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
							Wingtip Deflection
							Engine Out
ACTIVE		ACTIVE		ACTIVE	ACTIVE		Approach Velocity
							Fuel Volume

Wingtip Engine SBW Sensitivity Analysis



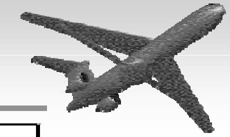
Tip SBW 1995	Tip SBW NLF	Tip SBW AERO	Tip SBW Structures	Tip SBW Propulsion	Tip SBW Systems	Tip SBW 2010	Tot Change -111226 Sum Change **18.5%**
7499.5	7500.0	7500.0	7499.9	7497.9	7499.9	7499.7	Range
182.1	182.2	176.6	176.9	177.2	179.3	198.6	Span (ft)
39.1	38.2	38.7	37.5	39.0	39.1	31.8	Root Chord (ft)
7.6	7.2	7.9	7.5	7.8	7.6	7.5	Tip Chord (ft)
4258	4129	4114	3981	4152	4187	3907	S_w (ft^2)
7.78	8.04	7.58	7.86	7.56	7.68	10.10	AR
14.16%	14.10%	14.28%	14.18%	14.21%	14.21%	14.36%	Root t/c
7.78%	7.44%	8.08%	7.89%	7.98%	7.92%	7.56%	Break t/c
7.44%	7.17%	7.69%	7.62%	7.63%	7.65%	6.85%	Tip t/c
39.4	38.6	38.7	39.9	39.5	39.8	30.2	Wing $\Lambda_{1/4}$ (deg)
25.7	26.2	25.5	26.3	25.8	26.3	23.5	Strut $\Lambda_{1/4}$ (deg)
58.4%	58.2%	57.7%	57.9%	57.9%	57.4%	56.8%	η Strut
100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	η Engine
73643	67736	71283	69369	72495	72959	51851	T_{max} (lbs)
38540	38376	38650	38513	38567	38301	40736	Cruise Altitude (ft)
20.31	22.01	20.94	20.22	20.03	20.31	25.25	L/D
56443	54328	52263	42759	53549	55047	41854	Wing Wt. (lbs)
25803	24977	23099	23867	23841	24927	25213	Bending Matl (lbs)
340294	332497	333364	318563	335878	335963	300676	Zero-Fuel Weight
217143	193589	205391	204374	210206	214364	145618	Fuel Wt. (lbs)
557520	**526083**	**538755**	**522934**	**546095**	**550326**	**446294**	TOGW (lbs)
	5.6%	3.4%	6.2%	2.0%	1.3%	20.0%	% TOGW Improvement
	4.2%	2.1%	2.3%	1.2%	0.5%	12.8%	% Fuel Improvement
1586.38	1551.86	1566.52	1551.29	1574.42	1574.94	1461.97	Total Cost ($M)
85.73	84.17	84.39	81.56	84.88	83.57	76.70	Acquisition Cost ($M)
606.44	577.37	590.25	579.80	596.75	598.05	504.86	DOC ($M)
894.21	890.32	891.89	889.93	892.80	893.33	880.41	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
							2nd Segment Climb
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
ACTIVE			ACTIVE			ACTIVE	Wingtip Deflection
							Engine Out
ACTIVE		ACTIVE	ACTIVE	ACTIVE	ACTIVE		Approach Velocity
							Climb Constraint
							Initial Cruise ROC
							Fuel Volume

Underwing Engine SBW Sensitivity Analysis



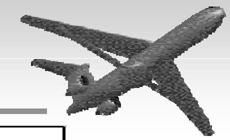
Wing SBW 1995	Wing SBW NLF	Wing SBW AERO	Wing SBW Structures	Wing SBW Propulsion	Wing SBW Systems	Wing SBW 2010	Tot Change **-135978**
							Sum Change **-27.4%**
7498.2	7498.0	7499.9	7498.9	7498.5	7508.4	7499.3	Range
227.1	217.1	212.7	217.9	223.0	227.3	220.1	Span (ft)
36.0	34.7	33.8	33.8	35.7	36.0	29.4	Root Chord (ft)
4981	4601	4412	4501	4860	4989	3970	S_w (ft^2)
10.36	10.25	10.26	10.54	10.23	10.35	12.20	AR
13.81%	13.89%	14.22%	13.60%	13.81%	13.81%	14.00%	Root t/c
7.26%	7.50%	7.00%	6.62%	7.21%	7.29%	7.15%	Outboard t/c
7.64%	8.08%	7.32%	7.21%	7.65%	7.67%	7.37%	Outboard t/c
36.2	35.4	31.1	36.1	36.1	36.3	29.8	Wing $\Lambda_{1/4}$ (deg)
24.9	27.0	24.3	25.3	25.3	24.9	21.6	Strut $\Lambda_{1/4}$ (deg)
63.7%	62.5%	64.1%	62.7%	63.2%	63.7%	62.4%	η Strut
79.5%	82.6%	83.9%	80.7%	80.7%	79.5%	83.8%	η Engine
77745	72939	73927	70892	76285	76632	56562	T_{max} (lbs)
38536	38481	38891	38446	38561	38682	40097	Cruise Altitude (ft)
21.03	22.57	21.48	21.00	20.90	21.16	25.30	L/D
82685	71738	65728	60285	78471	82285	50287	Wing Wt. (lbs)
12157	10144	9600	7936	11542	12378	7227	Strut Wt. (lbs)
5376	4097	3768	3787	5087	5449	2967	Offset Wt. (lbs)
45999	38202	34038	40883	42893	45757	33335	Bending Matl (lbs)
228225	200881	208875	207958	218235	224867	151342	Fuel Wt. (lbs)
600534	**555770**	**557802**	**546574**	**584174**	**593661**	**464556**	TOGW (lbs)
0	-7.5%	-7.1%	-9.0%	-2.7%	-1.1%	-22.6%	% TOGW Change
91.40	88.16	87.07	85.28	90.24	89.40	79.01	Acquisition Cost ($M)
636.54	598.53	602.89	595.45	622.80	628.06	518.75	DOC ($M)
899.55	894.00	894.25	892.86	897.53	898.73	882.68	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	2nd Segment Climb
		ACTIVE				ACTIVE	Balanced Field Length
ACTIVE	ACTIVE	ACTIVE		ACTIVE		ACTIVE	Wingtip Deflection
							Engine Out
							Approach Velocity
							Fuel Volume

Cantilever Wing Range Effects



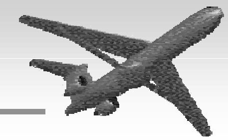
Cant 4000	Cant 5000	Cant 6000	Cant 7000	Cant 8000	Cant 9000	Cant 10000	Cant 11000	Cant Max	
4000	5000	6000	7000	8000	9000	10000	11000	**11906**	Range (nmi)
196.4	202.4	211.2	220.2	231.0	239.8	248.9	249.4	250.2	Span (ft)
52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	Root Chord (ft)
4343	4498	4757	5121	5534	5746	6223	6160	6480	Sw (ft^2)
8.88	9.10	9.37	9.47	9.64	10.01	9.96	10.09	9.66	AR
15.61%	15.17%	15.12%	15.04%	15.14%	14.99%	15.01%	14.87%	14.69%	Root t/c
10.75%	10.58%	10.63%	10.48%	10.62%	10.61%	10.62%	10.62%	9.83%	Outboard t/c
5.49%	5.28%	5.00%	5.02%	5.21%	5.36%	5.01%	5.25%	6.20%	Outboard t/c
34.1	34.0	34.1	33.8	34.1	34.2	33.9	34.2	33.4	Wing L1/4 (deg)
60655	64883	68917	73499	78184	83986	91426	103085	118178	Tmax (lbs)
42573	41919	41814	42094	42127	41058	41188	38992	36987	Cruise Altitude (ft)
21.69	22.13	22.68	23.17	23.68	24.03	24.29	23.97	23.30	L/D
41461	46610	53031	59970	68424	78424	88661	98142	108286	Wing Wt. (lbs)
27223	31882	37653	43901	51539	61269	70703	80205	90005	Bending Matl (lbs)
97179	120225	144765	171752	201312	235901	276144	330385	399848	Fuel Wt. (lbs)
405310	**439630**	**477044**	**518210**	**563994**	**617150**	**678548**	**755682**	852366	TOGW (lbs)
78.07	80.43	83.09	85.98	89.22	92.70	96.74	100.82	105.57	Acquisition Cost ($M)
543.38	550.63	561.32	575.50	592.71	614.34	641.19	677.05	857.95	DOC ($M)
941.93	920.42	906.02	895.97	888.84	883.97	880.82	879.57	930.78	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	2nd Segment Climb
								ACTIVE	Balanced Field Length
	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Engine Out
								ACTIVE	Approach Velocity
									Fuel Volume

Fuselage Eng.T-Tail SBW Range Effects



SBW-fuse 4000	SBW-fuse 5000	SBW-fuse 6000	SBW-fuse 7000	SBW-fuse 8000	SBW-fuse 9000	SBW-fuse 10000	SBW-fuse 11000	SBW-fuse 12000	SBW-fuse 13000	SBW-fuse Max	
4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	**13304**	Range (nmi)
198.8	208.5	215.0	220.9	228.1	234.3	233.6	244.9	261.2	257.9	262.5	Span (ft)
27.3	28.3	28.2	30.1	30.4	32.0	34.6	36.9	38.7	42.0	43.3	Root Chord (ft)
3334	3648	3763	4137	4344	4683	4983	5495	6126	6509	6807	S_w (ft^2)
11.86	11.92	12.29	11.80	11.97	11.73	10.95	10.91	11.14	10.22	10.12	AR
13.94%	13.78%	13.71%	13.78%	13.80%	13.88%	13.60%	13.10%	13.20%	13.23%	13.21%	Root t/c
7.54%	7.13%	7.12%	6.95%	7.15%	7.17%	6.75%	7.09%	7.14%	6.83%	6.68%	Outboard t/c
6.86%	6.53%	6.79%	6.36%	6.72%	6.65%	5.69%	6.58%	6.92%	6.25%	6.08%	Outboard t/c
27.5	28.7	29.1	29.9	30.2	31.1	31.0	30.1	31.0	31.1	30.6	Wing $\Lambda_{1/4}$ (deg)
20.7	20.6	21.0	20.8	21.1	21.2	21.6	22.6	22.9	22.1	21.8	Strut $\Lambda_{1/4}$ (deg)
66.1%	67.2%	67.4%	68.7%	68.4%	68.5%	68.6%	63.2%	67.2%	66.0%	66.7%	η Strut
48134	50840	53778	58187	61843	66897	75658	82100	88492	103686	108450	T_{max} (lbs)
40025	40697	40263	40951	40859	40943	40415	40540	40881	41571	41656	Cruise Altitude (ft)
23.50	24.47	25.01	25.23	25.64	25.80	25.30	25.61	26.07	25.34	25.22	L/D
41236	47042	52298	56970	62689	68530	73411	83976	97297	103034	108225	Wing Wt. (lbs)
6493	7343	8019	9023	9912	11107	12413	12612	15855	15227	15688	Strut Wt. (lbs)
2231	2540	2835	3247	3478	3801	4646	5614	6333	7025	7109	Offset Wt. (lbs)
27104	31950	36805	40184	45501	50321	53544	63953	75851	79733	84097	Bending Matl (lbs)
86202	104107	124129	147456	171325	199396	237726	274929	315517	377323	399999	Fuel Wt. (lbs)
380952	**409516**	**439224**	**473298**	**508164**	**548776**	**601136**	**657972**	**721974**	**804260**	837288	TOGW (lbs)
11.3%	13.4%	14.3%	14.1%	14.9%	15.5%	13.9%	16.8%				% Fuel Reduction
6.0%	6.8%	7.9%	8.7%	9.9%	11.1%	11.4%	12.9%				% TOGW Reduction
75.14	77.46	79.43	81.73	83.92	86.44	89.20	92.99	97.39	101.24	103.01	Acquisition Cost ($M)
512.07	515.17	521.51	533.11	544.32	560.02	584.19	608.56	636.00	674.93	759.17	DOC ($M)
936.54	914.97	900.24	890.03	882.32	876.83	873.52	871.14	869.73	869.87	895.99	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE				2nd Segment Climb
				ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
											Engine Out
											Approach Velocity
											Fuel Volume

Wingtip Engine SBW Range Effects



SBW-tip 4000	SBW-tip 5000	SBW-tip 6000	SBW-tip 7000	SBW-tip 8000	SBW-tip 9000	SBW-tip 10000	SBW-tip 11000	SBW-tip 12000	SBWtip maxr	
4000	5000	6000	7000	8000	9000	10000	11000	12000	**12114**	Range (nmi)
178.6	191.1	191.9	195.8	198.5	198.5	198.4	209.0	222.0	215.2	Span (ft)
30.2	30.9	30.8	31.6	33.6	35.7	36.1	40.4	47.9	51.2	Root Chord (ft)
3305	3640	3643	3812	4049	4176	4349	4966	6043	6413	S_w (ft^2)
9.65	10.03	10.11	10.06	9.73	9.44	9.05	8.79	8.16	7.22	AR
14.39%	14.37%	14.33%	14.34%	14.31%	14.14%	14.24%	13.97%	13.70%	13.62%	Root t/c
7.34%	7.55%	7.46%	7.51%	7.49%	7.29%	7.37%	7.04%	6.80%	6.80%	Outboard t/c
6.85%	6.87%	6.85%	6.83%	6.85%	6.76%	6.82%	6.90%	6.67%	6.40%	Outboard t/c
28.9	30.0	30.0	30.1	30.6	31.4	31.4	32.0	32.3	32.6	Wing $\Lambda_{1/4}$ (deg)
23.6	23.5	23.6	23.5	23.6	24.1	23.8	25.5	25.9	25.2	Strut $\Lambda_{1/4}$ (deg)
56.2%	56.6%	56.6%	56.6%	56.8%	55.5%	56.3%	56.5%	57.0%	57.9%	η Strut
45000	46292	47626	49813	53814	60390	66005	67753	69668	73316	T_{max} (lbs)
40708	40708	40708	40708	40357	39557	40557	40257	40257	39057	Cruise Altitude (ft)
23.84	24.55	24.91	25.10	24.99	24.88	24.94	24.98	24.26	22.75	L/D
30879	35660	37578	40260	42667	45642	47014	52999	60860	59913	Wing Wt. (lbs)
4125	4918	4873	5021	5235	4807	5260	6112	6873	6630	Strut Wt. (lbs)
3113	3837	3834	3976	4181	4186	4406	5078	5566	5969	Offset Wt. (lbs)
16695	20301	21961	24014	25580	28026	28499	32902	37963	35638	Bending Matl (lbs)
80057	97131	114874	134991	158957	186235	213127	245034	294200	326248	Fuel Wt. (lbs)
357540	**383050**	**405305**	**431677**	**462911**	**499382**	**533471**	**576456**	**641327**	677111	TOGW (lbs)
17.6%	19.2%	20.6%	21.4%	21.0%	21.1%	22.8%	25.8%			% Fuel Reduction
11.8%	12.9%	15.0%	16.7%	17.9%	19.1%	21.4%	23.7%			% TOGW Reduction
71.48	73.45	74.44	75.84	77.46	79.34	80.87	83.35	86.98	87.93	Acquisition Cost ($M)
490.32	492.56	494.14	500.44	511.38	525.80	537.57	554.51	585.55	627.26	DOC ($M)
931.36	910.19	895.06	884.52	877.03	871.67	867.11	864.11	863.36	872.78	IOC ($M)
ACTIVE		ACTIVE	ACTIVE	ACTIVE	ACTIVE		ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
										2nd Segment Climb
			ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE			Wingtip Deflection
						ACTIVE	ACTIVE	ACTIVE	ACTIVE	Engine Out
										Approach Velocity
ACTIVE	ACTIVE	ACTIVE							ACTIVE	Initial Cruise ROC

Underwing Engine SBW Range Effects

SBW-wing 4000	SBW-win 5000	SBW-win 6000	SBW-wing 7000	SBW-win 8000	SBW-win 9000	SBW-wing 10000	SBW-win 11000	SBW-win 12000	SBW-wing 13000	SBW-wing maxr	
4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	**13979**	Range (nmi)
204.5	207.8	224.5	229.9	236.8	242.3	249.6	249.9	259.9	262.3	262.5	Span (ft)
28.1	30.2	29.5	29.4	29.8	31.4	32.8	34.8	36.8	39.7	42.5	Root Chord (ft)
3447	3778	4022	4117	4312	4651	4989	5304	5795	6258	6712	S_w (ft^2)
12.13	11.43	12.53	12.83	13.01	12.63	12.49	11.78	11.65	11.00	10.27	AR
13.07%	13.31%	12.95%	12.88%	12.76%	12.79%	12.79%	12.84%	12.81%	12.84%	12.89%	Root t/c
6.59%	7.55%	6.73%	6.47%	6.38%	6.47%	6.89%	6.86%	6.86%	6.89%	7.46%	Outboard t/c
8.49%	9.05%	8.39%	8.25%	8.18%	8.12%	8.41%	8.25%	8.32%	8.21%	8.43%	Outboard t/c
27.0	28.4	27.4	27.0	27.5	27.6	28.8	29.3	29.8	30.3	31.4	Wing $\Lambda_{1/4}$ (deg)
24.9	25.9	25.3	25.1	25.3	25.6	26.3	26.0	26.2	26.2	26.6	Strut $\Lambda_{1/4}$ (deg)
62.9%	59.2%	63.8%	64.4%	63.2%	62.8%	61.6%	63.9%	64.3%	65.5%	63.3%	η Strut
86.6%	87.5%	82.9%	82.5%	80.7%	79.5%	79.5%	72.4%	72.5%	67.5%	60.7%	η Engine
45208	49335	51172	52913	56209	60796	65416	73022	79275	90162	103557	T_{max} (lbs)
40728	41282	41987	41622	41444	41715	41672	41425	41510	41042	40519	Cruise Altitude (ft)
24.50	24.26	25.74	26.09	26.66	26.70	26.92	26.50	26.66	26.11	25.47	L/D
38381	40276	48720	53247	59849	64850	71711	76620	85929	93477	100744	Wing Wt. (lbs)
5419	6091	7844	7811	8908	10141	9786	12120	13159	14486	14607	Strut Wt. (lbs)
2263	2620	2810	2648	3161	3866	3890	4929	5597	6500	6666	Offset Wt. (lbs)
23714	24525	32417	36669	42753	46945	53006	56997	65162	71401	77267	Bending Matl (lbs)
80520	100938	116978	137046	158367	184422	212310	249139	286181	338617	399824	Fuel Wt. (lbs)
366842	**394693**	**422759**	**450678**	**483205**	**520031**	**560812**	**610516**	**664945**	**736297**	816265	TOGW (lbs)
17.1%	16.0%	19.2%	20.2%	21.3%	21.8%	23.1%	24.6%				% Fuel Reduction
9.5%	10.2%	11.4%	13.0%	14.3%	15.7%	17.4%	19.2%				% TOGW Reduction
73.25	75.06	77.49	79.08	81.30	83.52	86.06	88.61	91.98	95.61	98.84	Acquisition Cost ($M)
496.57	503.48	506.98	513.44	523.50	537.60	553.40	575.30	598.23	631.16	833.68	DOC ($M)
933.40	912.29	897.72	887.03	879.40	873.83	869.70	867.05	865.21	864.88	926.32	IOC ($M)
ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Shock Cl Constraint
	ACTIVE		ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	2nd Segment Climb
				ACTIVE		ACTIVE	ACTIVE	ACTIVE	ACTIVE	ACTIVE	Balanced Field Length
	ACTIVE		ACTIVE	ACTIVE	ACTIVE						Wingtip Deflection
									ACTIVE	ACTIVE	Engine Out
											Approach Velocity
ACTIVE	ACTIVE	ACTIVE									Initial Cruise ROC
										ACTIVE	Fuel Volume