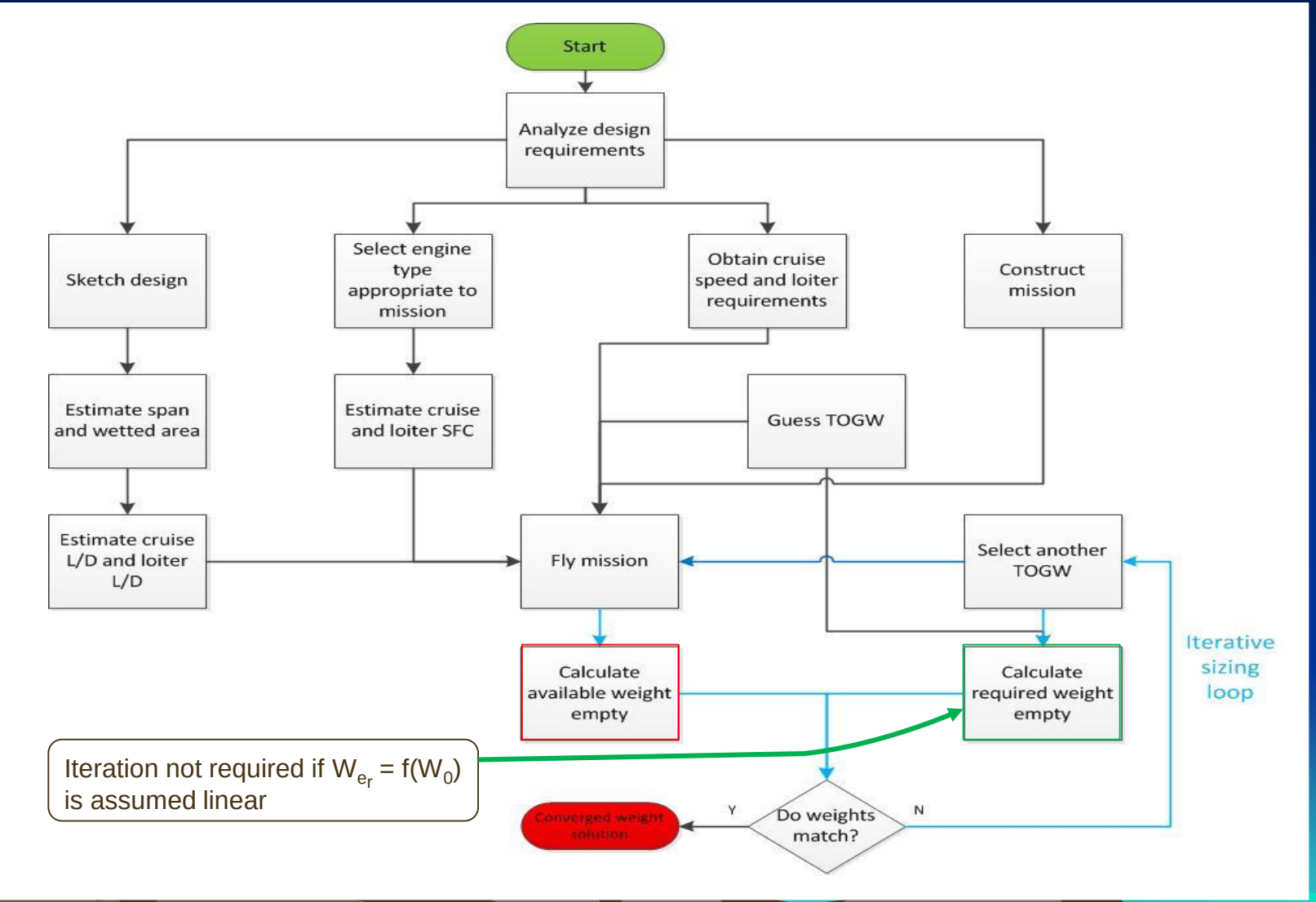
Initial Aircraft Sizing – A Critique

Tony Hays
California State University Long Beach
ahays@alum.mit.edu
www.adac.aero

Classes of Sizing Methods

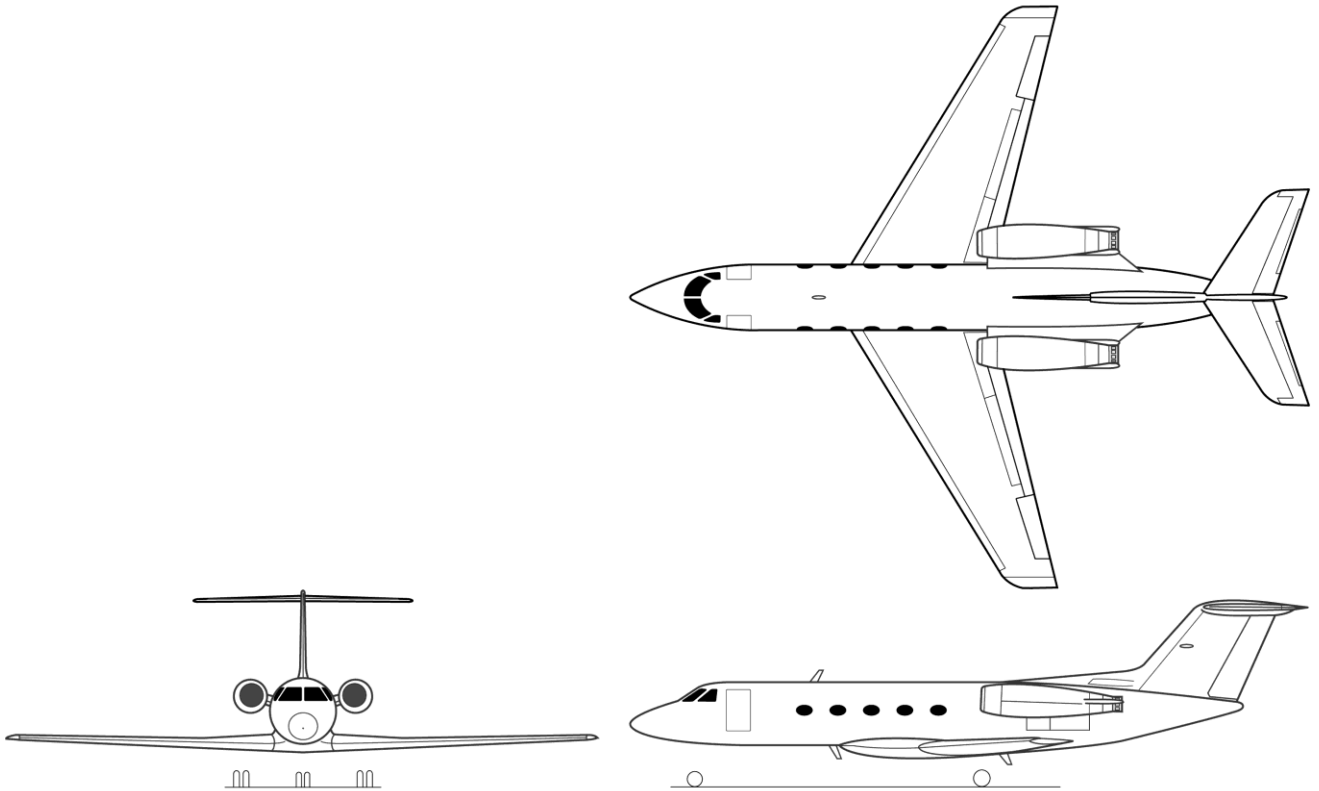
- Class 1. Rough estimate of TOGW
  - L/D based on overall aircraft geometry (AR, wetted area, etc)
  - Sfc based on estimates for mission segment
  - W_e as f(W_0) based on aircraft with similar geometry
- Class 2. Input variables based on detailed empirical analysis
  - Empirical C_{D_0} based on sum of component drags, simple analytical C_{D_i}
  - Thrust, fuel flow based on tabular data or engine cycle
  - W_e as f(W_0) based on detailed empirical equations
- Class 3. Detailed computational analysis
  - CFD-based lift and drag
  - Thrust, fuel flow based on detailed engine model
  - W_e as f(W_0) based on FEA for primary structure, empirical for non-structural

Initial Estimate of Take-Off Gross Weight



ADAC Aircraft Design & Consulting

Empty Weight Available – Draw Three View



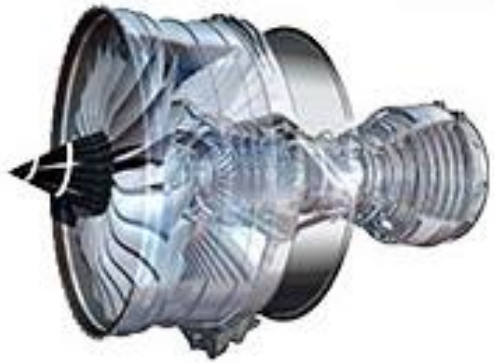
Empty Weight Available – Select Engine Type

GE9X

LEAP-1A/-1B

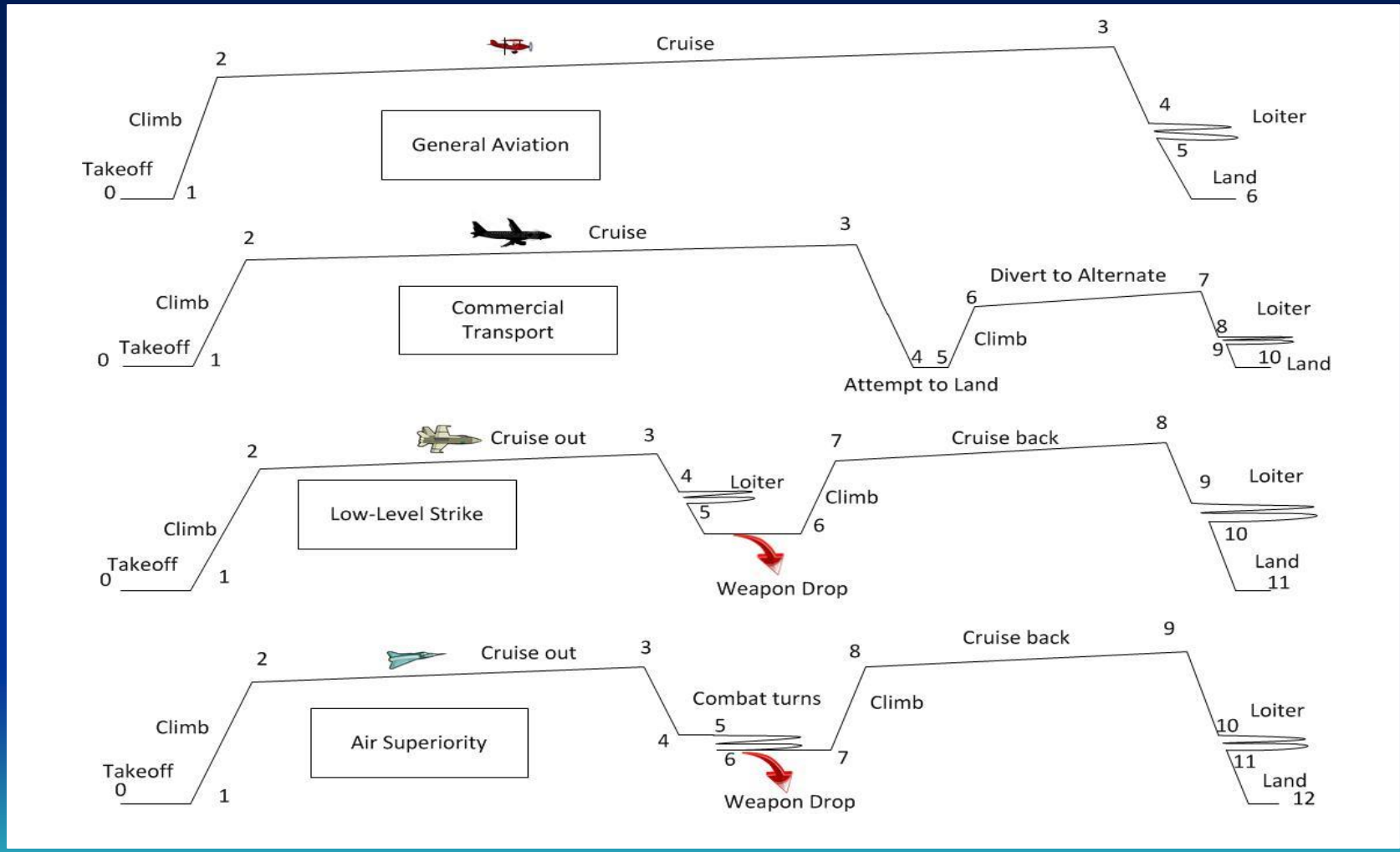
PW1100G/PW1500G

GEnx-2B



Trent XWB

Empty Weight Available – Define Mission



Use Excel Solver Add-In

- Select Data Tab
- If Solver doesn't appear on taskbar, then:
  - Click on Office button > Excel Options > Add-Ins > Manage [Disabled Items]
- Using Solver: Set target cell [F22] equal to [0] by changing [D10]

Mission						
	Ratio	Wt ratio	Wt [lb]			
0. TOGW (assumed)			28000			
1. Warmup and taxi	W_1/W_0	0.970	27160			
2. Climb	W_2/W_1	0.985	26753			
3. Cruise	W_3/W_2	0.730	19535			
4. Initial descent	W_4/W_3	1.000	19535			
5. Loiter	W_5/W_4	0.978	19112			
6. Descent and land	W_6/W_5	0.995	19016			
Block fuel [lb]	$W_{TO} - W_6$		8984			
Total fuel required [lb]	$1.06\ W_{BLOCK}$		9523			
Zero fuel weight [lb]	$W_{TO} - W_{TF}$		18477			
Weight empty (avail) [lb]	$W_{ZF} - W_{PL} - W_{CREW}$		16447			
			We(avail) - We(reqd) [lb]		108	

Empty Weight Matching

- For an assumed TOGW, match
  - Empty weight available (based on mission analysis)

  to
  - Empty weight required (based on statistical weight analysis of comparable aircraft, or component weight buildup)

Differences in Definitions of Empty Weight

- Military

  Empty weight = TOGW – (Fuel + Payload + Crew)

- Commercial

  Operating Empty Weight = TOGW – (Fuel + Payload)

  or

  Manufacturer's Empty Weight = TOGW – (Fuel + Payload + Operating Items)

  Empty weight values in references may be MEW or OEW

Operating Items

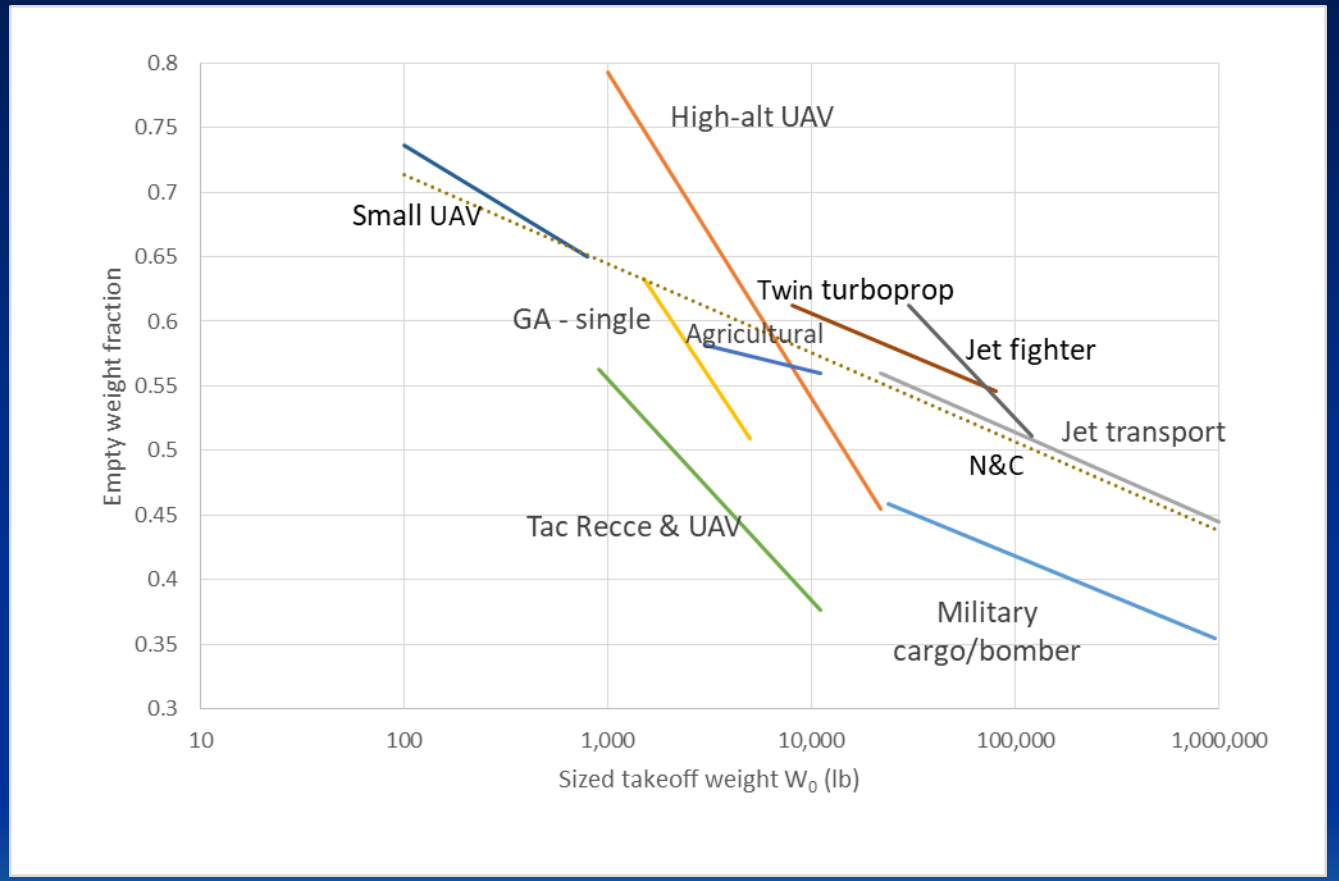
- Cockpit crew
- Cabin crew
- Crew baggage
- Flight kits
- Oil
- Unusable fuel
- Food, galley service, carts
- Galley inserts
- Passenger service equipment
- Potable water
- Lavatory fluids
- Evacuation slides/slide rafts
- Emergency transmitters
- Life vests
- Pallets
- Containers

Short range jet transport approx. 5% OEW
Long range jet transport approx. 6% OEW

Approach to Empty Weight Required

- Matches empty weight fractions
  (= Empty weight/TOGW)
- Based on existing designs (data points not shown)
- Log-linear scales
- Note differences in gradients for different classes of aircraft

$$W_{e_R}/W_o = A\, W_o^{\,C}\, K_{vs}$$



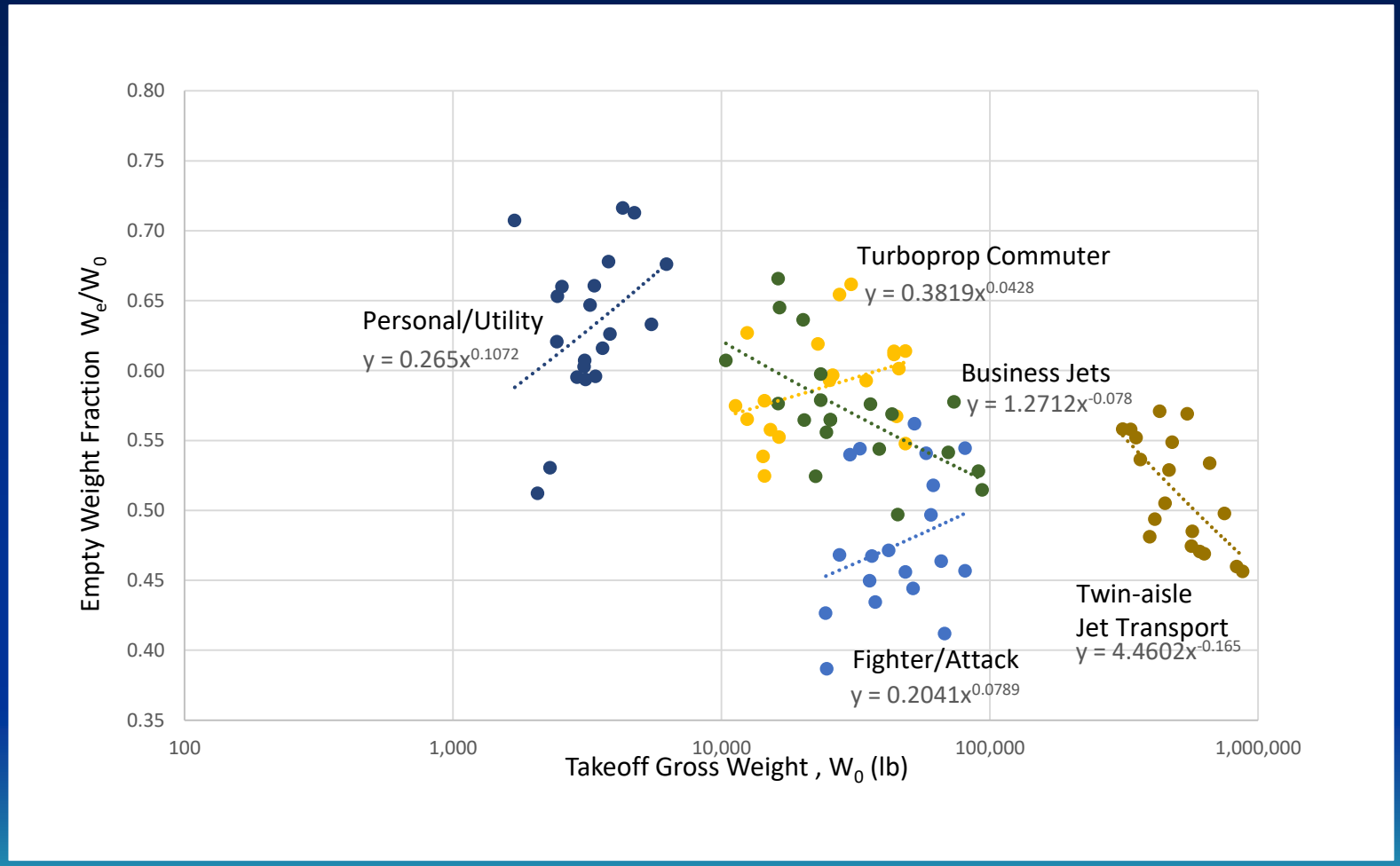
Solid lines from Raymer
Dashed line from Nicolai & Carichner

Schaufele Data for Empty Weight Required

- Matching empty weight fractions

(= Empty weight/TOGW)

- Based on existing designs
- Data from Schaufele
- Log-linear scales
- Note differences in gradients for different classes of aircraft



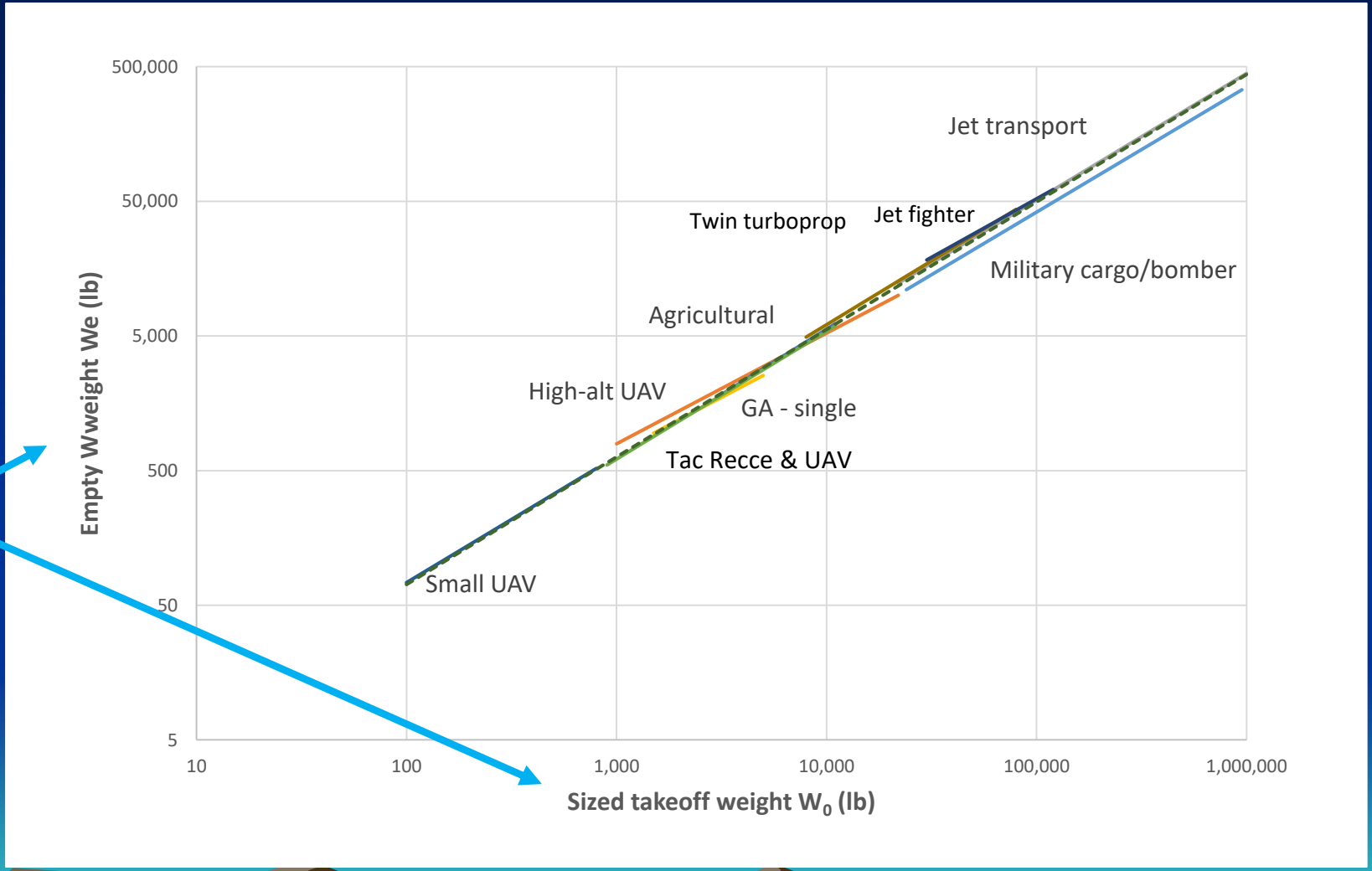
Dashed lines are power function best fit

Alternative Approach to Empty Weight Required

- Used by Nicolai, Roskam, Schaufele
- Same data as on previous chart
- Note log-log scales

$$W_{eR} = A\, W_o^{\,B}\, K_{vs}$$

Where B = C+1



Raymer Example of Manual Iteration

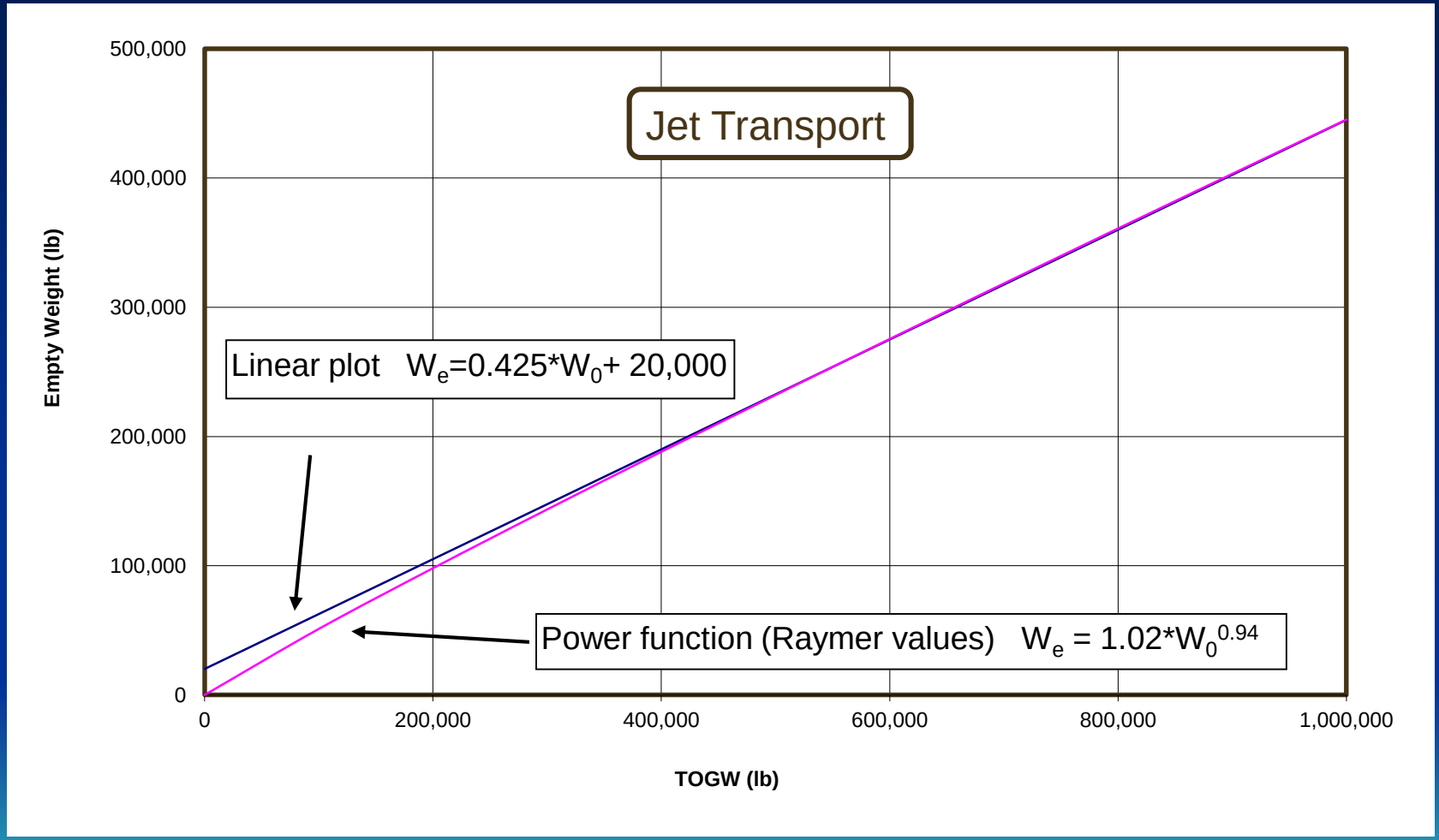
- Data copied from Raymer, Ch. 3, Box 3.1 ASW Sizing Calculations
- Convergence is uneven, because arbitrary $W_{0,guess}$ is selected
- Stop if $W_{0,guess}$ agrees within 5% of $W_{0,calculated}$

W_0, guess	W_e/W_0	W_e	W_0, calculated
50,000	0.4361	21,803	57,863
60,000	0.4305	25,832	56,198
56,000	0.4326	24,227	56,814
56,500	0.4324	24,428	56,733
56,700	0.4322	23,508	56,702

compare

- Gives false impression that TOGW can be calculated to within 100 lb.

Linear Relationship for Empty Weight Required



Assume Linear Empty Weight Relationship

- Similar to approach taken by Gundlach (Ch. 3)

Assume $W_{e_R} = GW_0 + \mathrm{K}$
Substitute in Raymer Eq. (3.2)

$$W_0 = W_{crew} + W_{payload} + \left(\frac{W_f}{W_0}\right) W_0 + \left(\frac{W_{e_R}}{W_0}\right) W_0$$

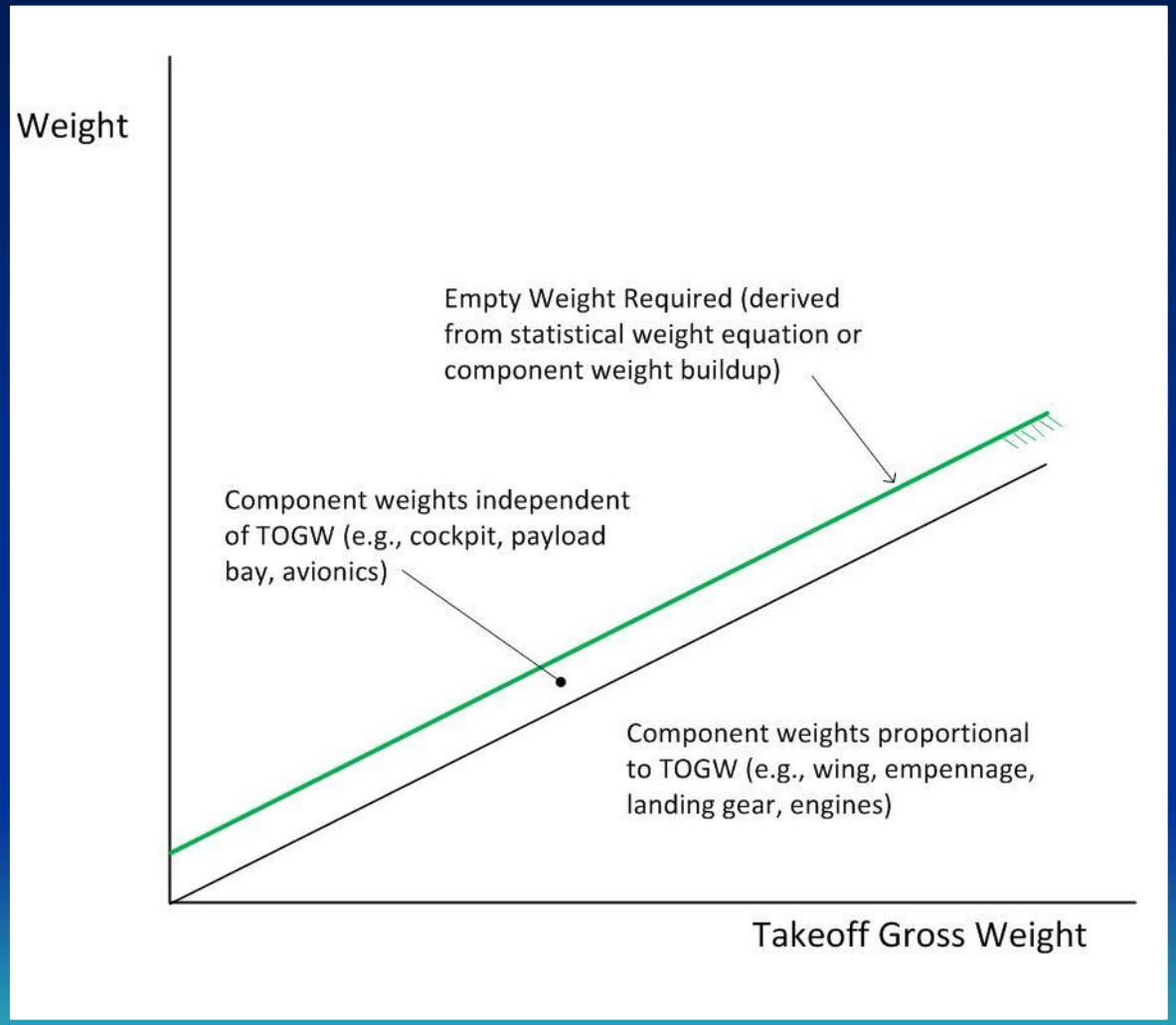
To obtain

$$W_0 = \frac{K + W_{payload} + W_{crew}}{\left(1 - \frac{W_f}{W_0}\right) - G}$$

Fuel fraction from mission analysis assumed constant

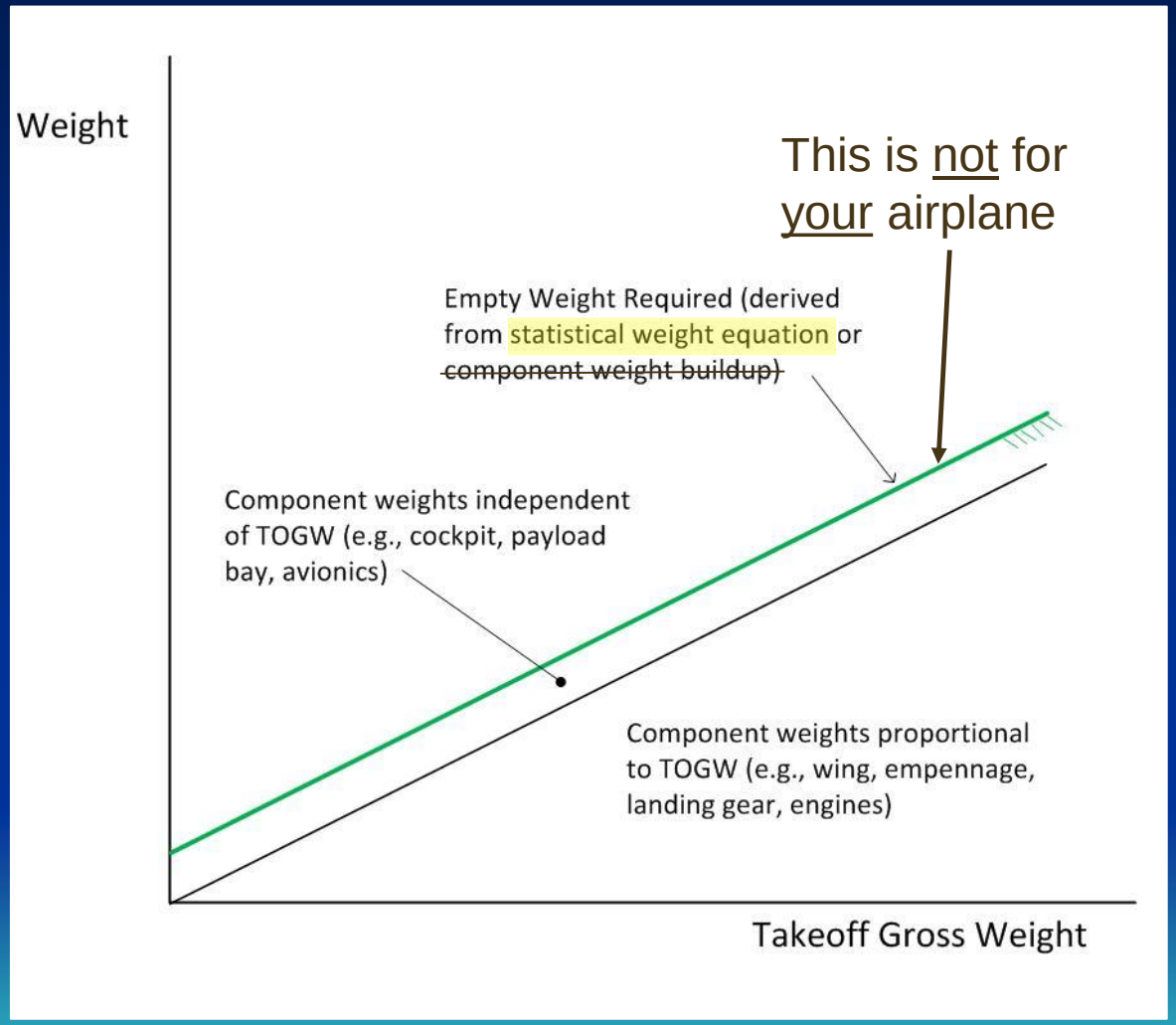
Empty Weight Required

- Empty weight required based on statistical weight relationship (or component weight buildup)



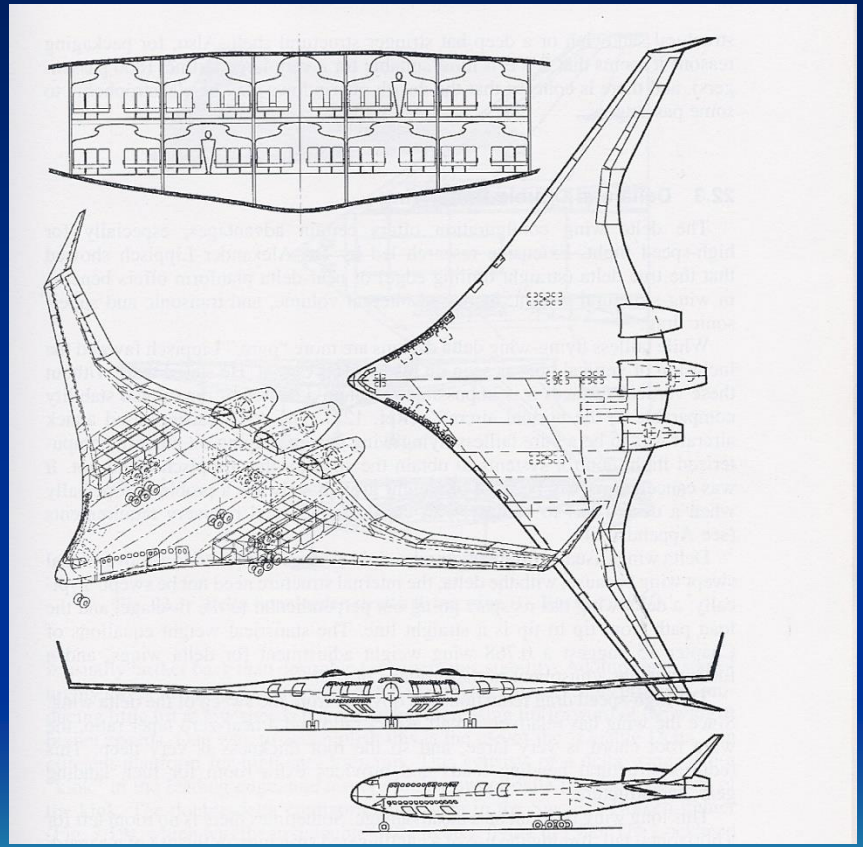
Empty Weight Required

- Empty weight required based on statistical weight relationship (or component weight buildup)



Blended Wing-Body

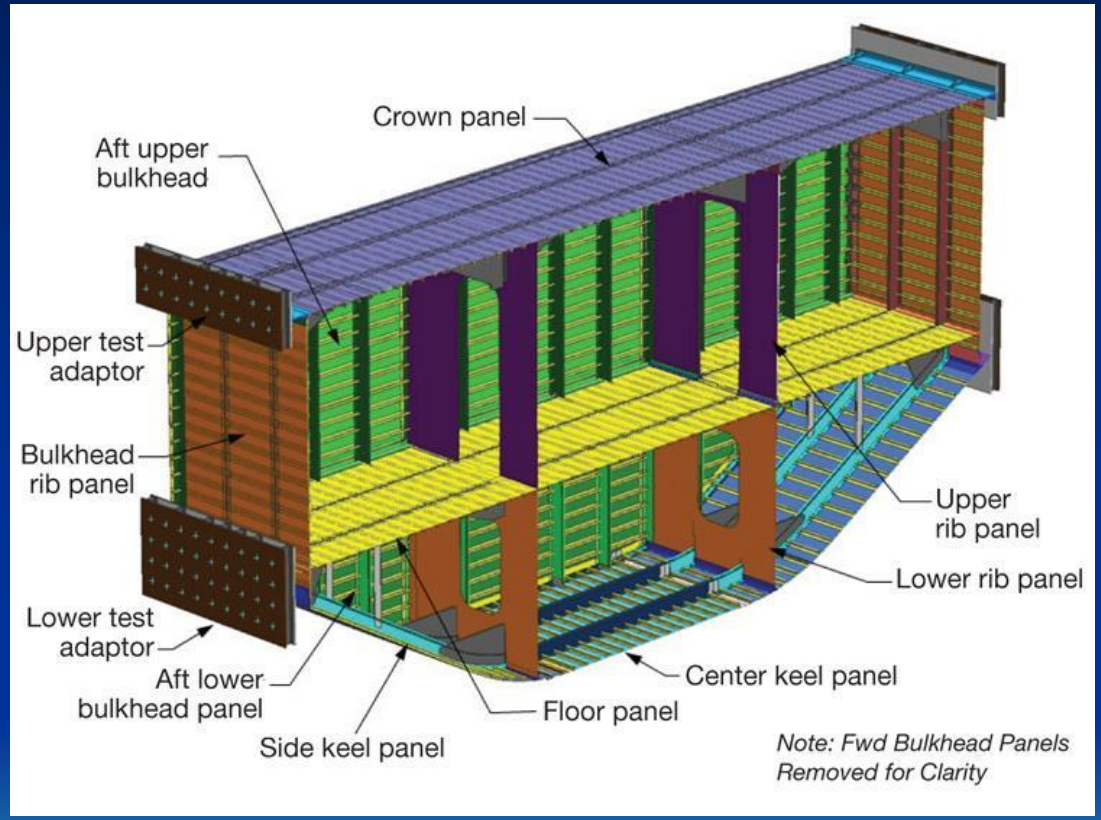
- Advantages
  - Higher L/D
  - Noise shielding of jet engines
- Disadvantages
  - Increased weight of non-cylindrical passenger cabin
  - Difficult passenger access/egress



Source: Raymer

Blended Wing-Body

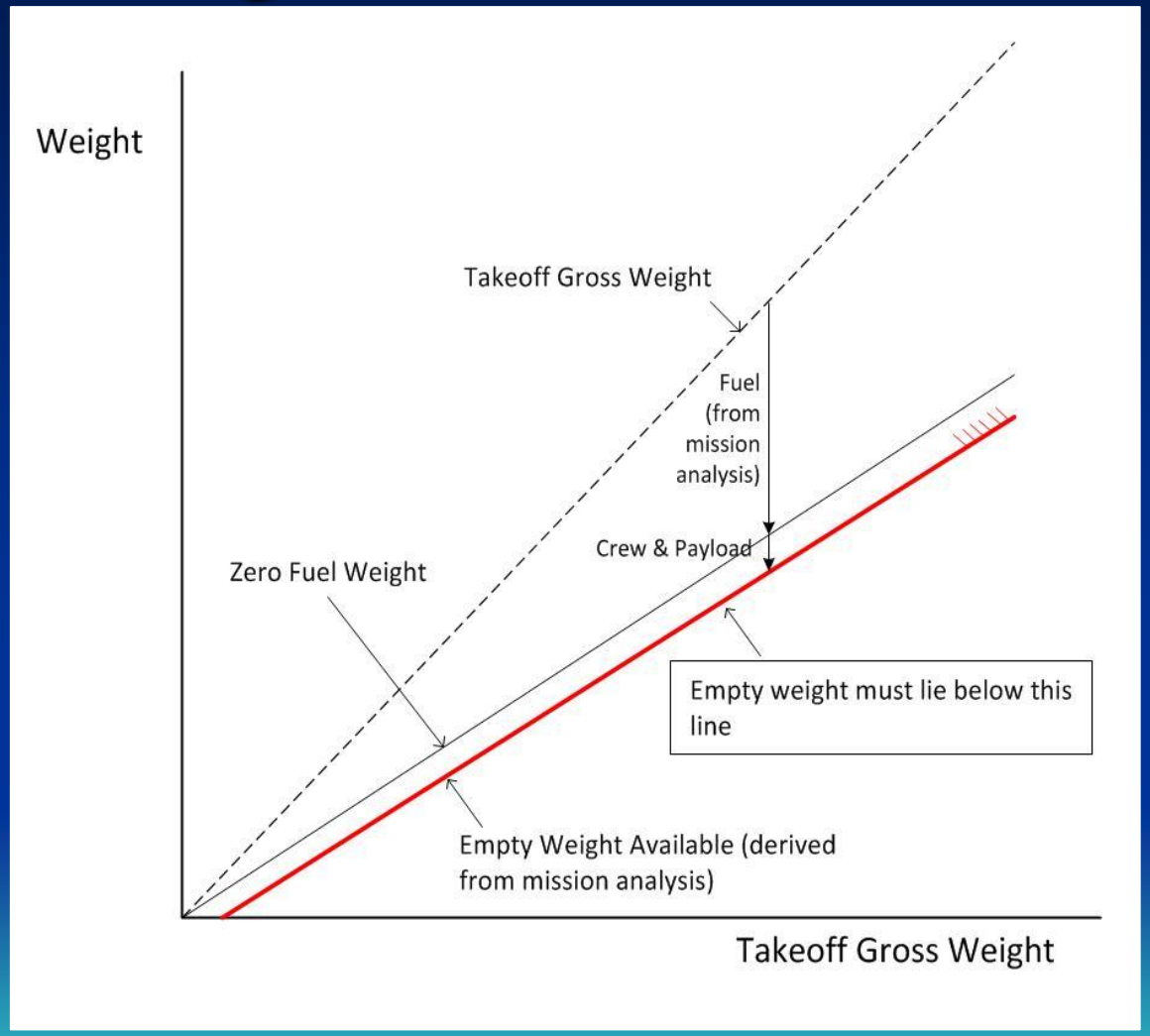
- 2011 NASA contract to Boeing to build and test composite non-circular pressurized structure



http://www.compositesworld.com/articles/prseus-preform-for-pressurized-cabin-walls

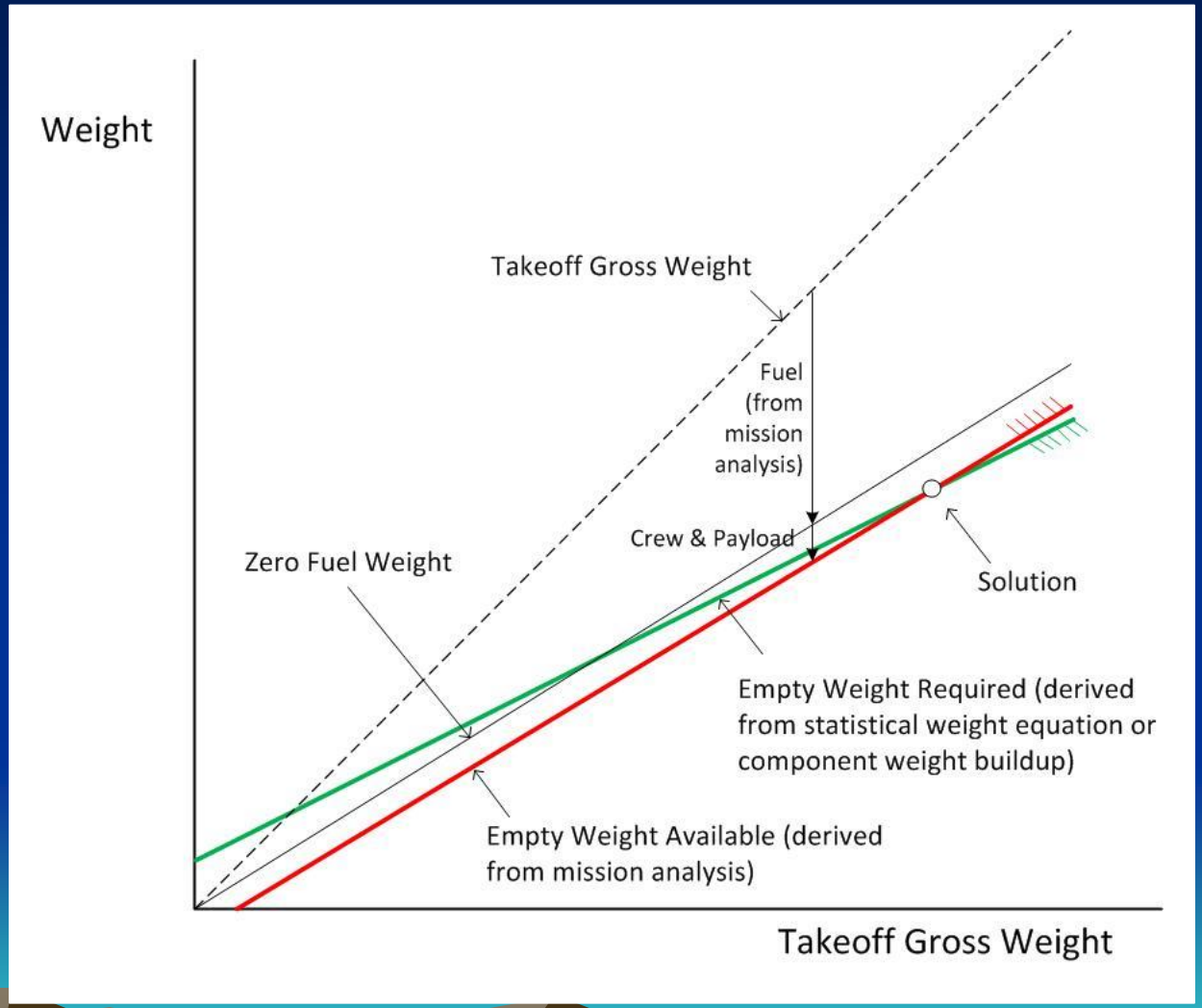
Empty Weight Available

- Empty weight available as a function of assumed TOGW
- Calculated from mission analysis

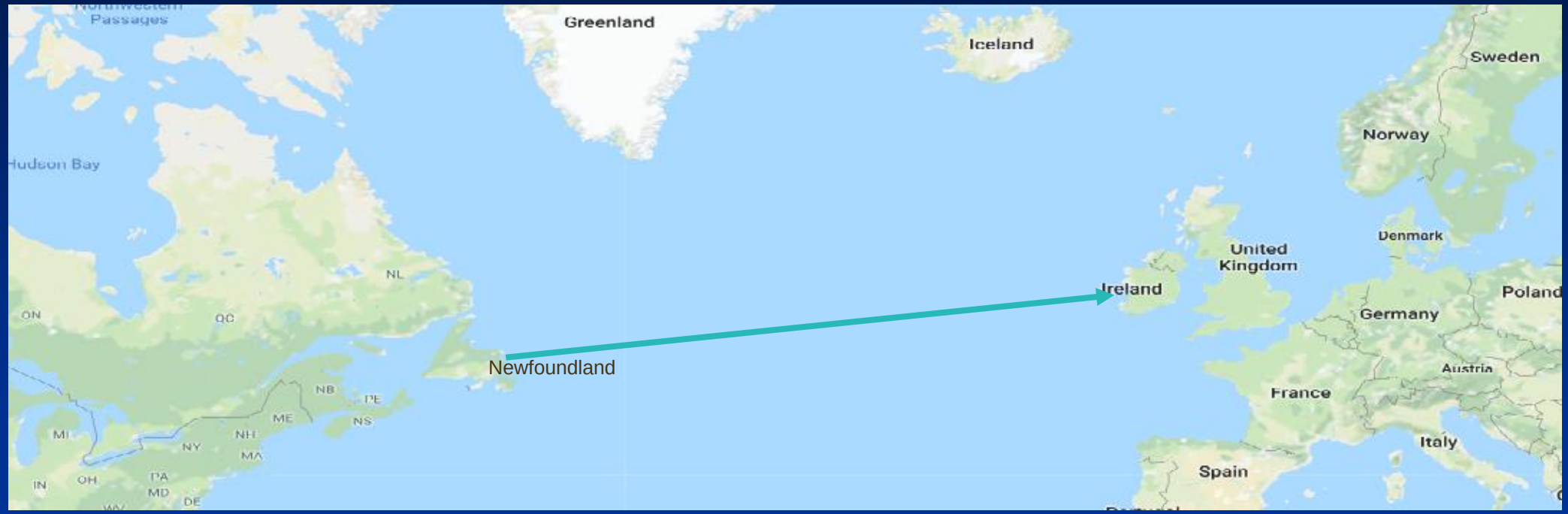


Empty Weight Solution

- Minimum empty weight is at intersection of empty weight available and required
- Estimated TOGW is very sensitive to calculated (or assumed) input values



Fly Airplane Across Atlantic

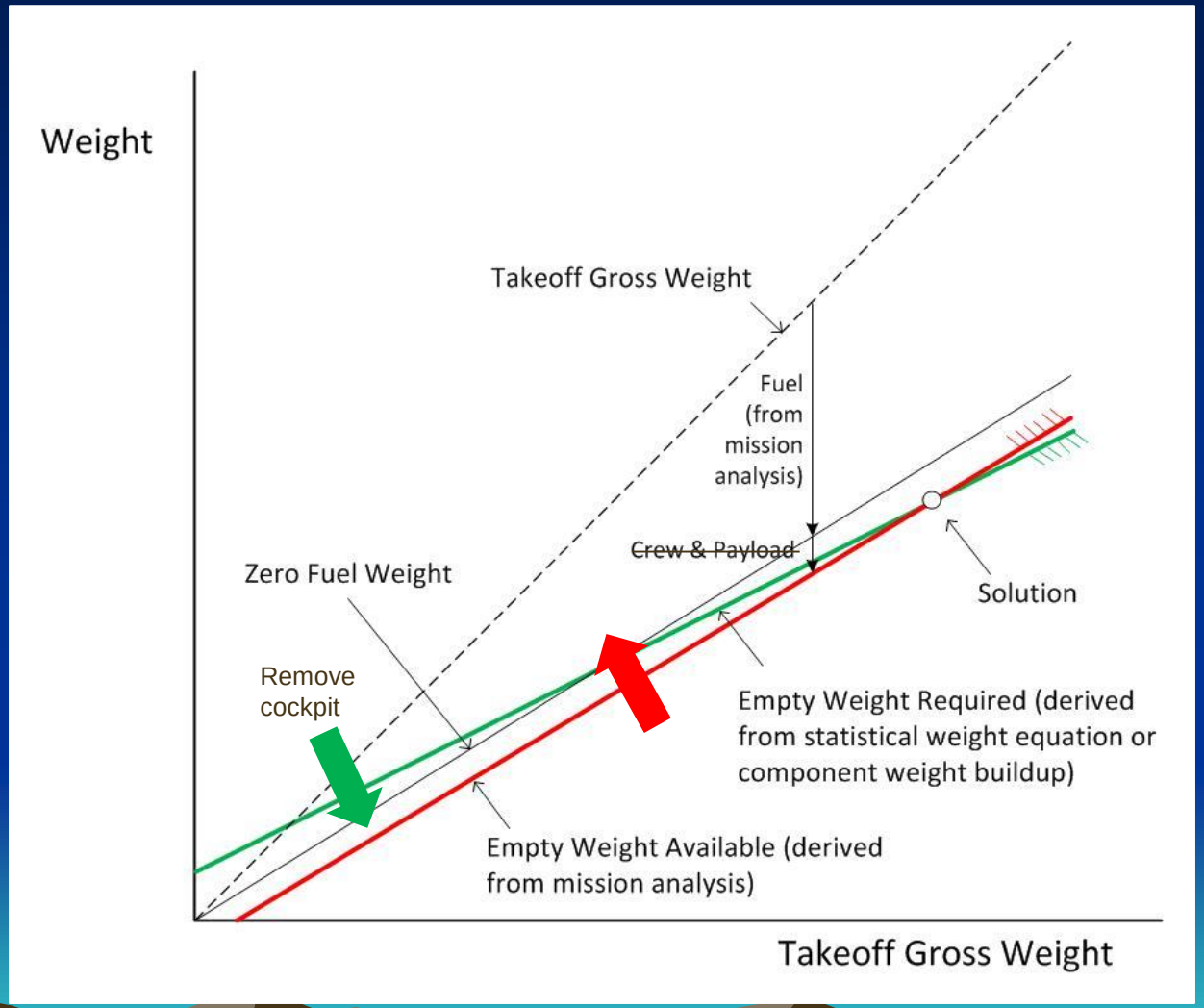


- 3028 km (1,882 nmi)
- No payload
- No pilot

- Nav/comm. systems
  - GPS
  - Autopilot
  - Satellite telemetry
  - Air/ground communications

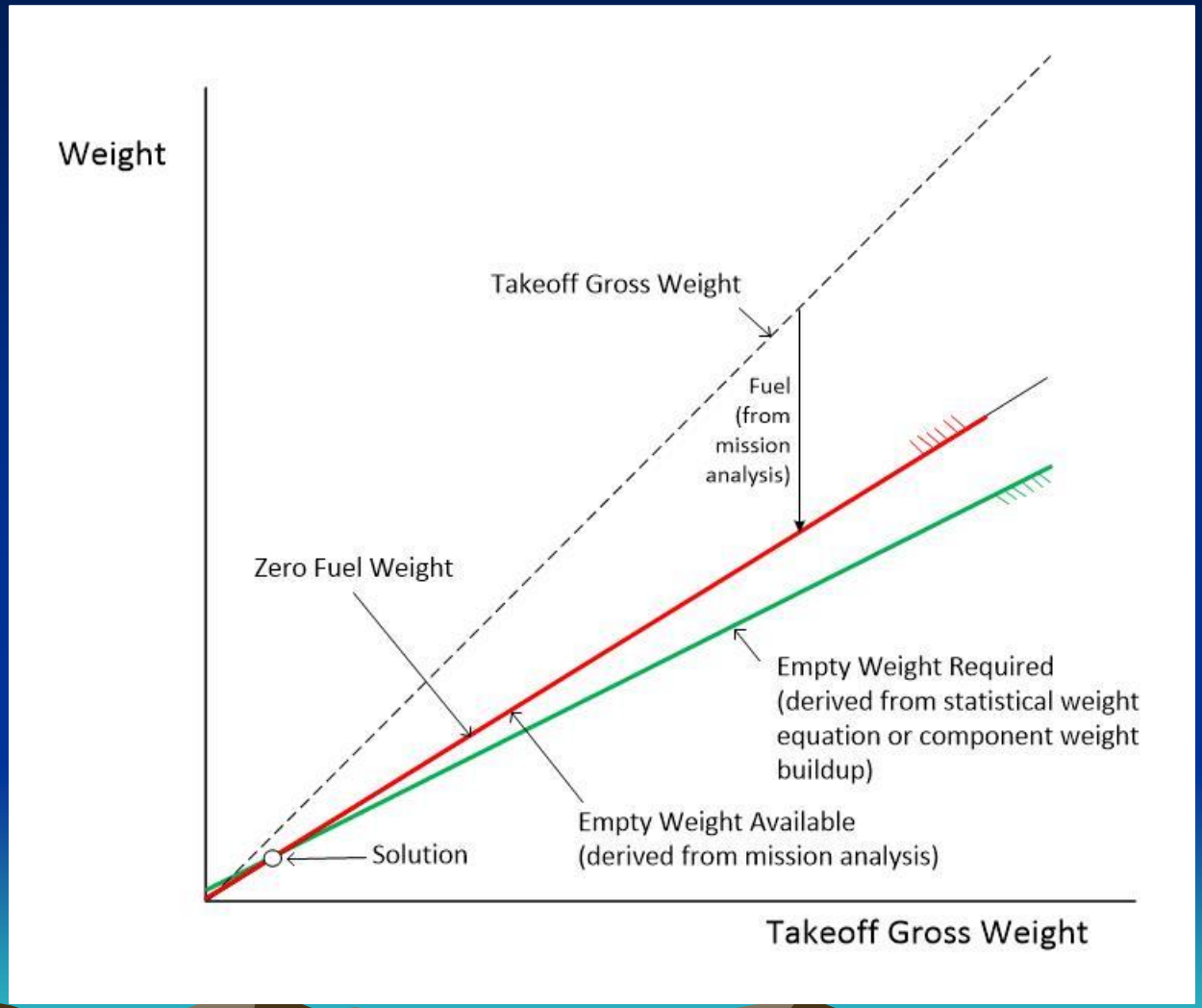
Empty Weight Solution

- Remove cockpit
  - Empty weight required moves down
- Remove crew and payload
  - Empty weight available moves up



Sensitivity to Payload and Crew Weight

- What is required TOGW?

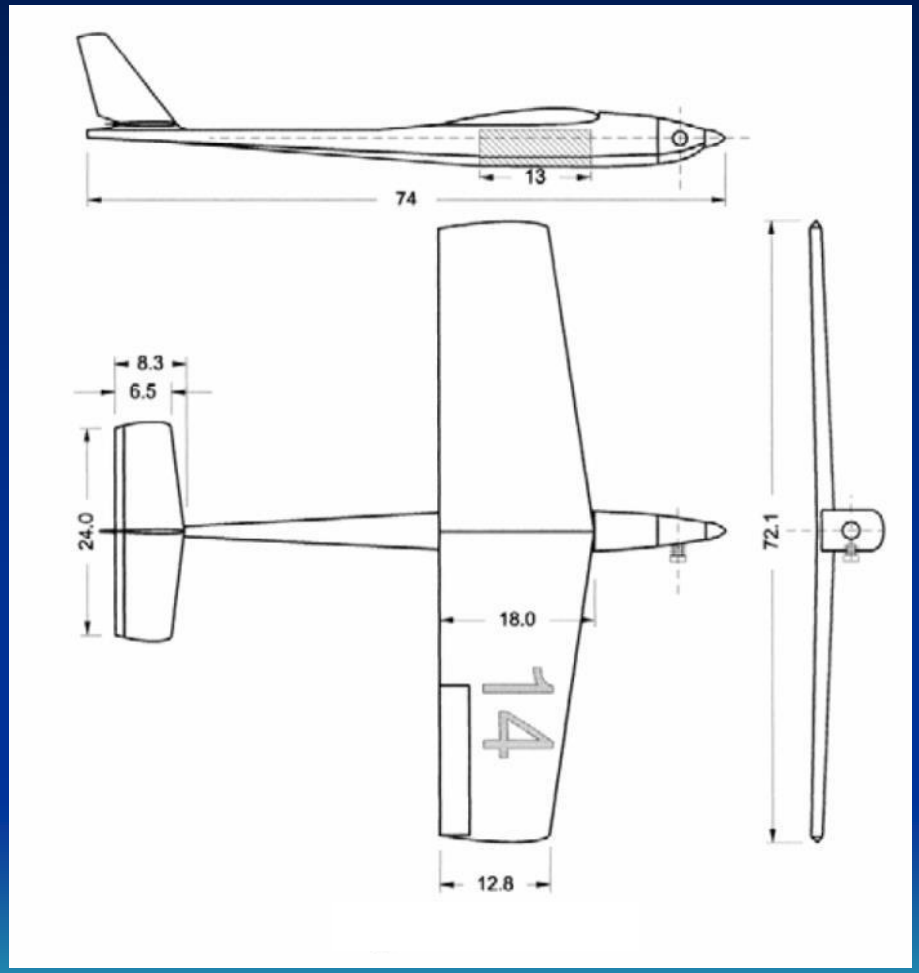


Model Airplane Flies Across Atlantic

- TAM 5
- August, 2003
- TOGW = 5 kg (11 lb)
- Dry weight = 2.7 kg (6 lb)
- EW fraction ~ 55%

http://www.barnardmicrosystems.com/UAV/milestones/atlantic_crossing_2.html

Model Airplane Flies Across Atlantic



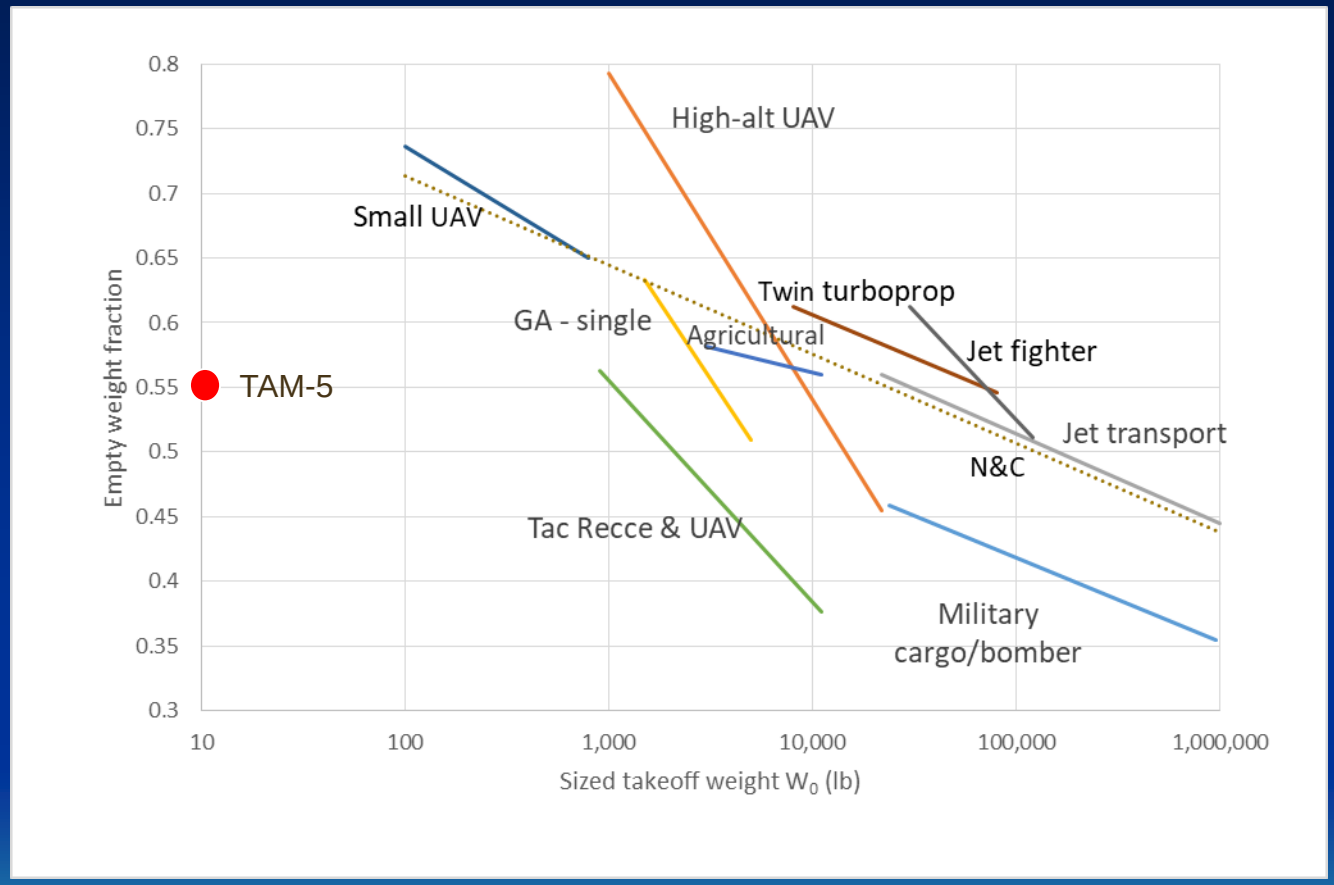
Source: http://www.barnardmicrosystems.com/UAV/milestones/atlantic_crossing_2.html

wingspan	1.9 m
length	1.8 m
take off weight	5 kg
frame weight	1.911 kg
fuel weight	2.2 kg
payload weight	0.043 kg
avionics weight	0.22 kg
engine capacity	10 cc
endurance speed	78 kph
cruise speed	78 kph
max speed	165 kph
max altitude	18,000 ft
endurance	38.5 hrs
operational range	3020 km

Raymer Approach to Empty Weight Required

- Matches empty weight fractions
  (= Empty weight/TOGW)
- Based on existing designs (data points not shown)
- Log-linear scales
- Note differences in gradients for different classes of aircraft

$$W_e/W_o = A\, W_o^{\,C}\, K_{vs}$$

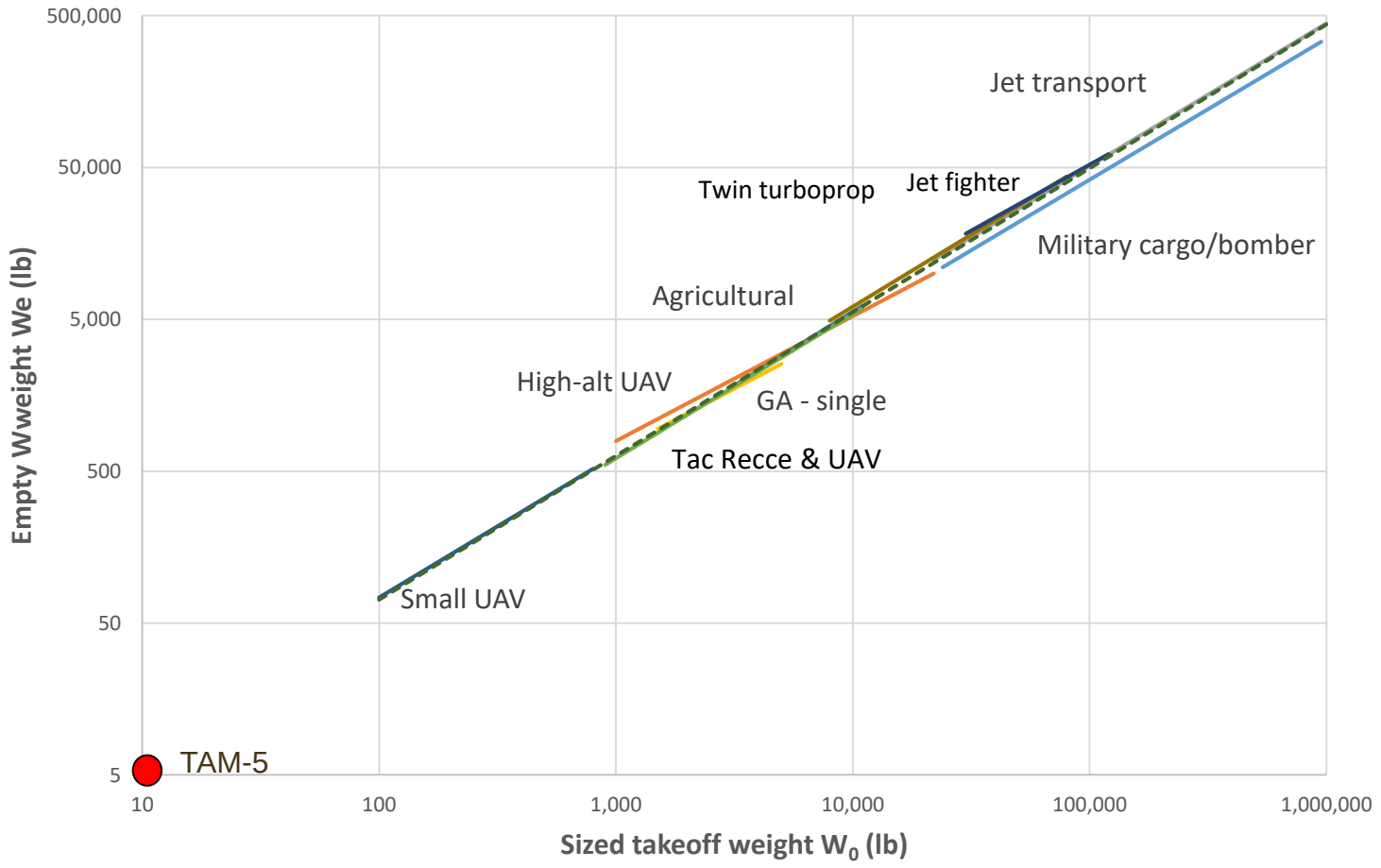


Alternative Approach to Empty Weight Required

- Used by Nicolai, Roskam, Schaufele
- Matches empty weight numerical values
- Note log-log scales

$$W_{eR} = A\, W_o^{\,B}\, K_{vs}$$

Where B = C+1



Conclusion – Limitations of this method

- Initial sketch is a rough estimate of geometry, so L/D is approximate
- SFC is also approximate
- So empty weight available is approximate
- Empty weight required applies not to your sketch, but to the class of airplane you are designing
- Lines representing empty weight available and empty weight required meet at an acute angle, so small changes make a large difference in TOGW especially if the payload and other weights independent of TOGW are small
- For a first estimate of TOGW, a non-iterative approach provides a solution that is as good as the iterative approach used in most textbooks