飞行器设计
Aircraft Conceptual Design
四川大学　2019 七月 3-4

Tony Hays
ahays@alum.mit.edu
www.adac.aero

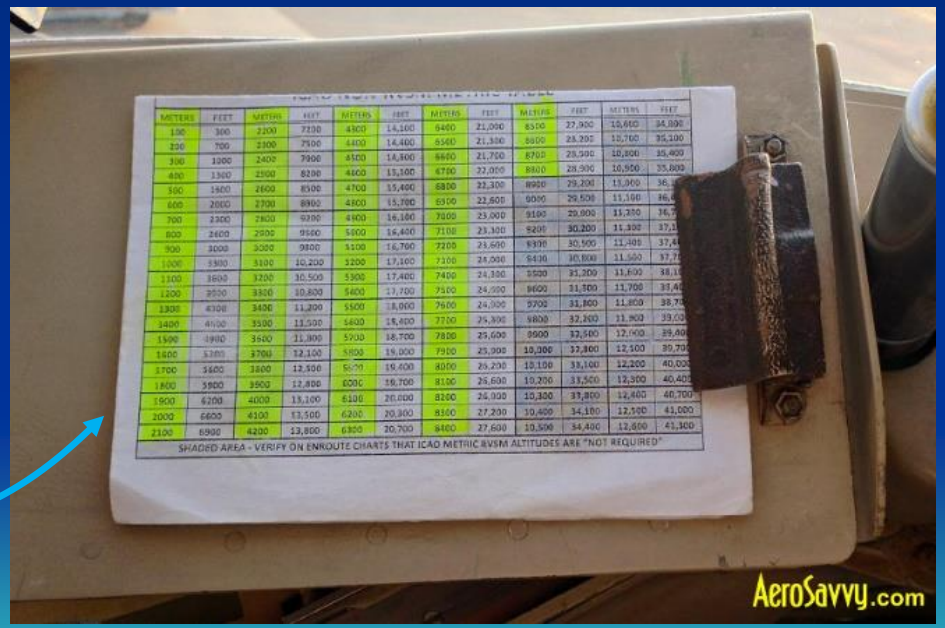
Introduction

- 8 hour course
- Condensed version of 32 hour course
  - Presentation material and notes available at www.adac.aero
- Student evaluation at end of course

Countries that don’t use metric system

Non-metric units in flight operations

- Distance in nautical miles (nm)
  - Historically, 1 nautical mile = 1 minute of latitude = 1/(360x60) of circumference of earth
  - Now defined as exactly 1852 m
- Speed in knots (nautical miles per hour)
- Altitude in feet (ft), except in China and N. Korea, which use meters
  - Pilots in these countries' airspace must use conversion charts or calculators



Non-metric units in flight operations

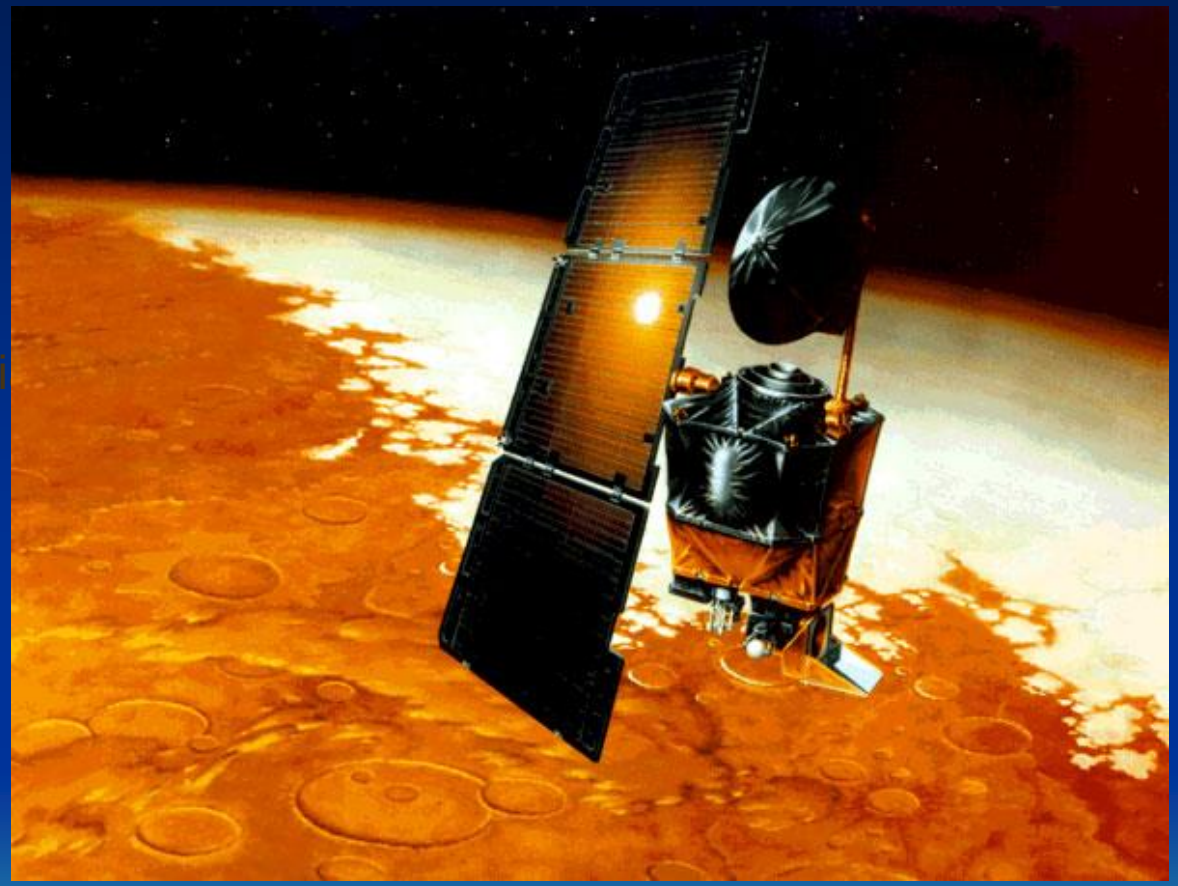
- Surface wind speed (at airports) in knots
  - Except China and Russia which is in m/sec (1 m/sec ≈ 2 kt)
- Runway length in feet
  - Everywhere else in meters
- Airport visibility in statute miles (= nautical mile/1.15)
  - Everywhere else in meters

Mars Climate Orbiter

NASA expected course correction force values in Newtons.
Lockheed gave values in lb.
(1 lb force = 4.4 N)

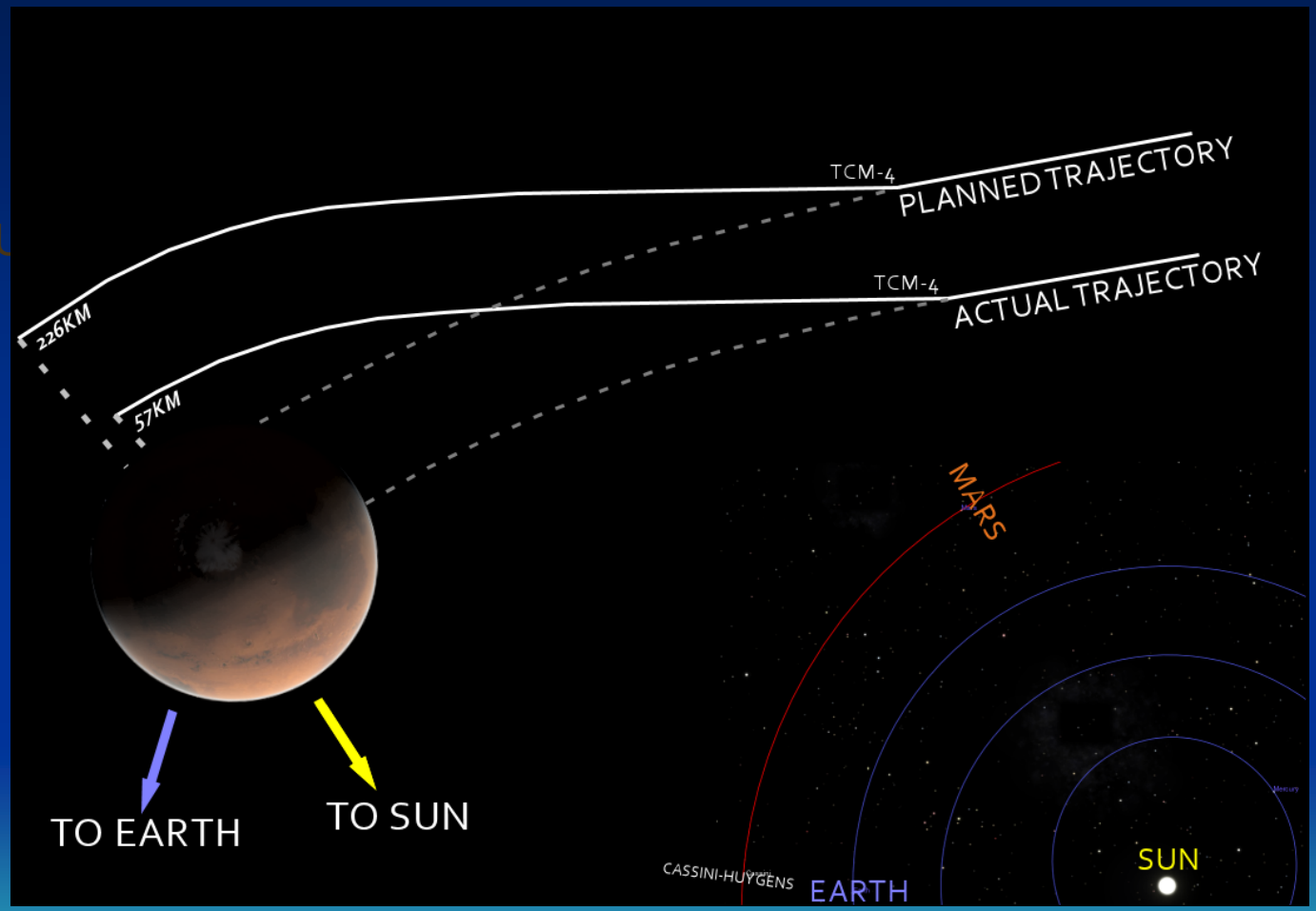
Cost: $125M

Read: “Why the Mars Probe Went off Course”
(sunnyday.mit.edu/accidents/mco-oberg.htm)



Confusion between JPL and Lockheed as to Applied ΔV

Figure not to scale



Schedule

- July 3 #1 08:15-09:00
  - Intro., class objectives
  - Atmosphere and speeds
  - Design requirements
- July 3 #2 09:10-09:55
  - Empty weight matching
  - Wing aerodynamics
  - Horizontal and vertical tail
- July 3 #3 10:15-11:00
  - Design constraints, T/W and W/S
  - Config. layout and loft
  - Special Considerations (Aero, LO, Damage tolerance, Systems)
- July 3 #4 11:10-11:55
  - Crew station, pax and payload
  - Propulsion, installation, secondary power

Schedule

- July 4 #1 08:15-09:00
  - Landing gear and subsystems
  - Aerodynamics: $C_{L_{max}}$, C_{D_0}, polars, drag plot, ML/D
- July 4 #2 09:10-09:55
  - “Bones” drawing
  - Weight equations
  - Stability and Control
- July 4 #3 10:15-11:00
  - Performance and flight mechanics
  - Costs
  - Trade Studies
- July 4 #4 11:10-11:55
  - Unconventional designs
  - What did we learn?
  - Final exam

Class Objectives

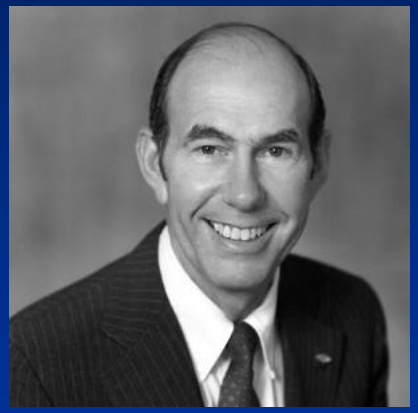
- Provide overview of procedures for commercial and military conceptual aircraft design
- Broadly follow sequence in Raymer “Aircraft Design – A Conceptual Approach”
- For more detailed presentation material and annotations to the book, go to www.adac.aero

Leaders in Aircraft Design Education

Dan
Raymer

Lee
Nicolai

Grant
Carichner



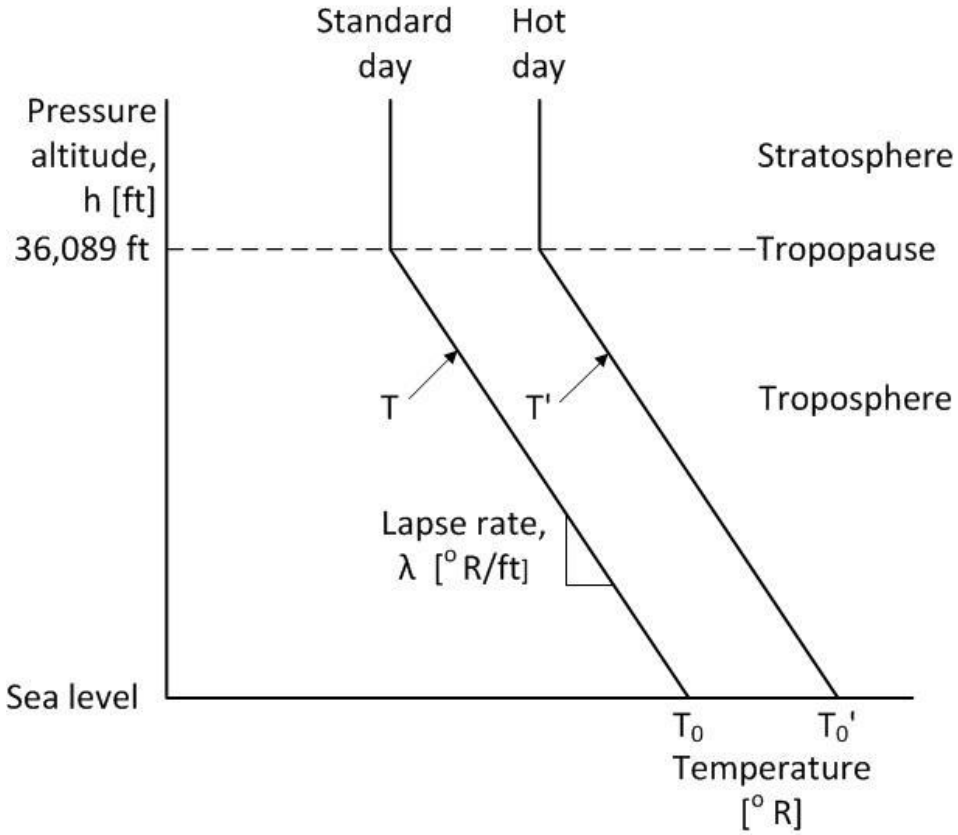
Roger
Schaufele

Jan
Roskam

Appendix B
Characteristics of the Atmosphere

International Standard Atmosphere

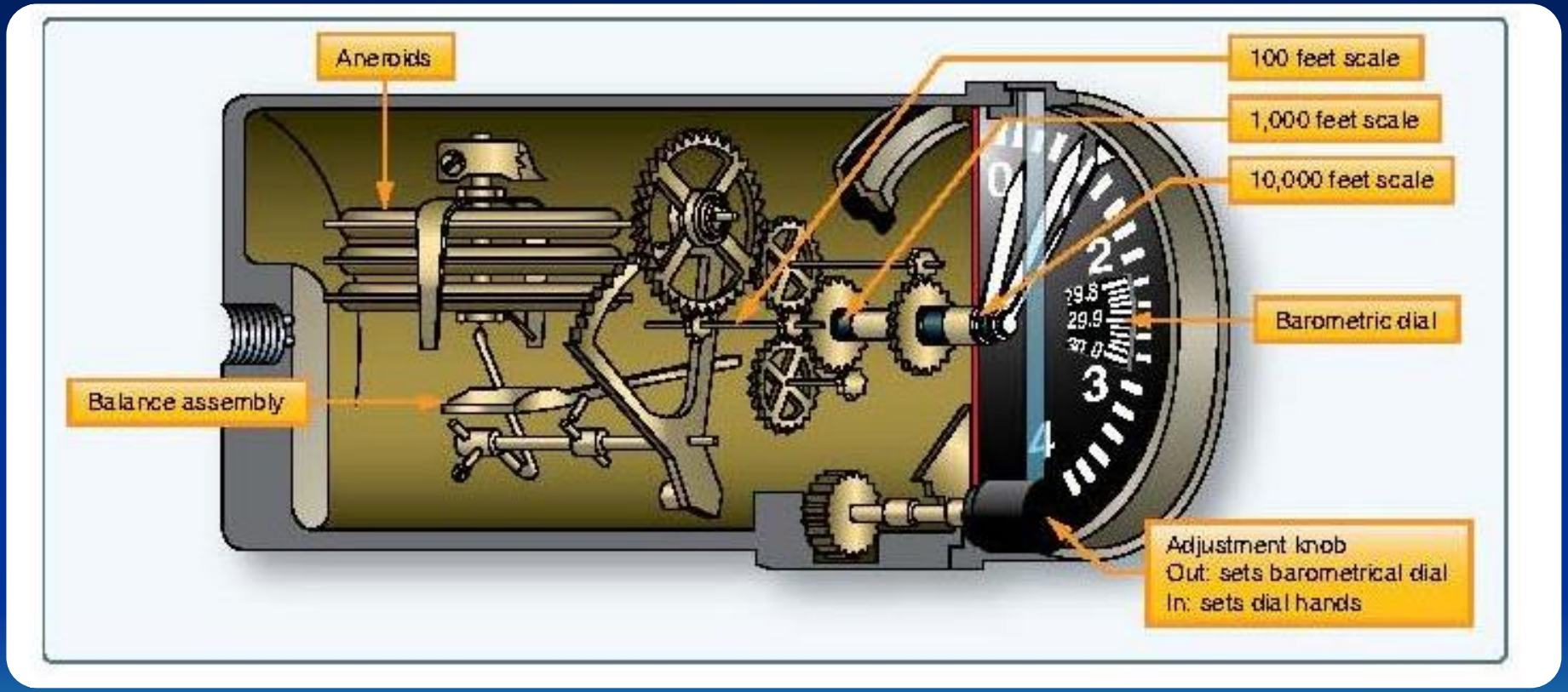
- Constant lapse rate ~ 0.6°C/1000 m (3° F/1000 ft) to tropopause 11,000 m MSL (36,089 ft)
- Constant temperature in stratosphere up to 20,000 m MSL (65,600 ft)
- Altitude is pressure altitude unless stated otherwise
- In practice, lapse rate is not uniform



Altimeter

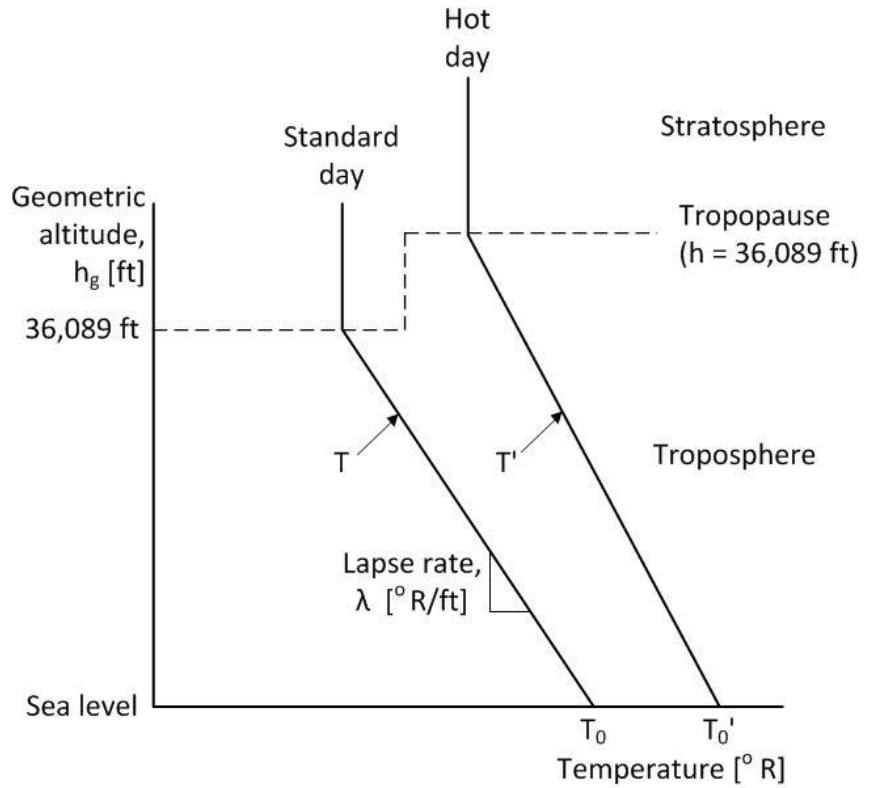
- Altimeter measures pressure, not altitude
- Pressure measured by an aneroid barometer, and converted to an altitude on display

Altimeter


Aneroids
100 feet scale
1,000 feet scale
10,000 feet scale
Barometric dial
Balance assembly
Adjustment knob
Out: sets barometrical dial
In: sets dial hands

Hot Day Conditions

- On a hot day the atmosphere expands upward
- At a given geometric altitude, the altimeter will experience a higher pressure (and show a lower altitude), than for a standard day
- E.g., on an ISA +10 C (+18 F) day, an aircraft at a geometric altitude of 6,000 ft MSL will show a pressure altitude of 5,795 ft



ADAC Aircraft Design & Consulting

Appendix B Characteristics of the Atmosphere

End

Appendix C
Airspeeds

Correction From Equivalent Airspeed to True Airspeed

Pitot-static tube on Cessna 172

V_{EAS} is speed at altitude for which dynamic pressure is equivalent to that of an airplane flying at sea level

ASI recognizes pressure, not density

$$p_{total} = p_{static} + q$$

$$q = \text{dynamic pressure} = p_{total} - p_{static}$$

$$= \frac{1}{2}\rho\left(V_{TAS}\right)^2 = \frac{1}{2}\rho_0\left(V_{EAS}\right)^2$$

where $\rho = \rho_{ambient}$ $\rho_0 = \rho_{sea\ level}$ $\sigma = \frac{\rho}{\rho_0}$

$$V_{TAS} = V_{EAS}\frac{1}{\sqrt{\sigma}} \quad \text{or} \quad V_{EAS} = \sqrt{\sigma}\ V_{TAS}$$

where $V_{TAS} = \text{true airspeed}$

Source: Schaufele

So

Airplane Drag Polar (Incompressible)

Airplane drag coefficient

$$C_D = C_{D_o} + C_{D_i} + \Delta C_{D_c}$$

where

C_{D_o} = zero lift drag coefficient

C_{D_i} = drag (viscous and inviscid) drag coefficient

$$C_{D_i} = \frac{C_L^2}{\pi A e}$$

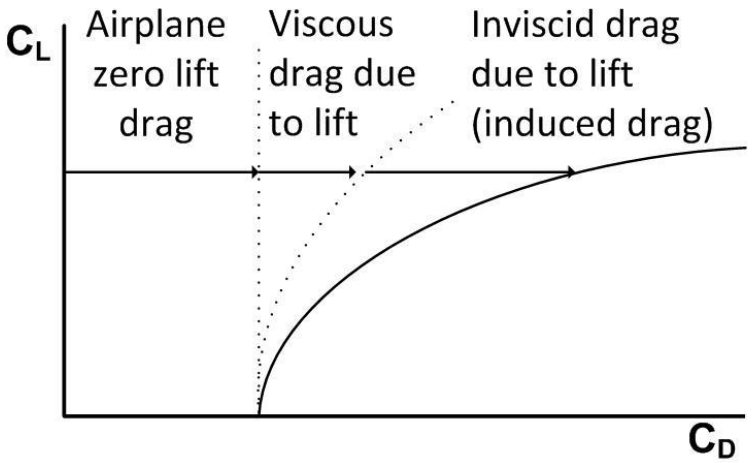
where

A = aspect ratio

e = airplane efficiency factor

ΔC_{D_c} = compressbility drag coefficient

Assume that maneuvers take place at Mach numbers for which ΔC_{D_c} can be ignored



Write $K = \frac{1}{\pi A e}$

where

K = drag due to lift factor

So

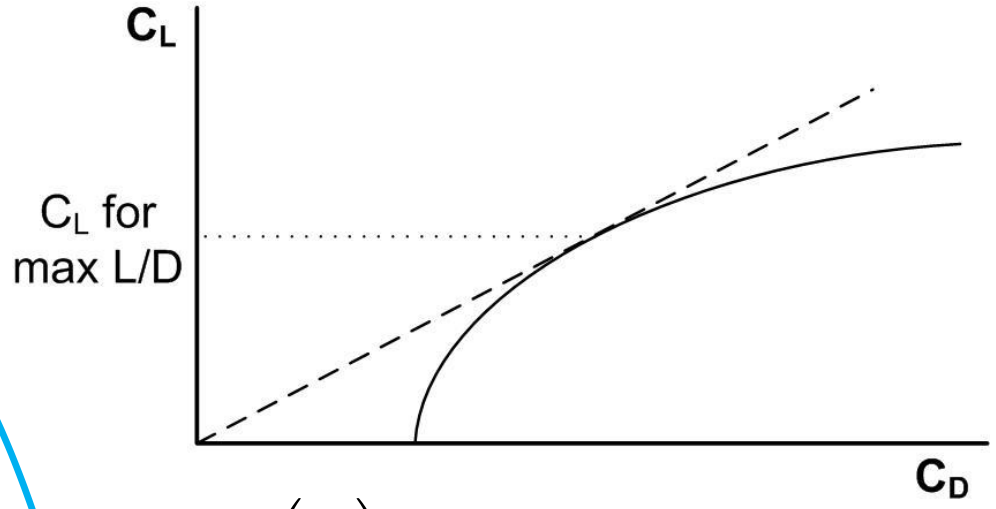
$$C_D = C_{D_o} + K C_L^2$$

Basis for all air performance

Climbing at Constant L/D

$$C_{L_{opt}} = \frac{L}{\frac{1}{2}\rho V^2 S}$$

- As airplane climbs, ρ decreases.
- V (=V_{TAS}) must increase to maintain constant C_L for max L/D



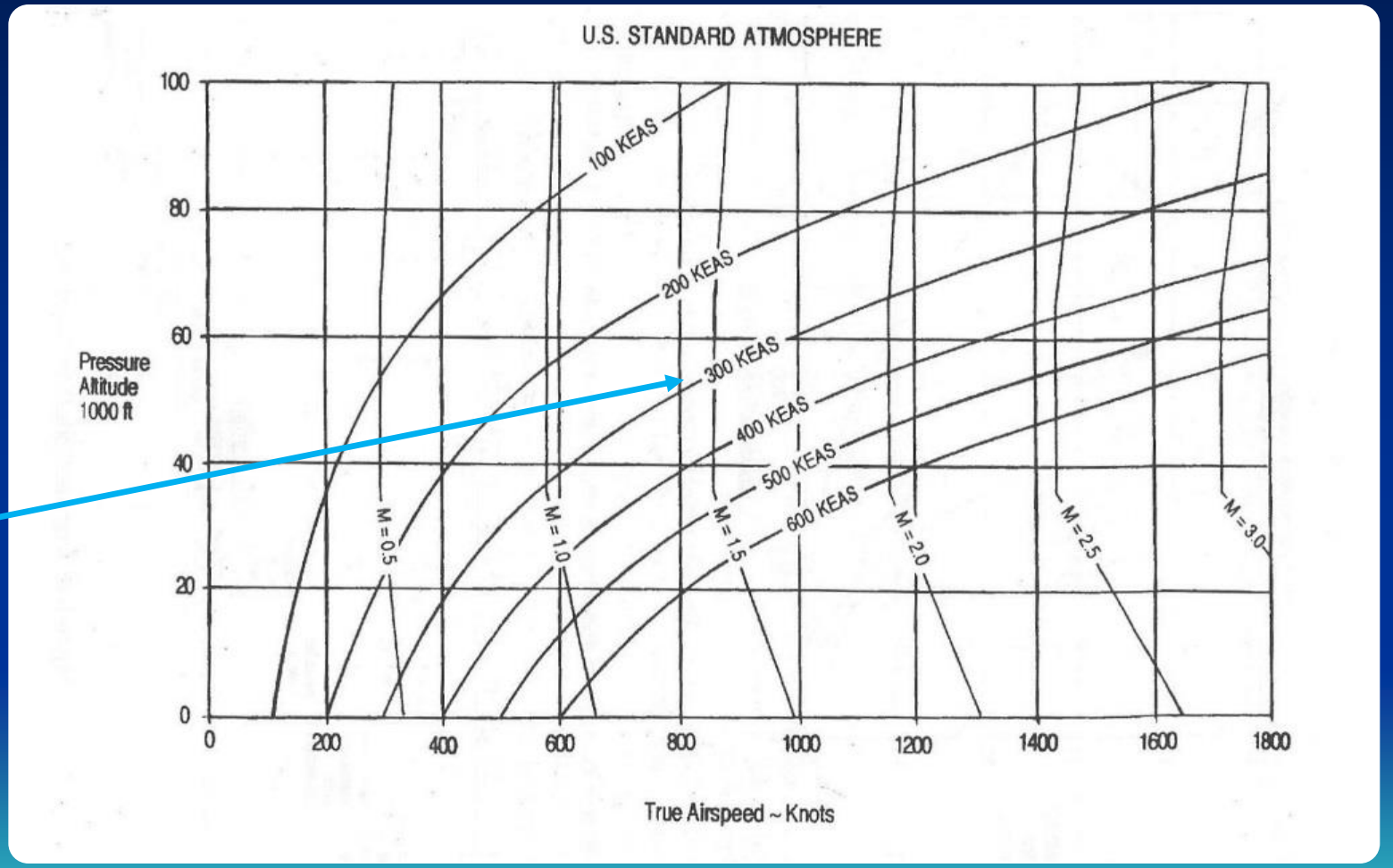
$$\rho V_{TAS}^2 = \rho_0 \left(\frac{\rho}{\rho_0} \right) V_{TAS}^2 = \rho_0 \, \sigma V_{TAS}^2 = \rho_0 \, V_{EAS}^2$$

Above 10,000 ft, pilot climbs at constant V_{IAS} (≈V_{EAS})

Relationship Between TAS, EAS, and Mach Number as Fn. Of Alt

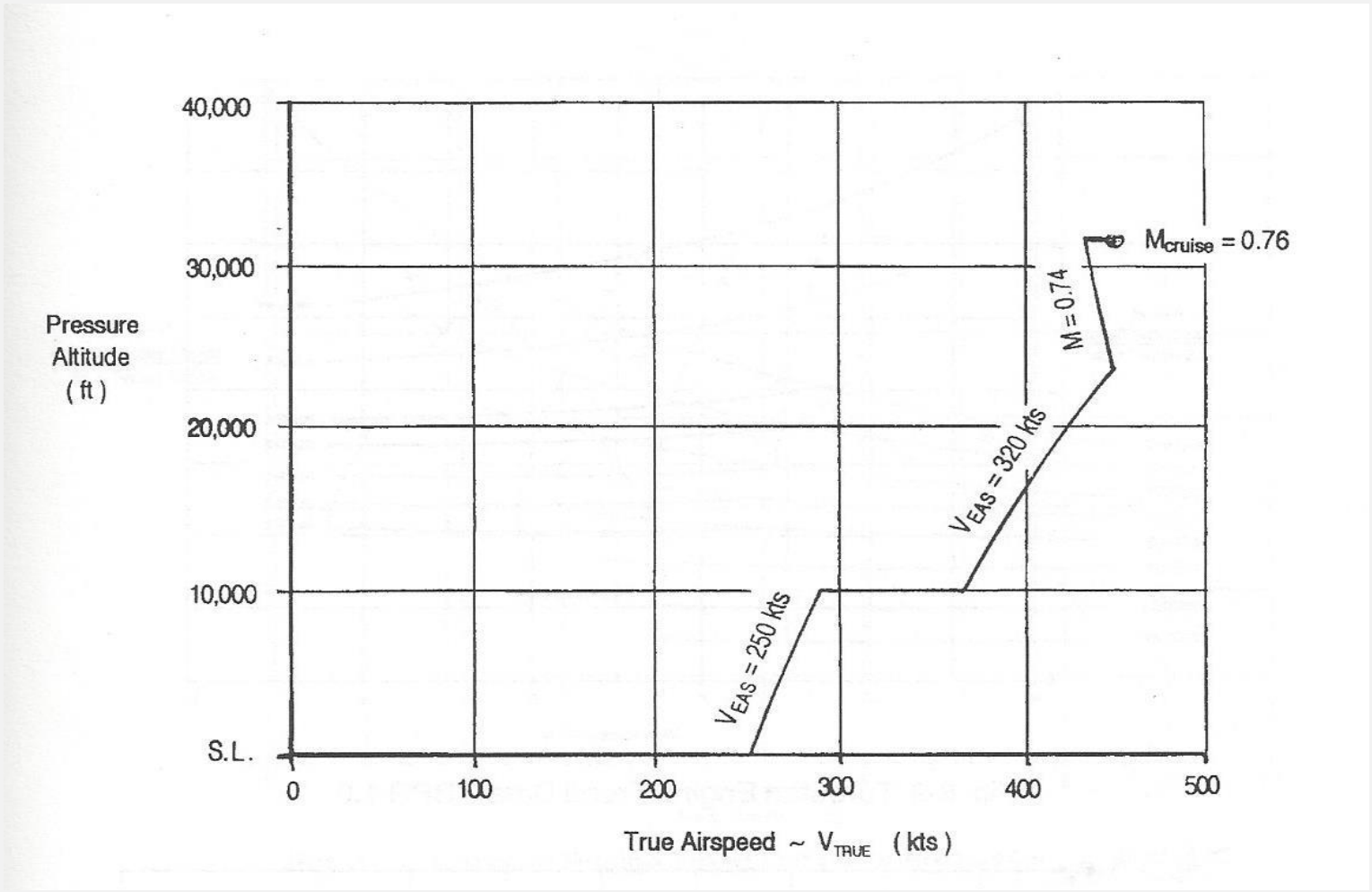
At low Mach number (M < 0.6), compressibility correction is small and $V_{IAS} \approx V_{EAS}$

Pilot flies at constant indicated airspeed (V_{IAS})



Source: Schaufele

DC-9 Climb Schedule



Best climb Mach number

Best climb speed

14 CFR § 91.117

Source: Schaufele

Appendix C
Airspeeds

End

Chapter 2 Overview
Section 2.1
Requirements

Requirements

- Types of requirements
- How requirements are derived
  - Commercial
  - Military

Performance Requirements

- Top level
  - Payload (weight and dimensions)
  - Range
- Second level
  - Takeoff and landing distance
  - Ceiling
  - Climb requirements
  - Maneuver requirements
  - etc

Defining Requirements

- Commercial aircraft: requirements usually defined by airlines (especially launch customer(s)) working closely with airframe, engine and systems manufacturers
- Military aircraft: requirements defined by the customer (usually the Federal Government) with contractor input
  - Interactions with contractors defined by law

Commercial Aviation Market

Commercial Requirements

- More collaborative approach than military
- Specifications may be developed in collaboration with one or more launch customers, e.g.
  - B.747 Pan Am
  - B.777 United Airlines
  - B.787 All Nippon Airways
  - A380 Six launch customers ⟶

747 Development

- Derivative of C-X proposal
- Developed to Pan Am requirements
- Pan Am team led by John Borger (Engineering VP), with direction from Juan Trippe (president)

Sorce: Wiki Commons

777 Development Team

- Joint development with UA, NH, AA, BA, CX, DL, JL, QF
- Led by Gordon McKinzie, Director of New Aircraft Development at UA

Sorce: Wiki Commons

787 Development

- 2004 Launch customer was NH (All Nippon Airways) for 50 aircraft
- Current orders and deliveries at 1400
- Launch customer risks initial operating problems

Sorce: Wiki Commons

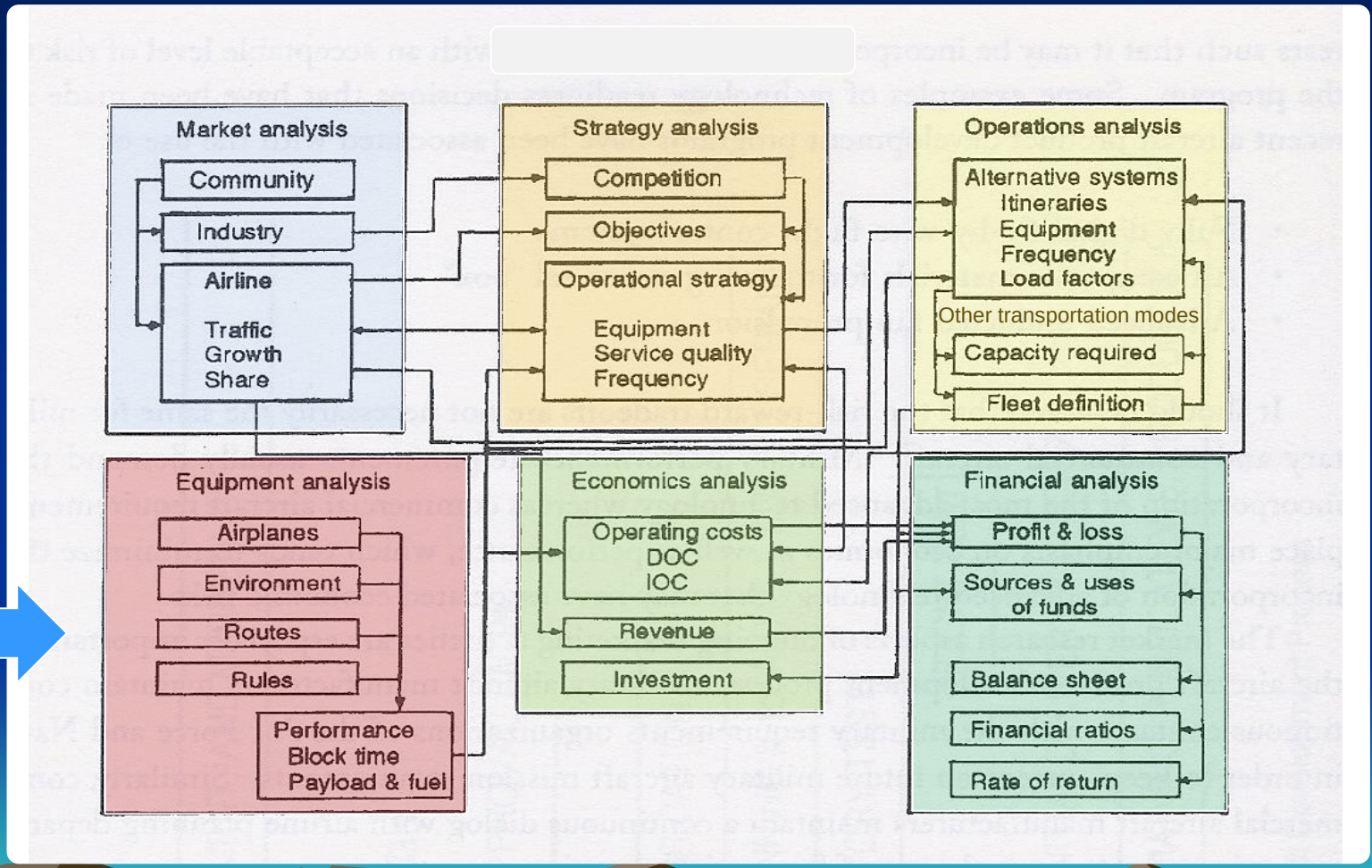
A380 Development

- Yr 2000 - Launch customers: five airlines (AF, EK, QF, SQ, VS) plus ILC
- 50 firm orders, plus 42 options
- Estimated $15B development, with breakeven at 250-300
- Current orders and deliveries at 290

Sorce: Wiki Commons

Configuration Development Analysis

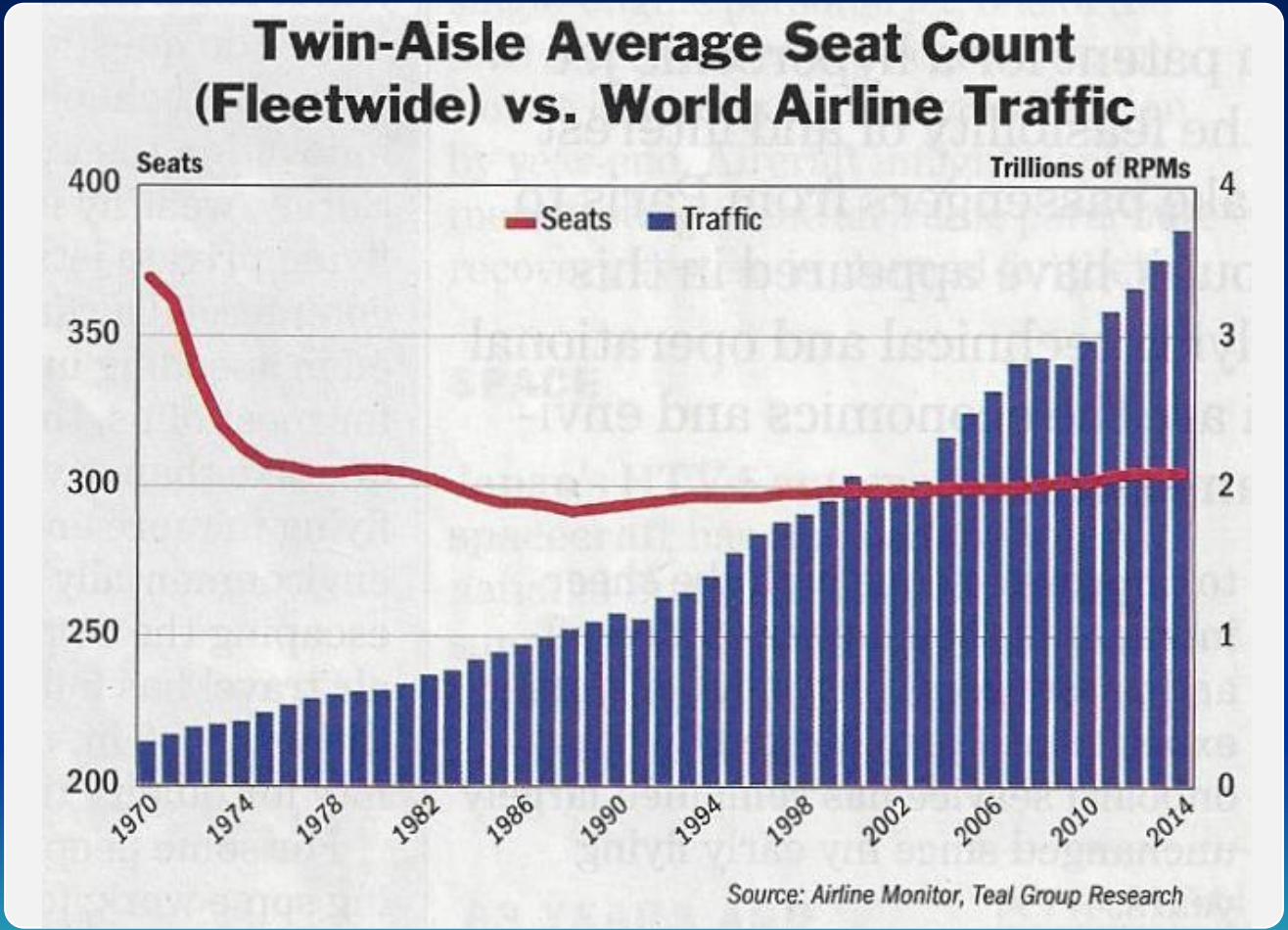
Primary design responsibility



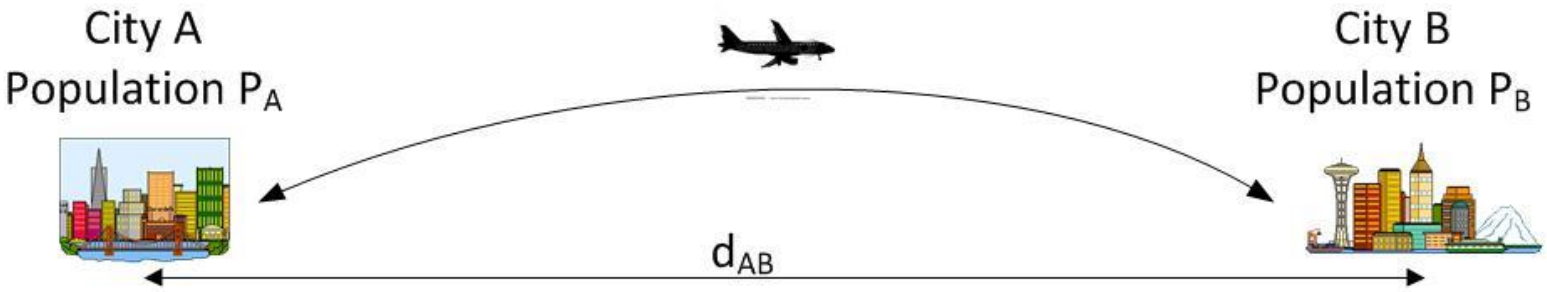
Source: Schaufele

Market Fragmentation

- As traffic increases, market fragments into more origin-destination traffic
- Originally:
  - SFO-NRT-PEK
  - SFO-NRT-HKG
  - SFO-NRT-SEL
    - Etc
- Now:
  - SFO-PEK
  - SFO-HKG
  - SFO-HND
  - SFO-CTU
    - Etc
- Average seat count is constant



Gravity Model



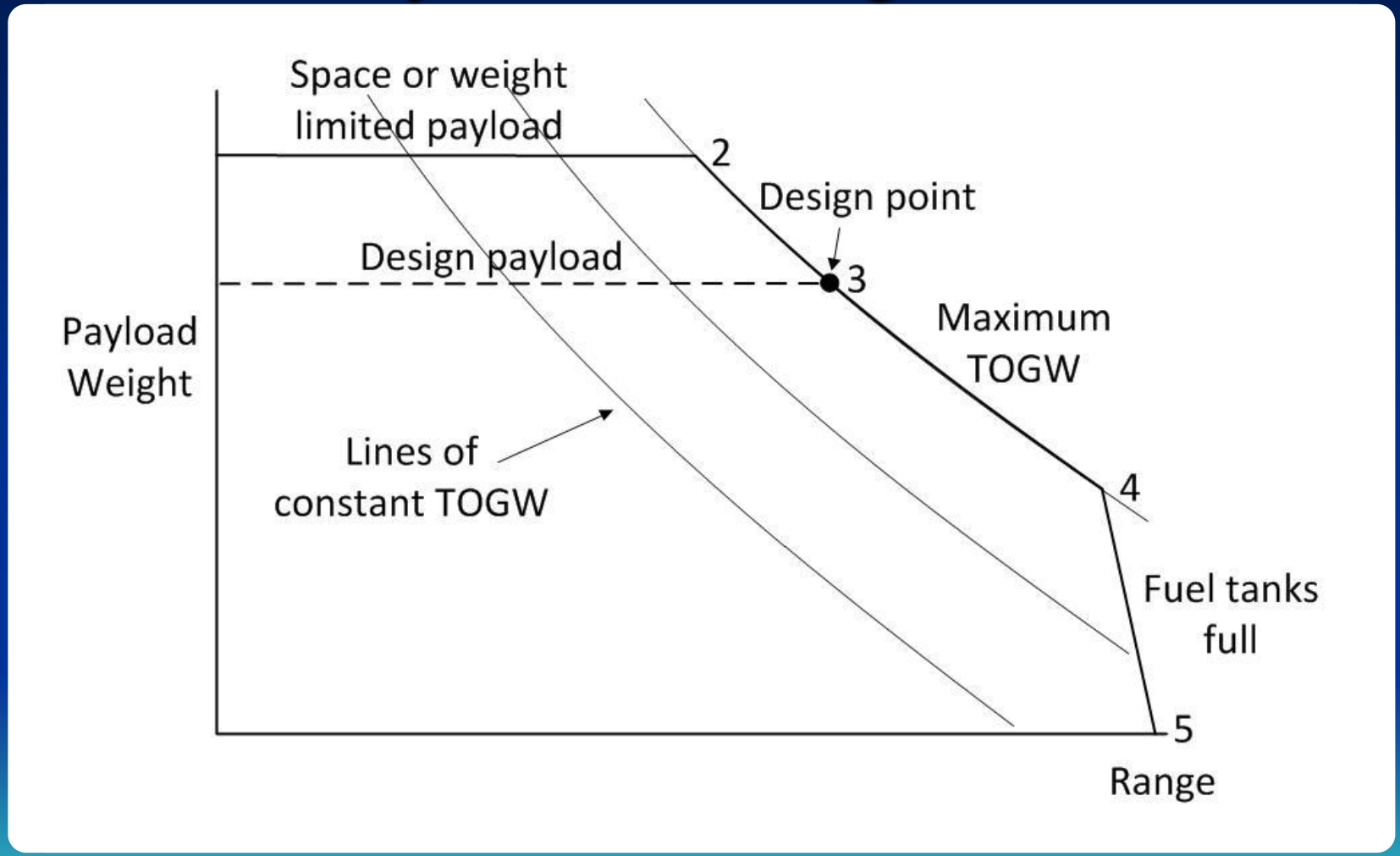
Traffic Volume V calculated as $V = k \frac{P_A P_B}{d_{AB}^2}$

where k is an empirical constant

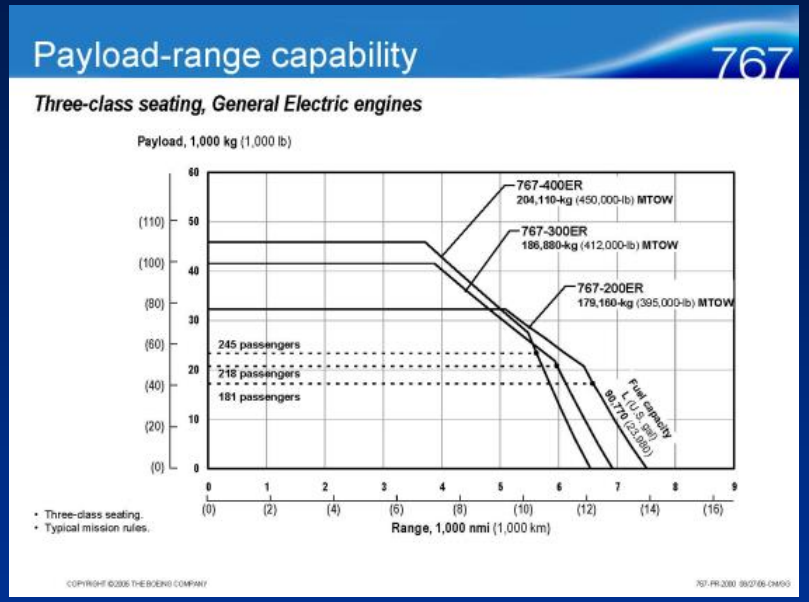
Gravity Model

- Empirical factor, k, is a function of variables such as
  - Trade between city pair
  - Income levels
  - Ethnic associations
- Exponent on distance may also need to be empirically adjusted.

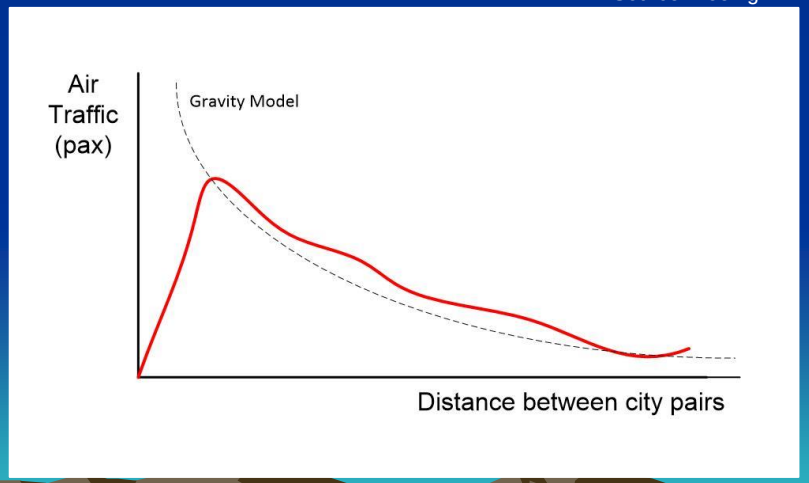
Payload-Range Plot



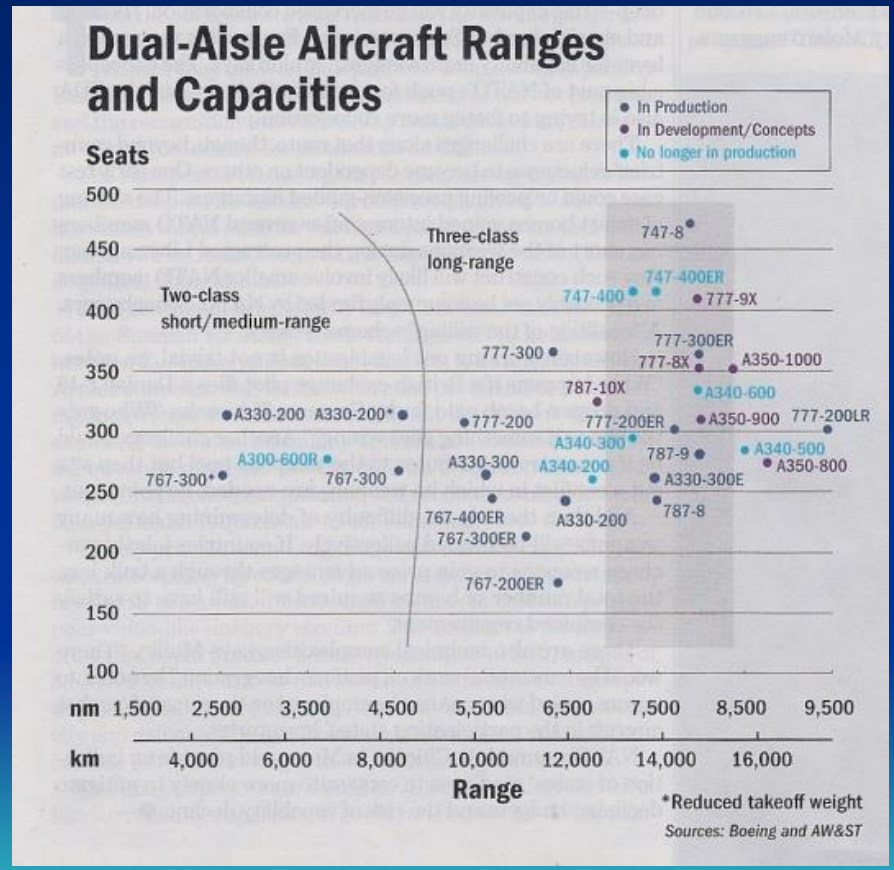
Compare Traffic Forecast to Existing Aircraft Types



Source: Boeing



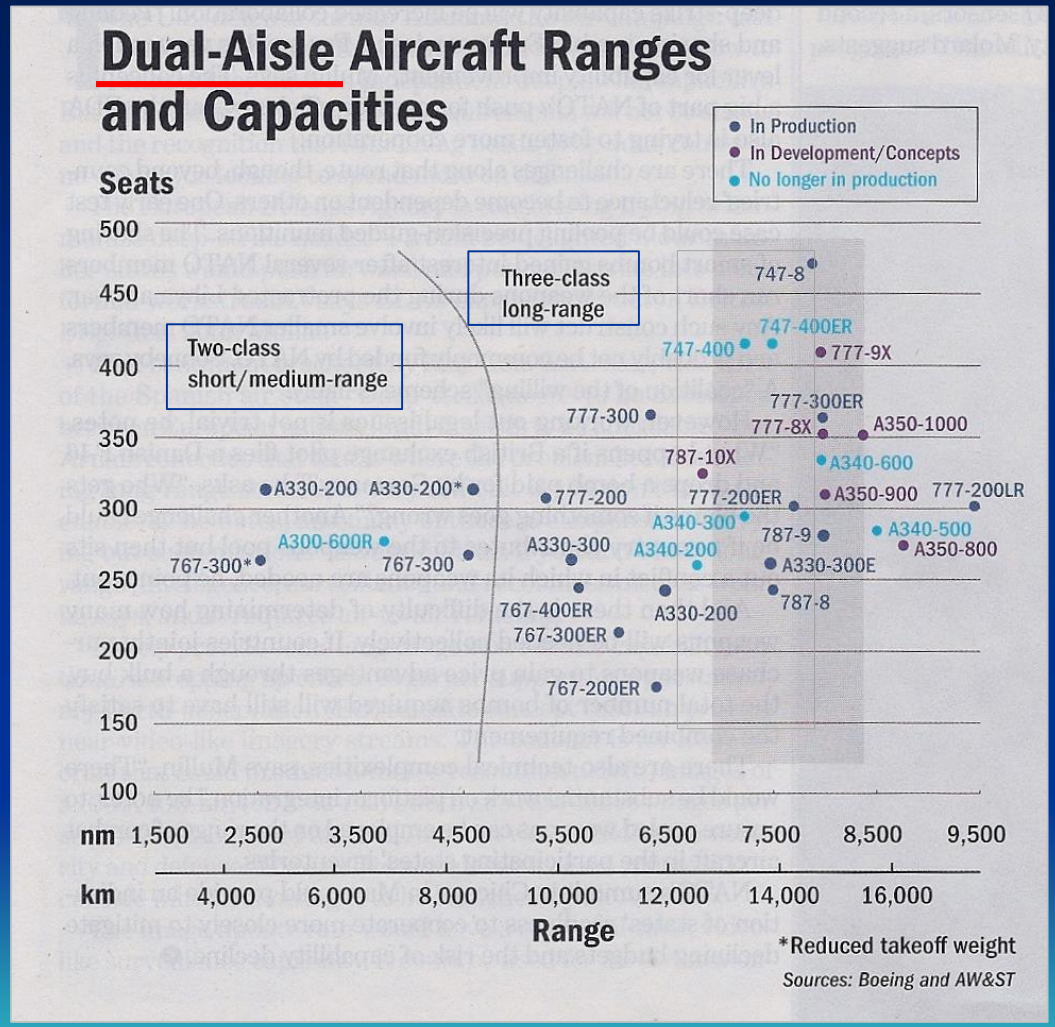
- Identify spaces in aggregated payload-range plot that will satisfy future demand



Source: AW&ST

Point-Design Payload-Range Data

- Differentiate product from others in market
- Satisfy demand based on market analysis



Source: AW&ST

Military Aviation Market

Development of Military Requirements

- Description of capability needs defined in the Initial Capabilities Document (ICD)
- Industry is invited to respond through a Request For Information (RFI)

Source: commons.wikipedia.net

Embraer A-29 Super Tucano

Military Requirements

- Draft Request For Proposal (DRFP) is an informal document. Government invites comments from potential bidders.
- RFP is a formal document stating government requirements. Once issued, all informal contact between government and bidders ends.

Military Requirements

- RFP is sent to qualified bidders and requests information which includes
  - Technical proposal
  - Recent government contracts
  - Senior personnel who will work on the contract
  - Facilities

Military Requirements

- Request For Quotation (RFQ) requests a detailed cost and schedule to perform the contract.
- Tasks are broken down into elements using a hierarchical Work Breakdown Structure (WBS).
- Engineers estimate hours to perform each task element.

KC-135 Replacement

- 2003 AF awards sole source contract to Boeing using B767
- 2006 project cancelled due to corruption
- 2008 AF announces contract award to EADS/Grumman using A330. Boeing protests successfully
- 2010 AF reissues RFP and Boeing wins with 767

KC-135R or T with CFM56 engines replacing JT-8Ds

ATF Competitive Fly-Off

- Northrop YF-23
- Lockheed YF-22

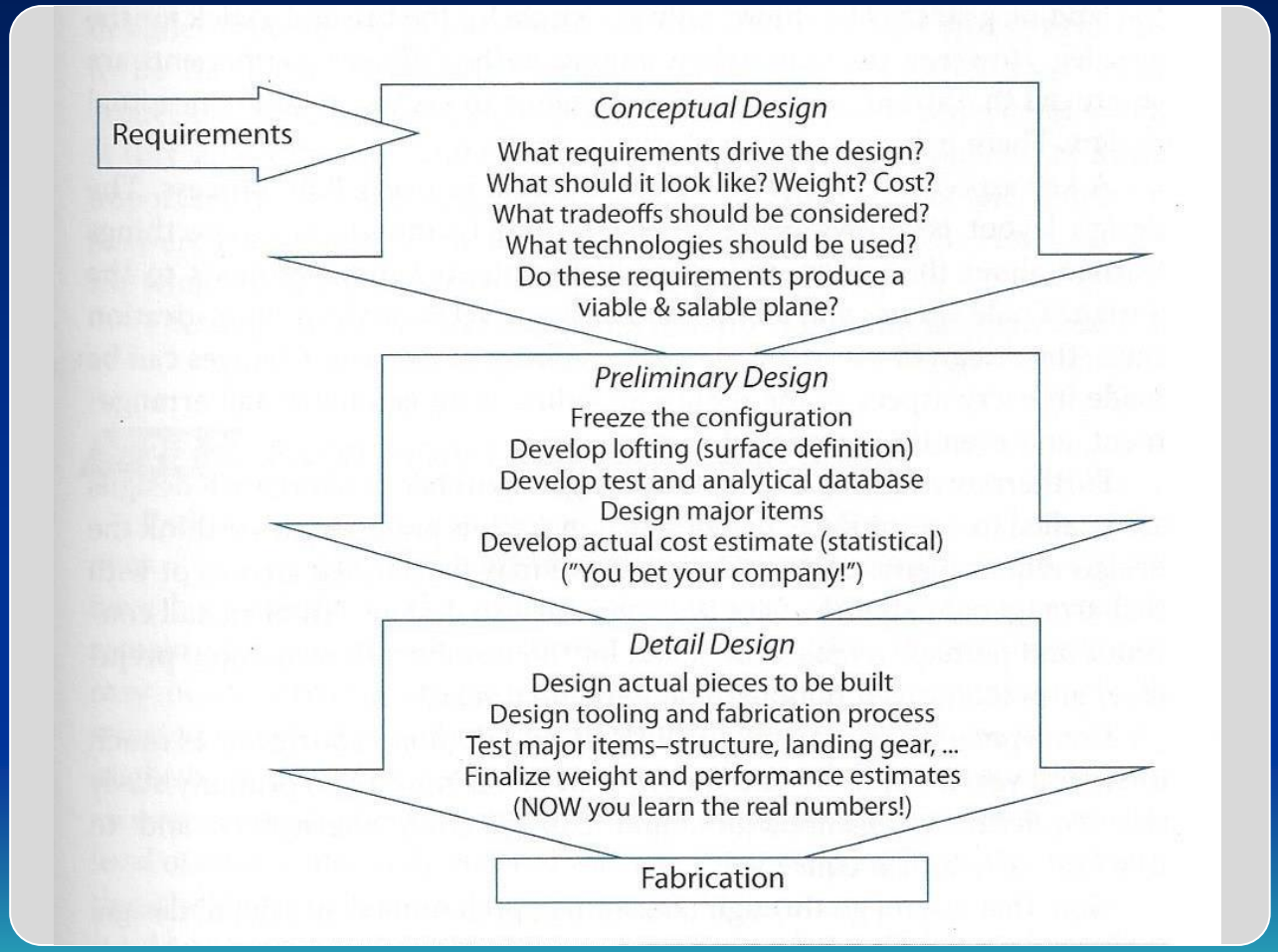
JSF Competitive Fly-Off

- Boeing X-32

- Lockheed Martin X-35

Section 2.2
Phases of Aircraft Design

Three Phases of Aircraft Design



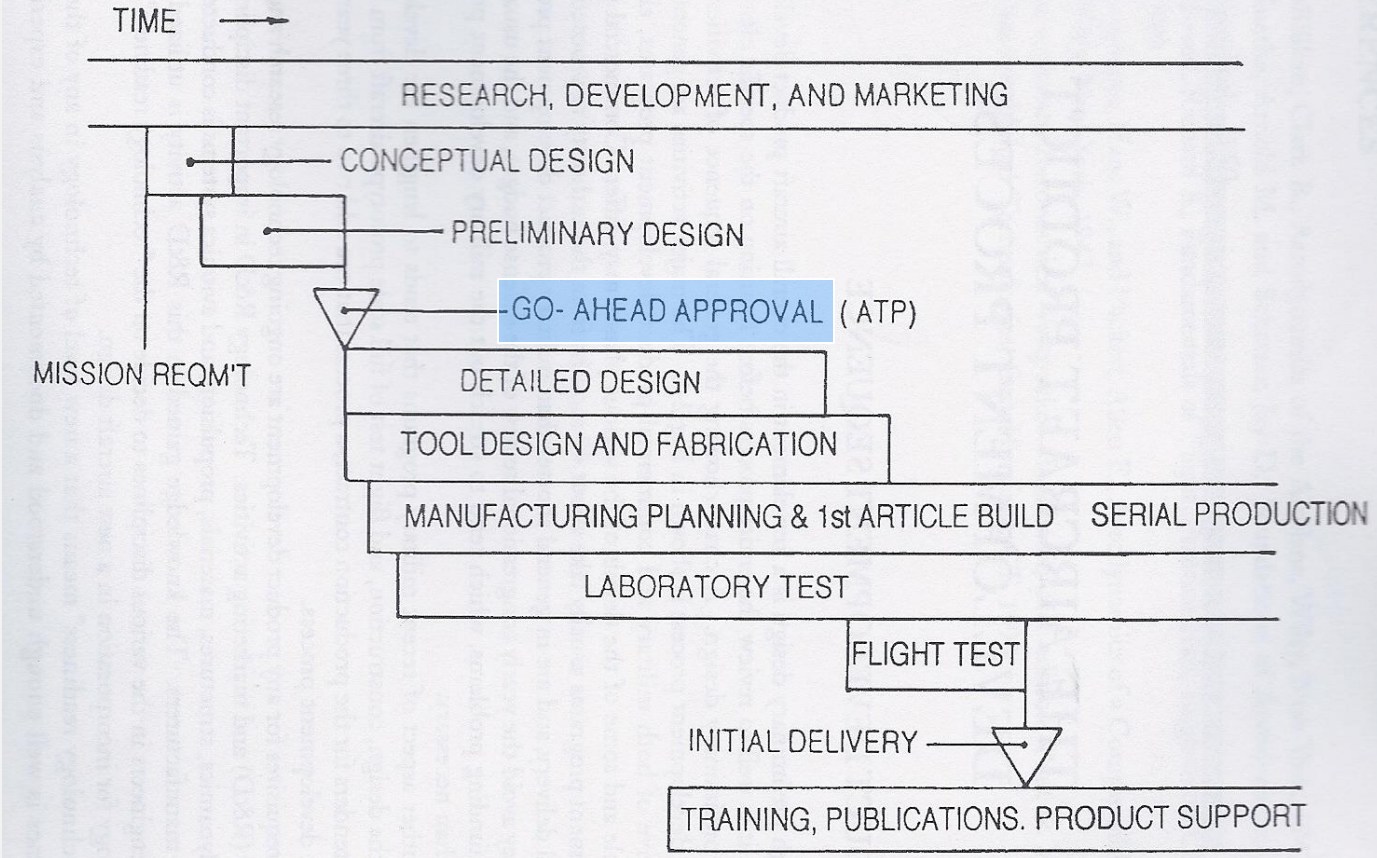
Source: Raymer

Section 2.3
Aircraft Conceptual Design Process
Risk Analysis

Risk Analysis

- Technical risk
  - Not developing product to specification and schedule
  - Team member or subcontractor not delivering product to specification and schedule
- Economic risk
  - Depression - traffic does not meet forecast
  - Fuel price
  - Exchange rates
  - Inflation
- Political risk

Commercial Development Schedule



Source: Schaufele

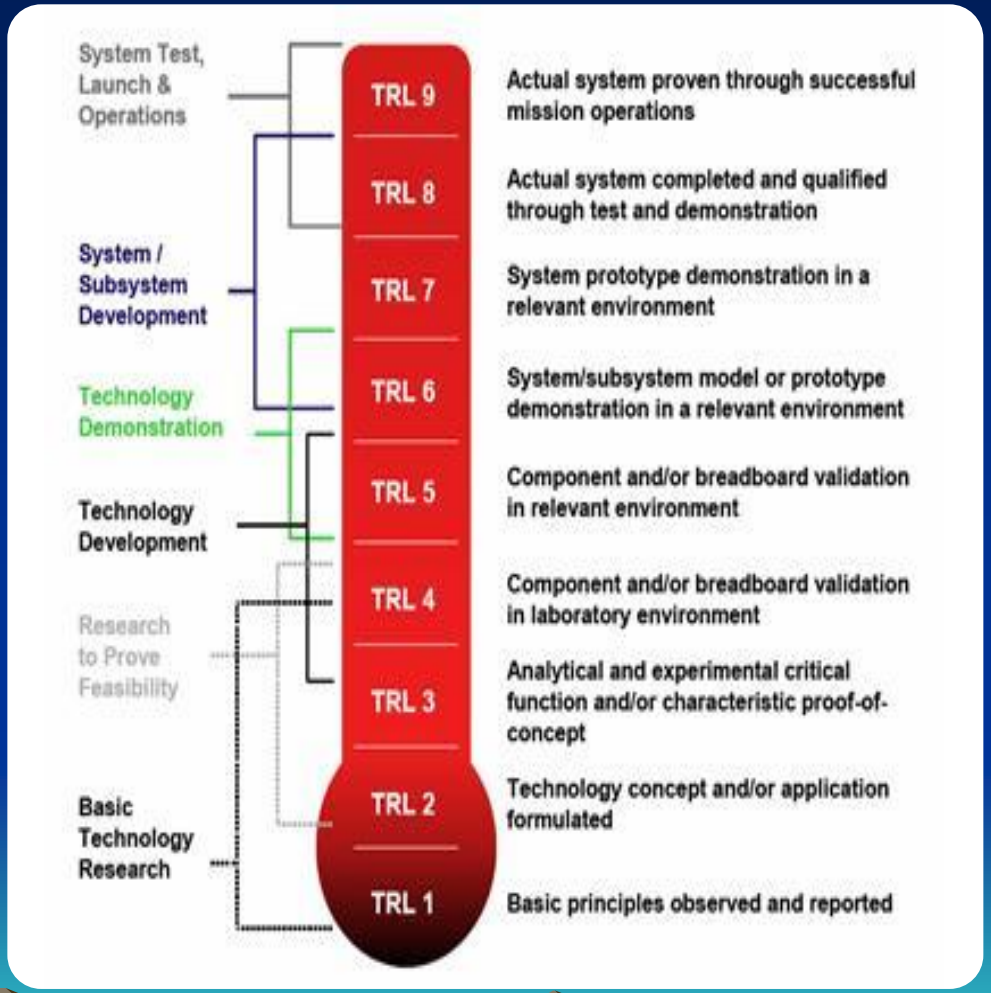
Risk Analysis

- Examples of missed schedule
  - Large scale composite manufacturing for B787
  - Europrop TP400-D6 engines for A400M
  - Hyfil blades for R-R RB.211

Source: en.wikipedia..com

Technology Readiness Levels

- At project go-ahead, every system should be at TRL 8 or above for commercial aircraft or engines, TRL 6 or above for military



Some Days Nothing Goes Right

Chapter 2 Overview
Section 2.1
Requirements

End

Chapter 3
First Estimate of Takeoff Gross Weight (TOGW)

Design Responsibilities

Primary responsibilities of Design Analysis Group:

- Size the airplane (calculate the takeoff gross weight)
- Determine thrust/weight (T/W), wing loading (W/S) and other design characteristics

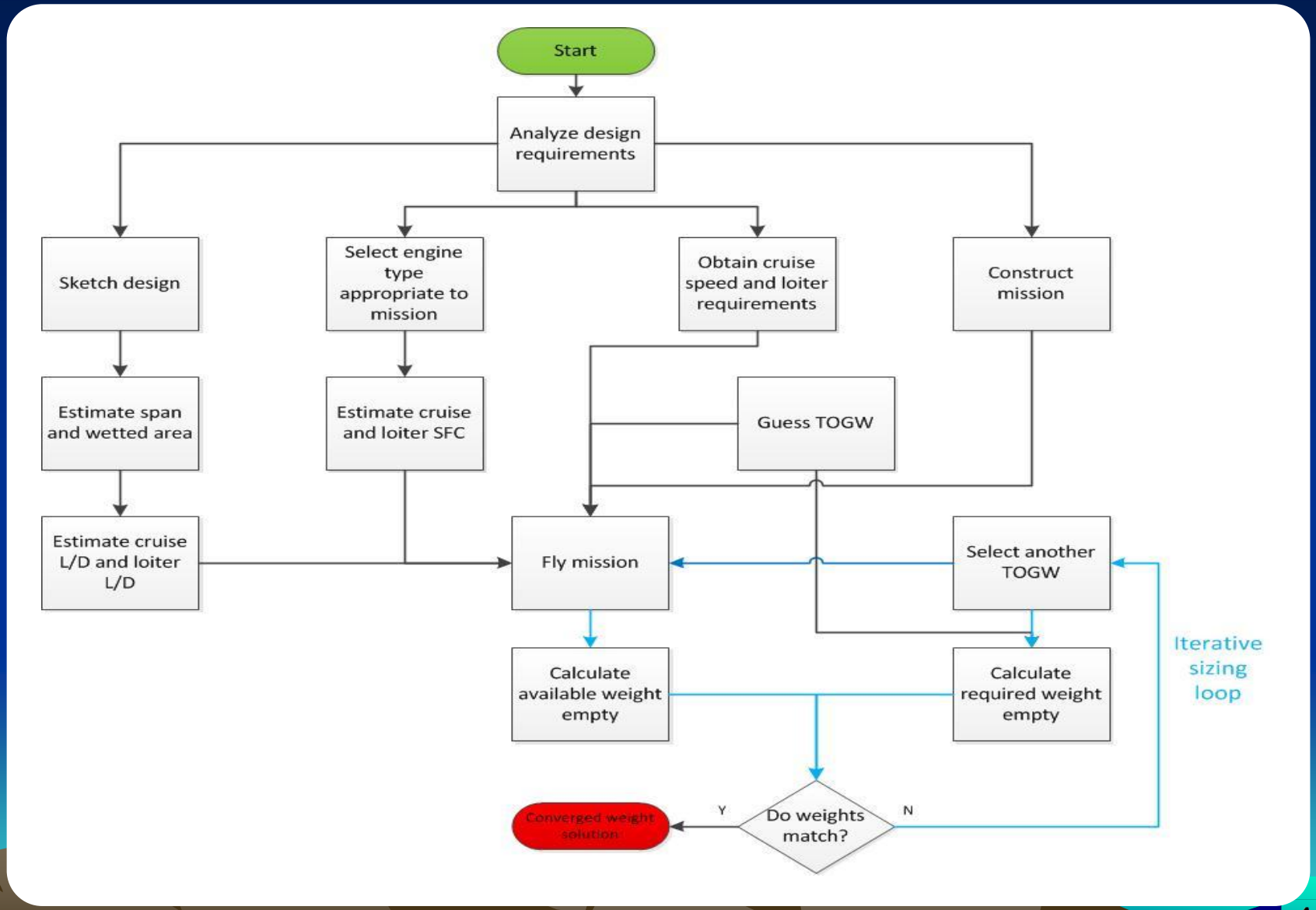
Primary responsibility of Configuration Design Group:

- Lay out a configuration that meets the design requirements

Joint responsibilities

- Optimize configuration to objective function (e.g. minimize DOC or LCC)

Initial Estimate of Take-Off Gross Weight



ADAC Aircraft Design & Consulting

Initial Estimate of TOGW

- Method for all aircraft sizing programs is “empty weight matching”
- For military aircraft TOGW is defined as

$$W_0 = W_{fuel} + W_{crew} + W_{payload} + W_{empty}$$

Useful load

So empty weight is

$$W_{empty} = W_0 - \left(W_{fuel} + W_{crew} + W_{payload}\right)$$

Useful load

Initial Estimate of TOGW

- Method for all aircraft sizing programs is “empty weight matching”
- For commercial aircraft TOGW is defined as

$$W_0 = W_{fuel} + W_{payload} + W_{operating\ empty}$$

So operating empty weight is

$$W_{operating\ empty} = W_0 - \left(W_{fuel} + W_{payload}\right)$$

where W_{oe} is defined as

$$W_{operating\ empty} = W_{manufacturers\ empty} + W_{operational\ items}$$

Includes crew and other items

Operational 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

Empty Weight Matching

- Match
  - Empty weight available (based on mission analysis)

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

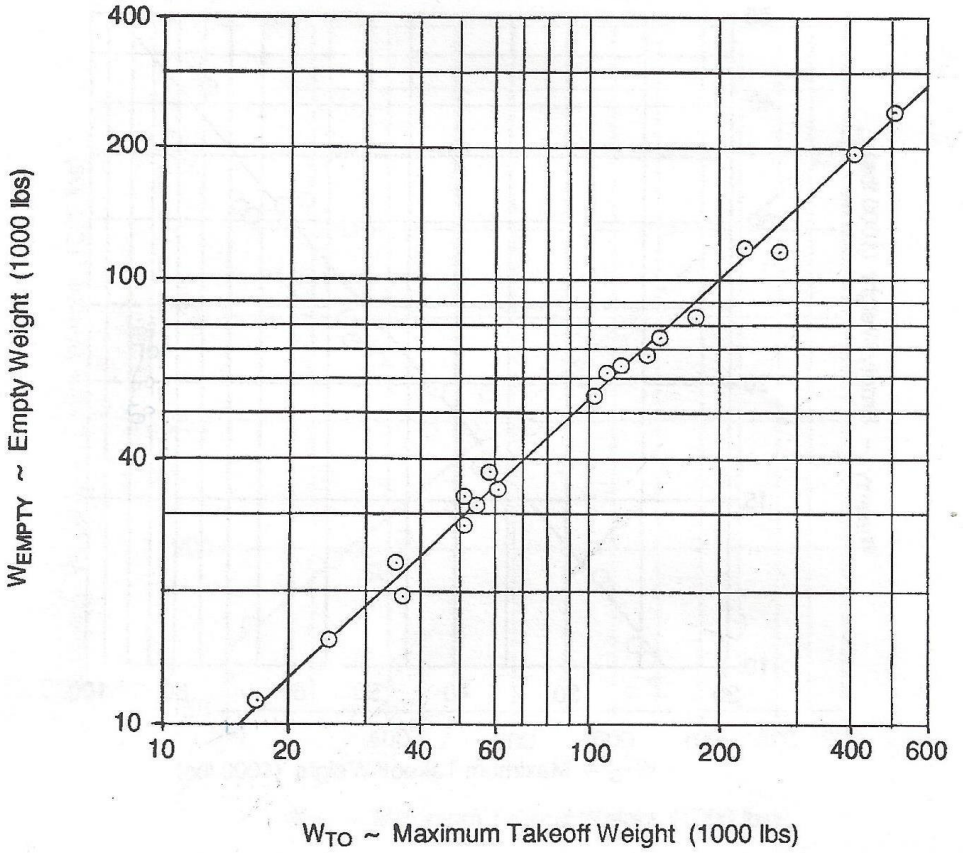
Empty Weight Available (Military)

$$W_E = W_{TO} - (W_{FUEL} + W_{CREW} + W_{PL})$$

- Assume value of TOGW
- Fly aircraft on simulated mission
- Calculate fuel consumed plus reserves
- Subtract fuel, crew, and payload weight from assumed TOGW
- Result is “empty weight available”

Estimation of Empty Weight Required

- Used by Nicolai, Roskam, Schaufele
- Trend line for empty weight of existing aircraft
- Note log-log scales

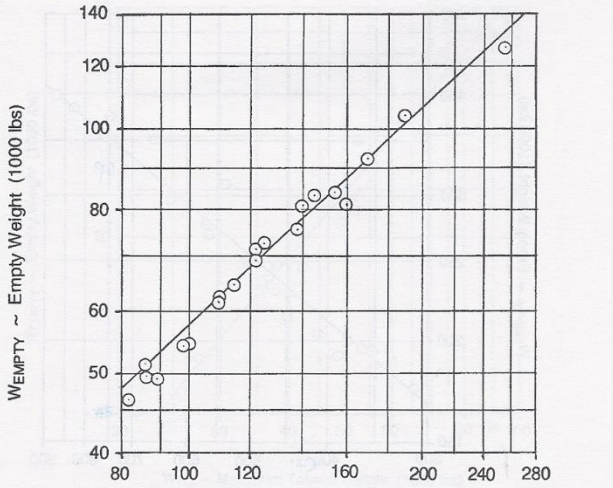


Weight Trend Data - Military Turboprop Transport

Source: Schaufele

Empty Weight Required

- For first estimate, empty weight required based on comparable aircraft ⟶
- Check whether empty weight is manufacturer's empty weight or operational empty weight
- For preliminary design, empty weight is based on component weight buildup



Aircraft	W_{TO}	W_{EMPTY}
British Aerospace BAe 146-100	82,250	47,000
Douglas DC-9-10	85,700	51,900
British Aircraft Corporation BAC-111	87,000	49,600
British Aerospace BAe 146-200	89,500	49,300
Fokker F 100	98,000	53,975
British Aerospace BAe 146-300	100,000	54,500
Douglas DC-9-30	108,000	61,400
Boeing 737-200	109,000	63,000
Douglas DC-9-40	114,000	64,600
Douglas DC-9-50	121,000	69,200
Boeing 717-200	121,000	70,790
Boeing 737-300	124,500	72,360
Boeing 737-400	138,500	76,180
McDonnell Douglas MD-81	140,000	80,700
Boeing 737-600	144,500	80,360
Boeing 737-700	154,500	83,790
McDonnell Douglas MD-83	160,000	80,968
Airbus A 320-200	169,800	92,400
Airbus A 321-100	187,400	105,600
Boeing 757-200	255,000	128,730

Estimating Empty Weight Required

Assume empty weight is in the form

$$W_e = K_{vs} A W_{TO}^{B}$$

where
K_{vs} = 1.04 for variable sweep
K_{vs} = 1 for fixed sweep
A and B are empirical constants

This does not produce a linear relationship between empty weight and TOGW, but the relationship is almost linear in the region of interest.

Weight Required Coefficients (Schaufele)

Aircraft Category	A (W in lb)	B
Personal/Utilitity	1.26	0.93
Turboprop Commuter	0.39	1.04
Bizjets	1.85	0.80
1-aisle Jet Transports	2.40	0.88
2-aisle Jet Transports	8.00	0.79
Fighter/Attack	0.07	1.18
Mil Turboprop Transports	1.36	0.92
Mil Jet Transports	1.34	0.92

Source: Schaufele

For passenger and cargo-carrying aircraft, coefficients apply to operating empty weight

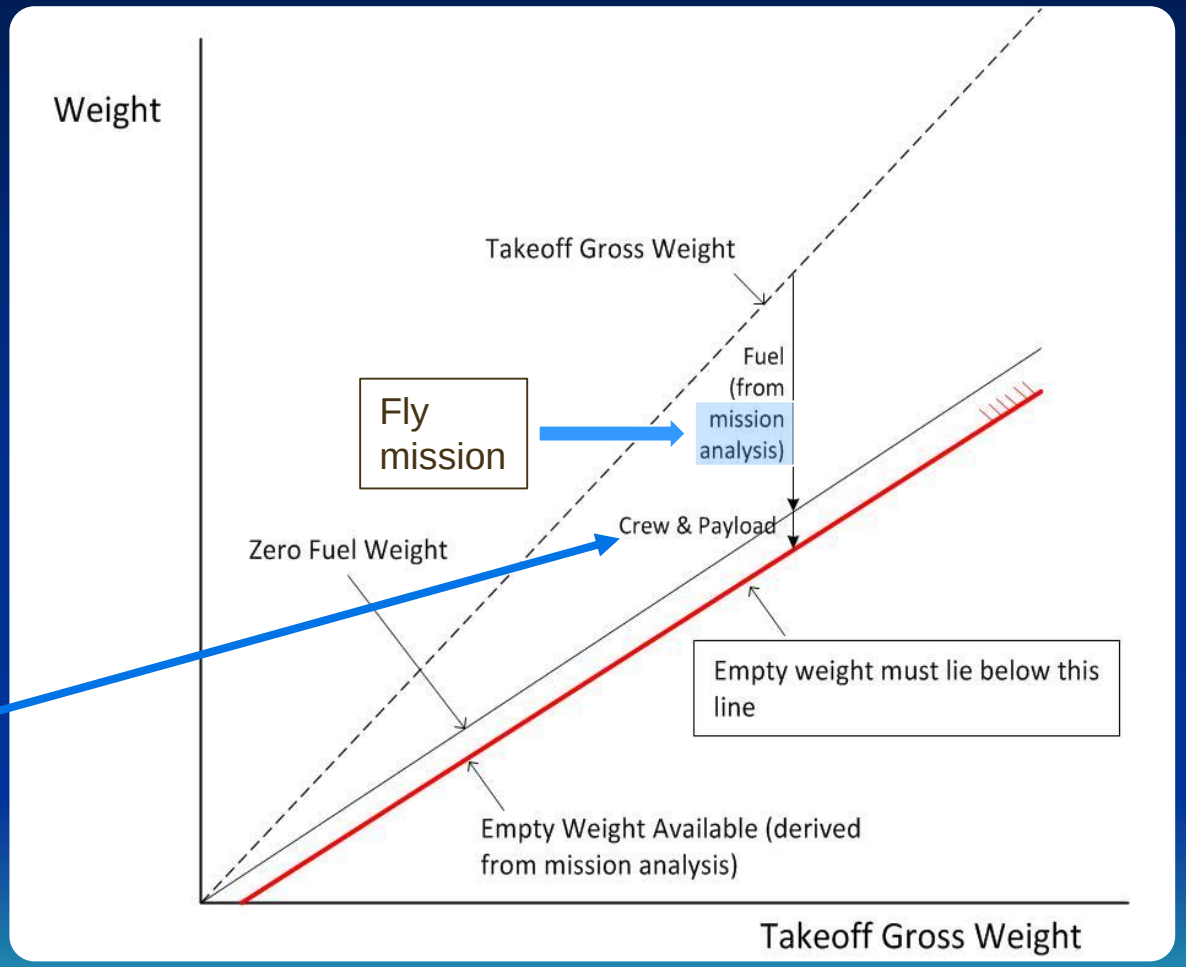
Weight Required Coefficients (Raymer)

Airplane Category	A (W in lb)	B
Sailplane - unpowered	0.86	0.95
Sailplane - powered	0.91	0.95
Homebuilt – metal/wood	1.19	0.91
Homebuilt – composite	1.15	0.91
General Aviation – single engine	2.36	0.82
General Aviation – twin-engine	1.51	0.90
Agricultural aircraft	0.74	0.97
Twin turboprop	0.96	0.95
Flying boat	1.09	0.95
Jet trainer	1.59	0.90
Jet fighter	2.34	0.87
Military cargo/bomber/ASW	0.93	0.93
Jet transport	1.02	0.94

Source: Raymer

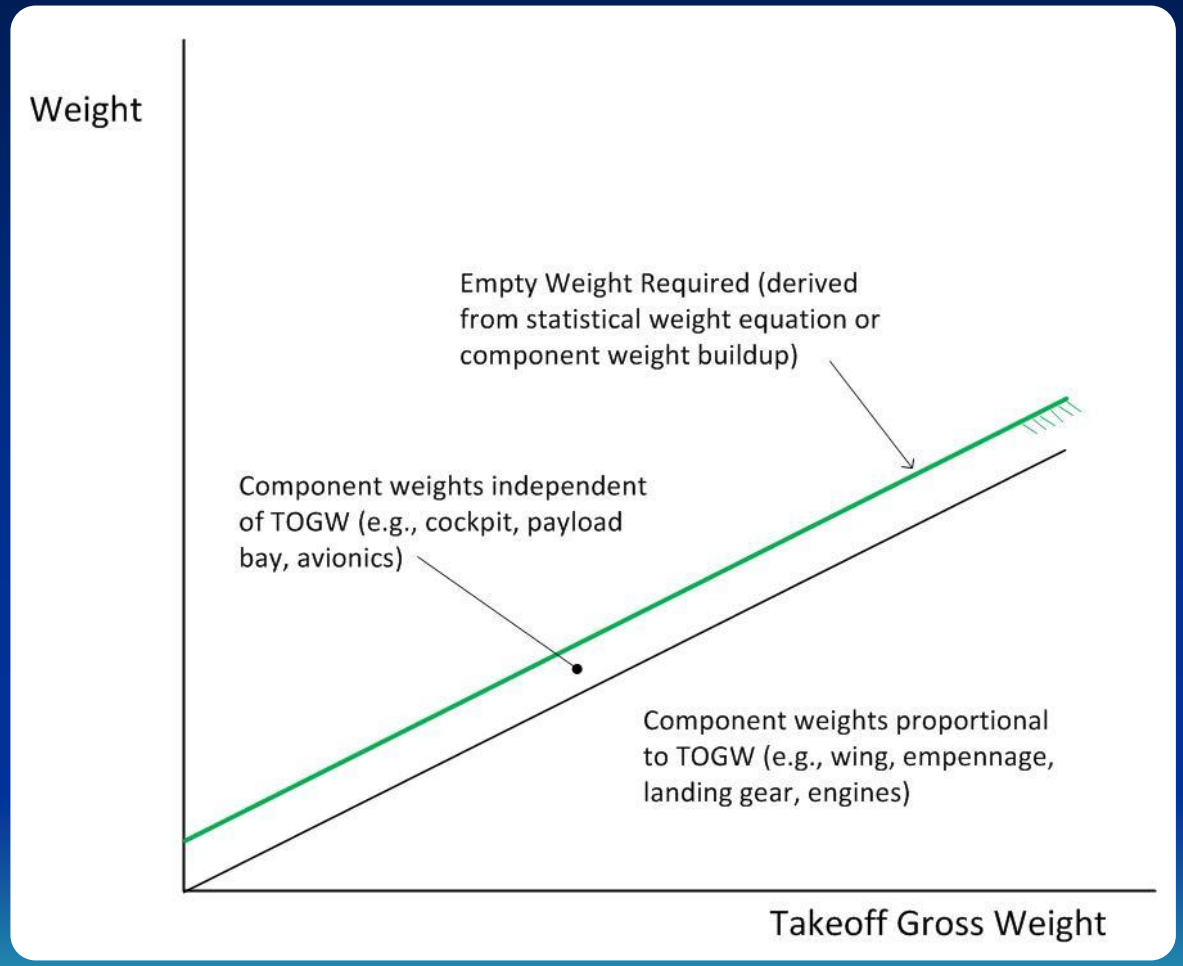
Empty Weight Available

- Empty weight available as a function of assumed TOGW
  - For military mission



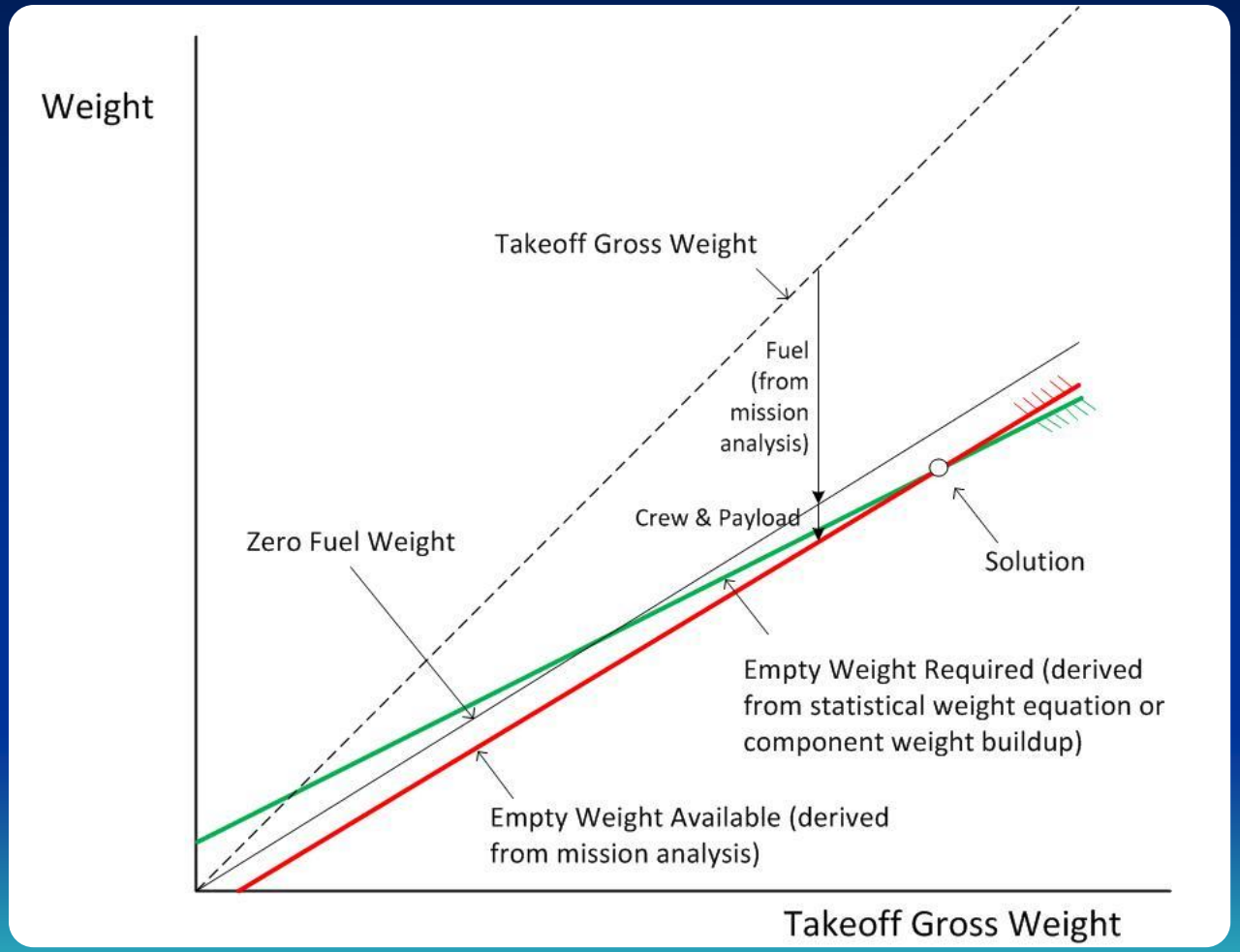
Empty Weight Required

- Empty weight required based on statistical weight relationship (or component weight buildup)
  - Shown here as linear, but not exactly linear in practice



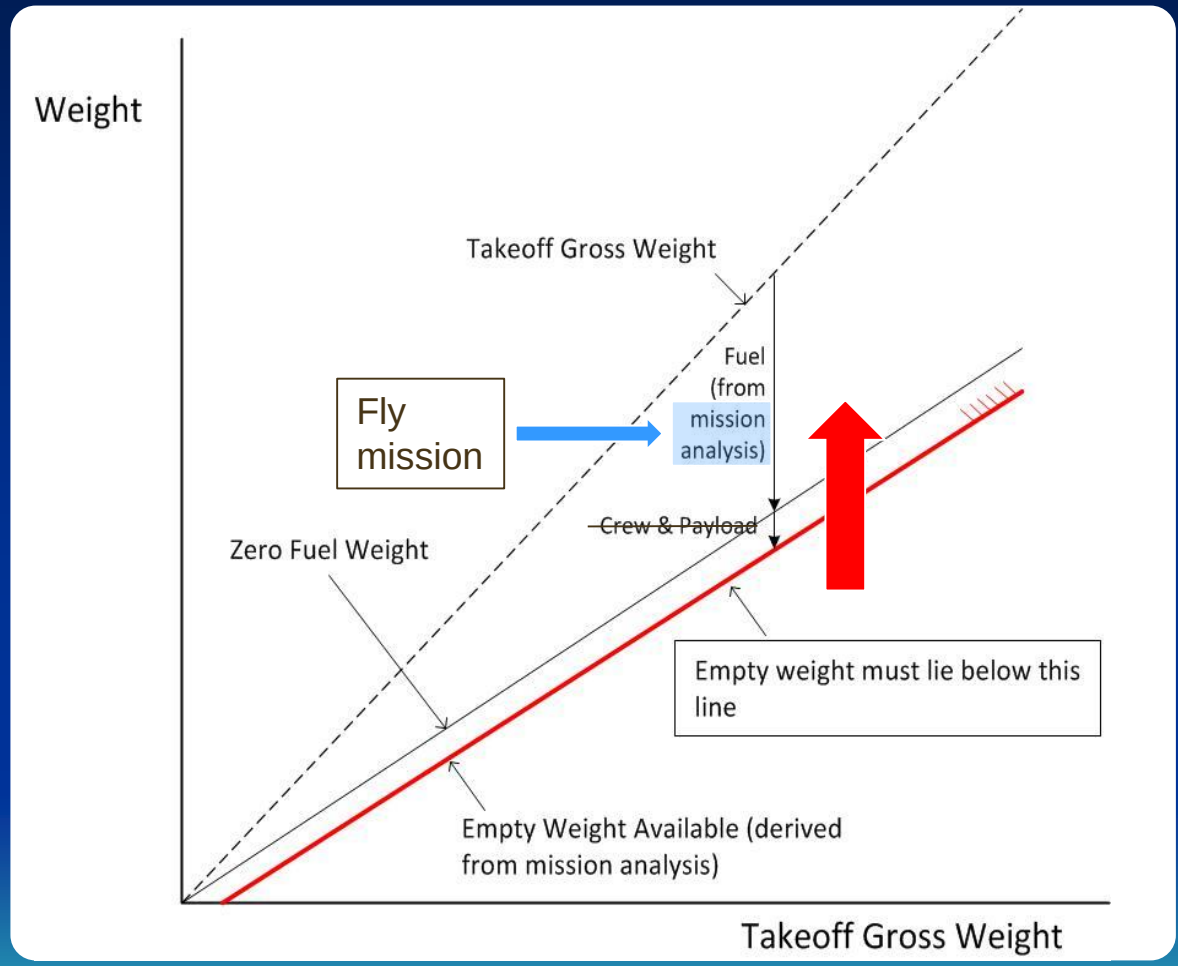
Empty Weight Solution

- Minimum empty weight is at intersection of empty weight available and required



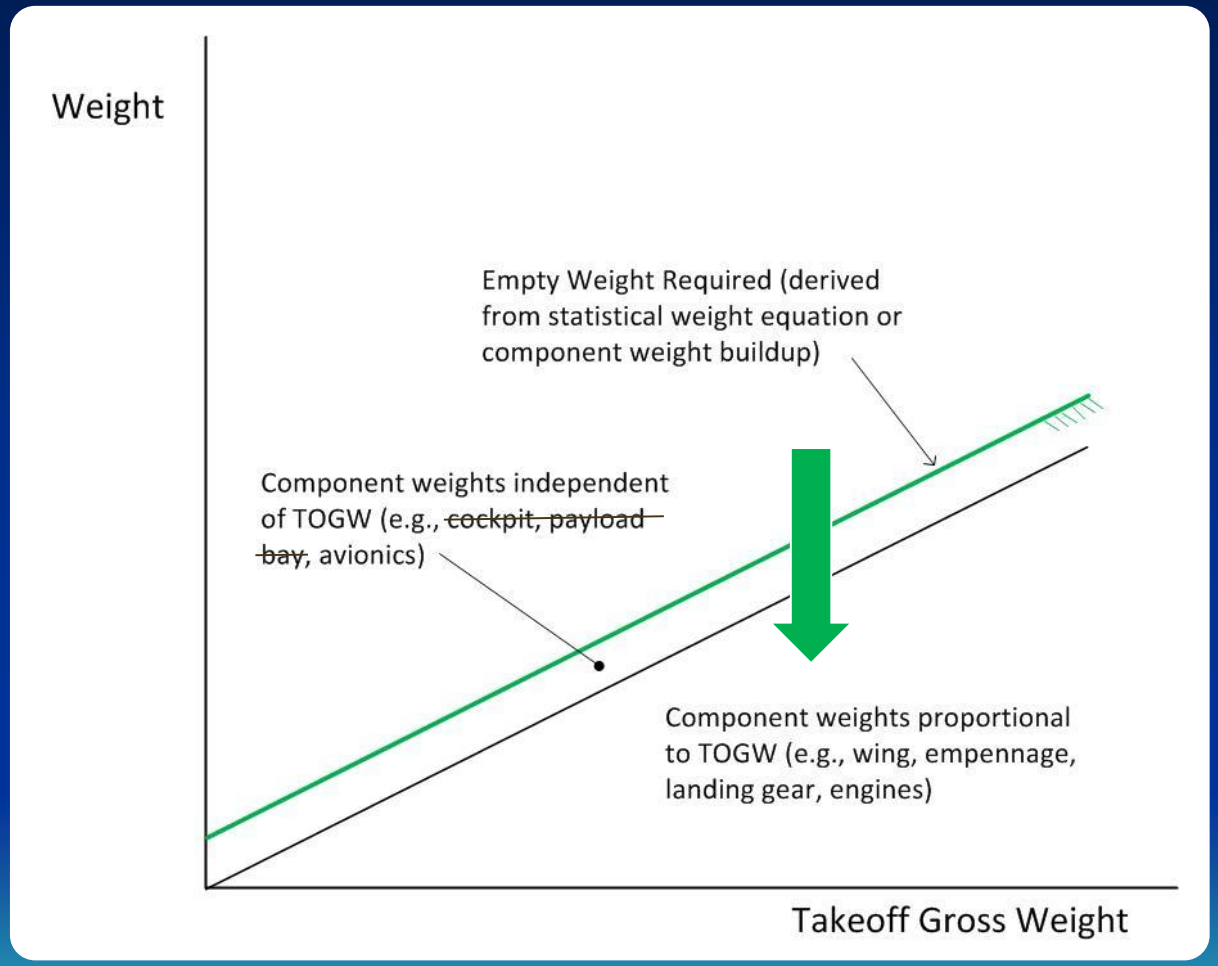
Empty Weight Available

- Minimum weight for unrefueled unmanned flight across Atlantic with no payload?
- Remove crew and payload
- Fixed weights include comm/nav systems



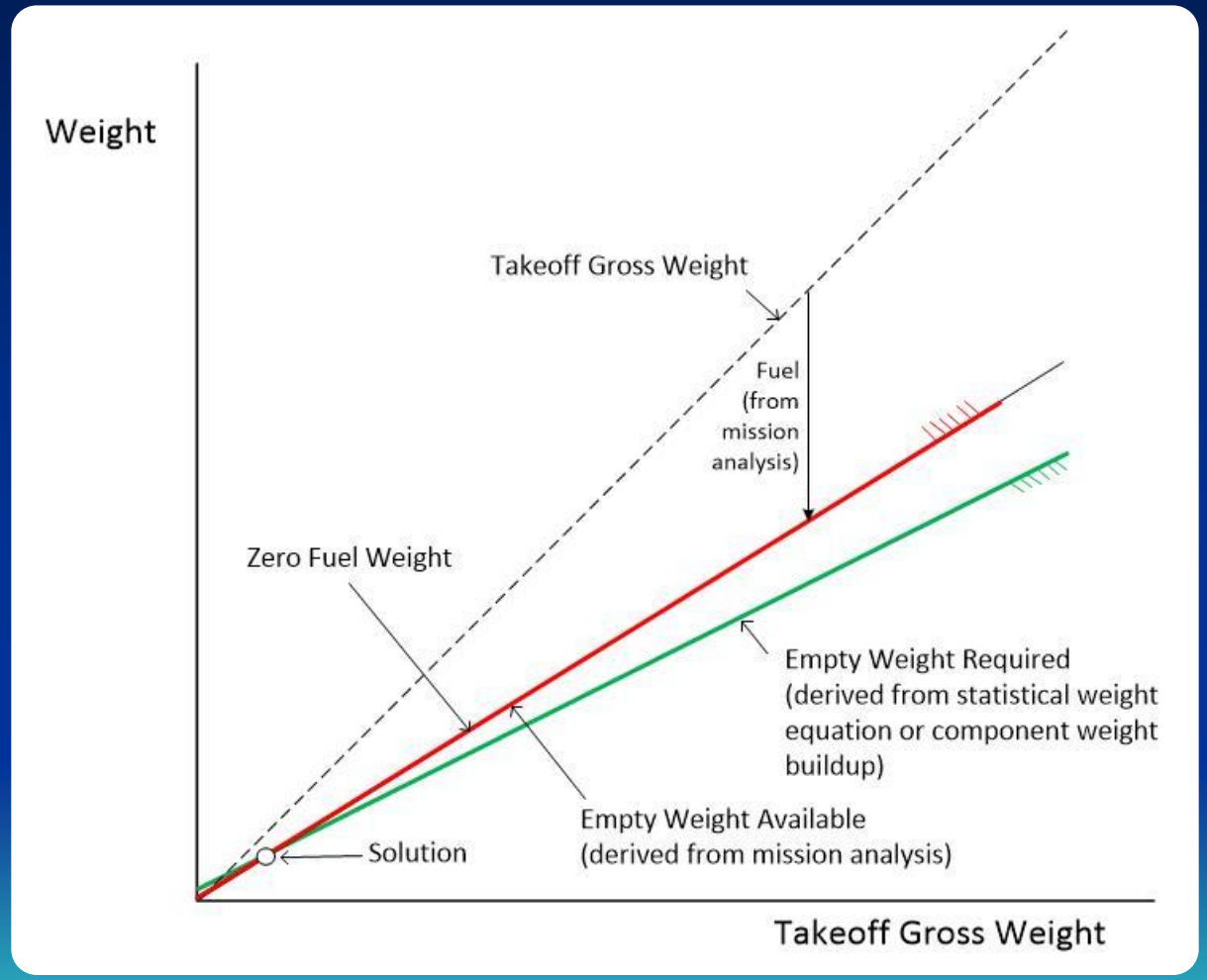
Empty Weight Required

- Remove cockpit and payload bay



Sensitivity to Payload and Crew Weight

- Elimination of crew and payload reduces TOGW significantly



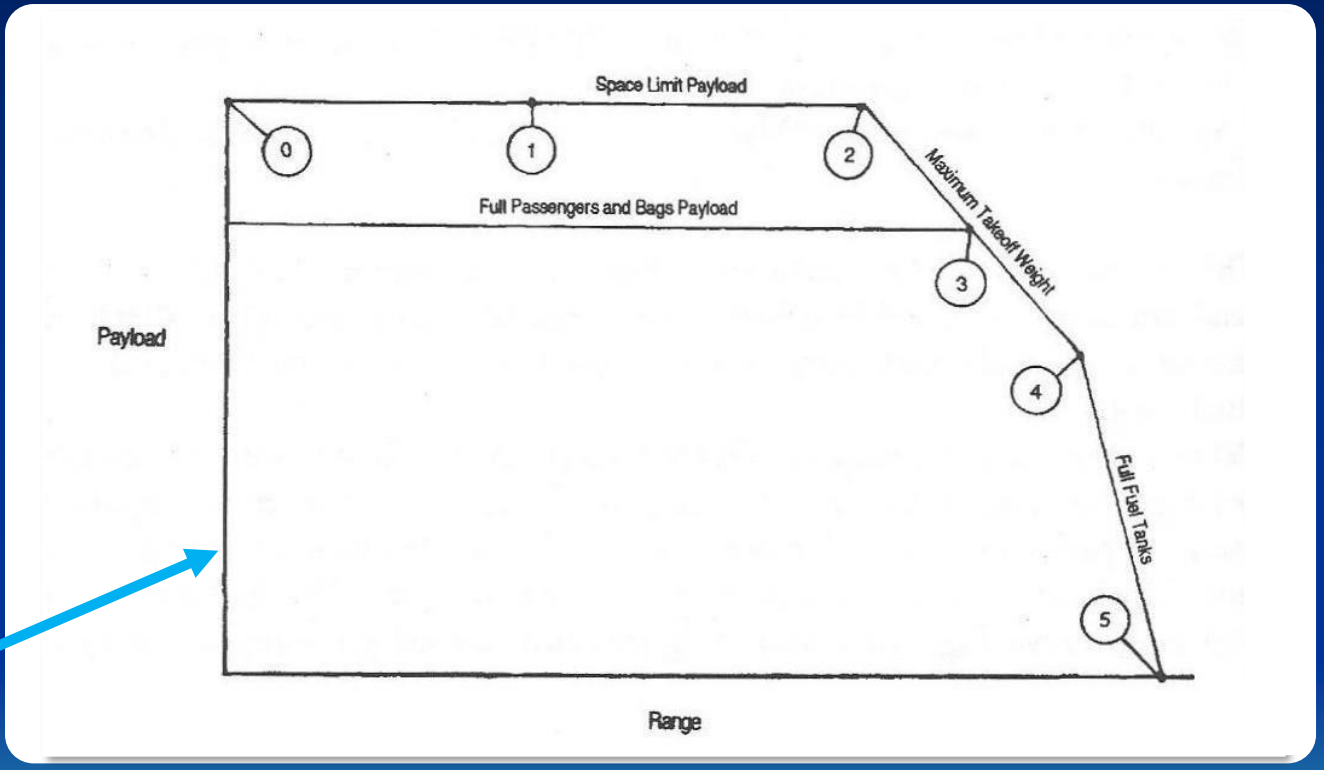
Model Airplane Flies Across Atlantic

- TAM-5
- August, 2003
- Flew from Canada to Ireland: 1,641 nmi (3038 km)
- TOGW = 11 lb (5 kg), dry weight = 6 lb (2.7 kg)
- Nav/comm system included GPS, autopilot, remote manual control

Source: www.barnardmicrosystems.com

Mission Sizing Program

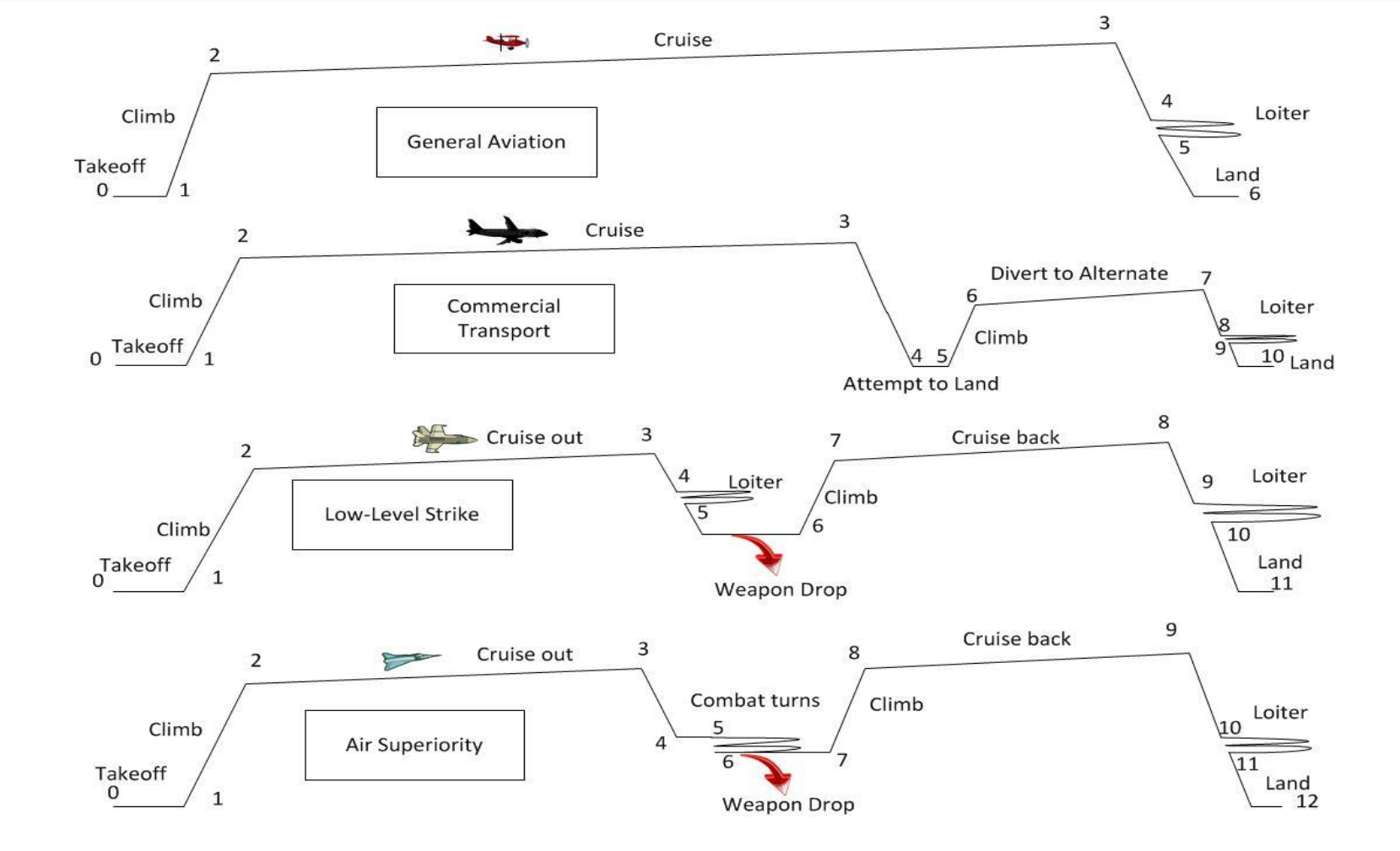
- Excel spreadsheet for mission sizing
  - Solver for convergence of TOGW
  - Statistical weight equations for empty weight required
    - Adjust for group weight reduction factors
  - Modify spreadsheet for other points on payload-range plot



Source: Schaufele

Commercial aircraft payload-range plot

Empty Weight Available – Define Mission



Segment Fuel Fractions – Simple Example

Mission segment	W_i / W_{i-1}
Warmup and takeoff	0.970
Climb	0.985
Cruise	Use Breguet range equation
Loiter	Use endurance equation
Descent	1
Landing	0.995

Source: Raymer

Raymer assumes 6% allowance for reserves and trapped (unusable) fuel

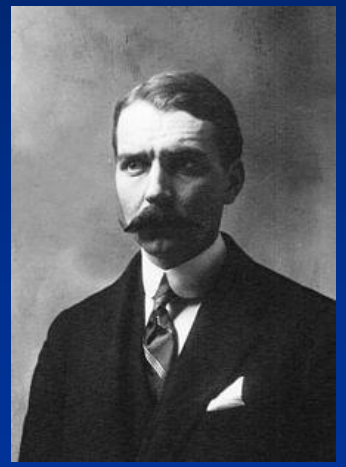
then total fuel for mission W_f is

$$W_f = 1.06\left(W_0 - W_x\right)$$

where W_x is aircraft weight at end of mission (assuming no payload drops)

For bizjets or commercial aircraft operations, use reserves defined by NBAA or FAR Part 121

Breguet Range Equation Design Drivers



Louis Charles Breguet

For given speed of sound, a, and initial weight, $W_{initial}$

$$R = \frac{a}{C}\left[M\left(\frac{L}{D}\right)\right]\ln\left(\frac{W_{initial}}{W_{final}}\right)$$

Propulsion

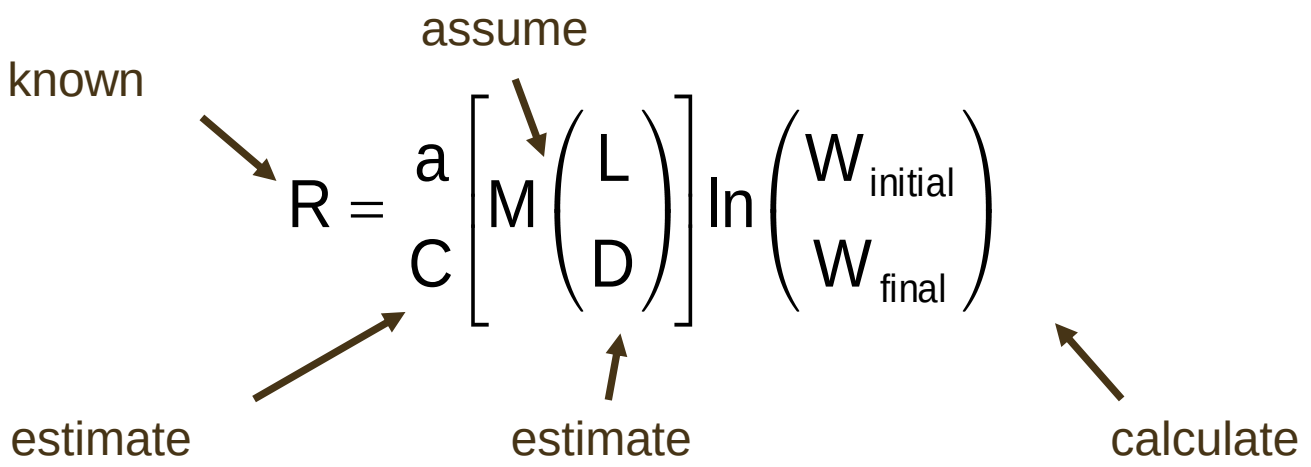
Aerodynamics

Structures and Materials

Source: Musée de lAir

Breguet Range Equation Design Drivers

For given speed of sound, a, and initial weight, $W_{initial}$



Source: Musée de lAir

Endurance Equation

Endurance equation is

$$E = \left(\frac{L}{D}\right)\left(\frac{1}{C}\right)\ln\left(\frac{W_{i-1}}{W_i}\right)$$

where

$E =$ endurance or loiter time $[\text{hours}]$

This may be rearranged to the form

$$\frac{\text{Weight at end of segment}}{\text{Weight at start of segment}} = \frac{W_i}{W_{i-1}} = e^{-\frac{EC}{\frac{L}{D}}}$$

Trends in Lift/Drag Ratio

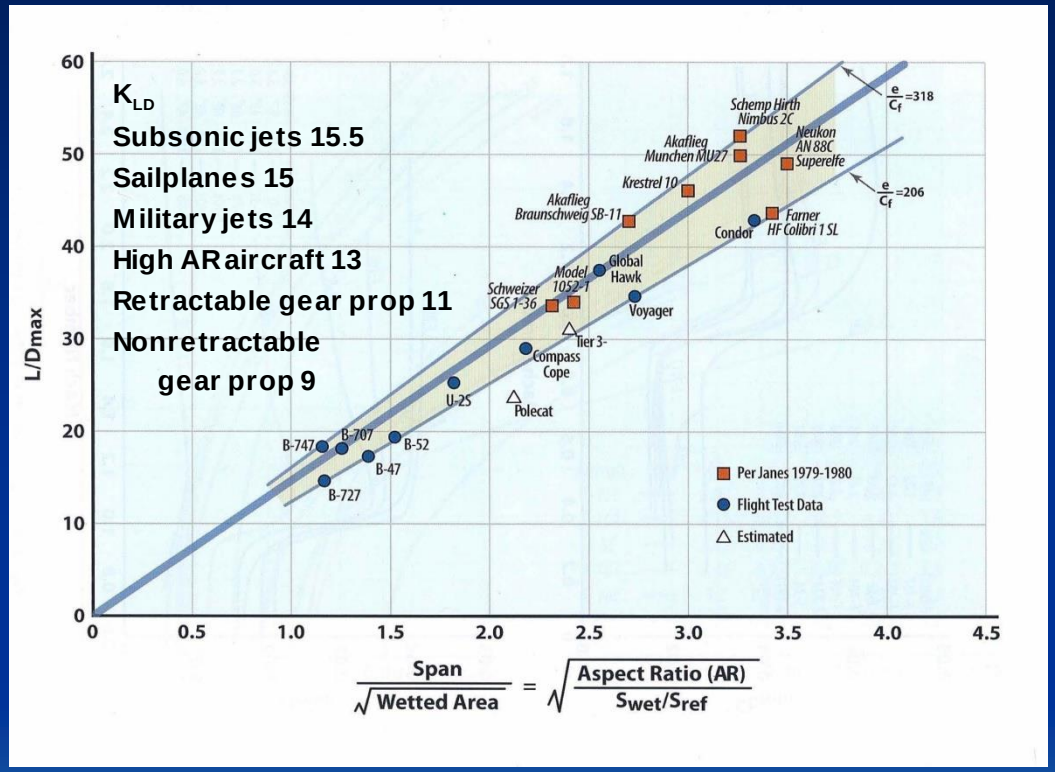
Can also write as

$$\left(\frac{L}{D}\right)_{max} = K_{LD}\frac{b}{\sqrt{S_{wet}}}$$

For a high – subsonic cruise aircraft, optimum L/D values are

$$\left(\frac{L}{D}\right)_{cruise} \approx 0.87\left(\frac{L}{D}\right)_{max}$$

$$\left(\frac{L}{D}\right)_{loiter} = \left(\frac{L}{D}\right)_{max}$$



Source: Nicolai

Cruise and Loiter L/D

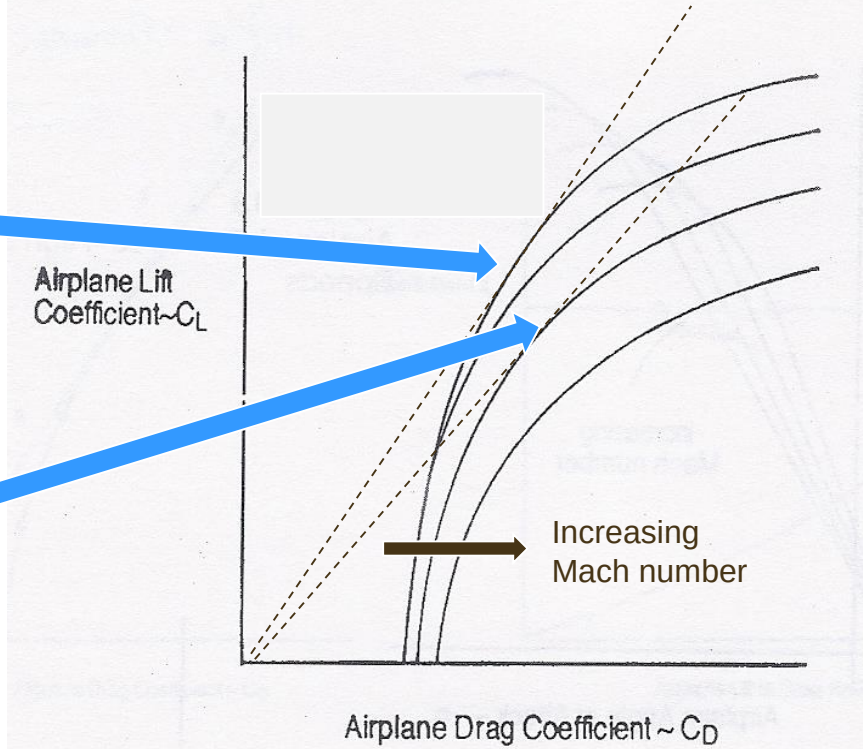
Loiter:
To maximize endurance,

fly at at condition to maximize $\left(\frac{L}{D}\right)_{incomp}$

Cruise:
To maximize range,

fly at condition to maximize $\left(V\frac{L}{D}\right)$

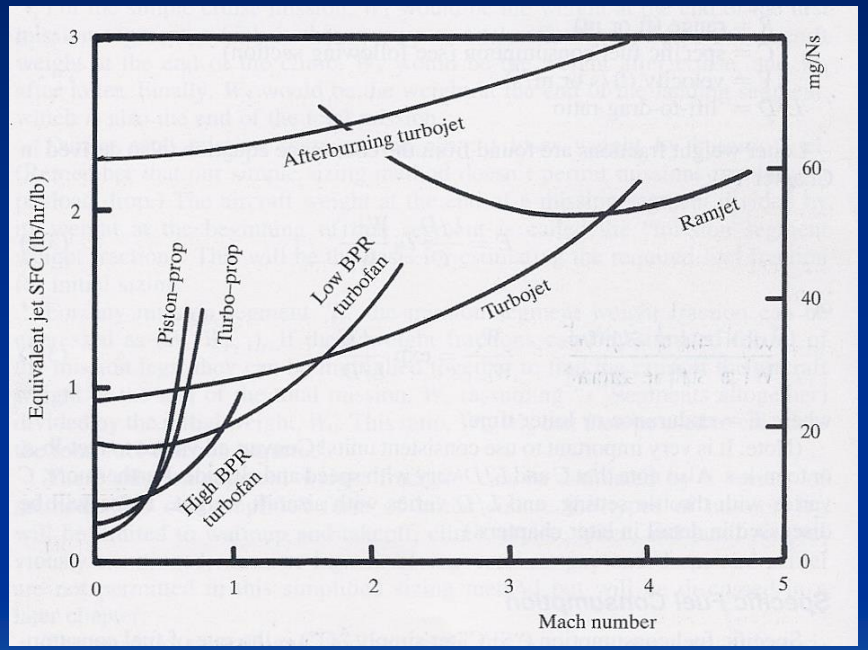
This occurs when $\frac{L}{D} \approx 0.87\left(\frac{L}{D}\right)_{max\ incomp}$



Source: Schaufele

SFC for Cruise and Loiter

Use this chart for trends in cruise SFC



Source: Raymer

Use these values for loiter sfc

Jet engine cycle	Loiter sfc
Pure turbojet	1.0
Low-bypass turbofan	0.9
High-bypass turbofan	0.55

You now have enough information to calculate first estimate of TOGW

Problem

- Weights database based on existing aircraft
- Can’t do better than aluminum-based structure
- Raymer suggests weight reduction factors for structural components
- Must allocate weight reductions over empty weight

Application of Advanced Technologies

Configuration	(L/D)max	Cruise sfc	Structural weight reduction factor	OEW	TOGW
Baseline	18.0	0.50	1.0	???	???
L/D improvement	**19.8**	0.50	1.0	???	???
SFC improvement	18.0	**0.45**	1.0	???	???
Structural weight reduction	18.0	0.50	**0.9**	???	???
All technologies applied	**19.8**	**0.45**	**0.9**	???	???

Notional values shown

Or: e.g. assume 10% increase in M_{DIV}

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

First Estimate of Takeoff Gross Weight (TOGW)

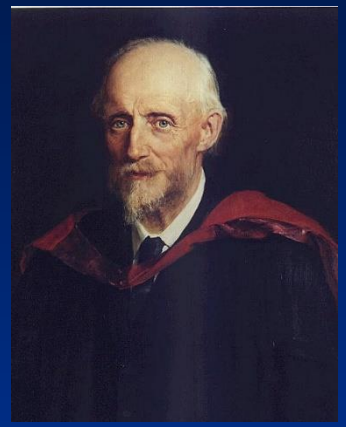
The End

Chapter 4
Airfoil and Wing/Tail Geometry Selection

This Section

- Non-dimensional aerodynamic force and moment coefficients
- Wing section and planform
- Spanwise wing loading
- Winglets
- Wing location
- Tail location
- Initial tail sizing

Force Ratios in Aerodynamics



By John Collier - Copied from johnbyrne.fireflyinternet.co.uk. Cropped photo of a painting of Osborne Reynolds painted in 1904 by John Collier., Public Domain, https://commons.wikimedia.org/w/index.php?curid=5827209

Reynolds Number:

$$R_e \left(\text{or} R_N \right) = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \left(\frac{\rho}{\mu} \right) V l = \frac{V l}{\nu}$$

where

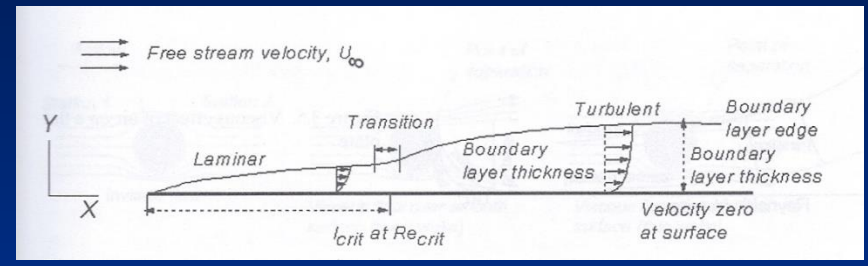
$\rho = \text{air density}$

$\mu = \text{absolute} \left(\text{or dynamic} \right) \text{viscosity}$

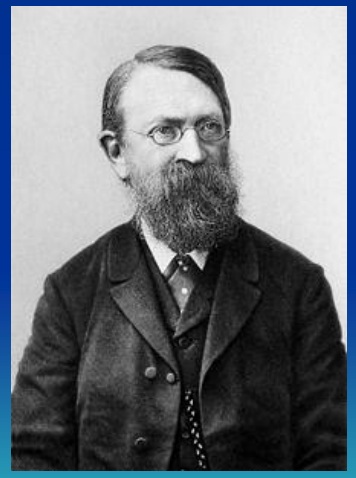
$\nu = \text{kinematic viscosity}$

$V = \text{free stream velocity}$

$l = \text{representative length}$



Source: Kundu



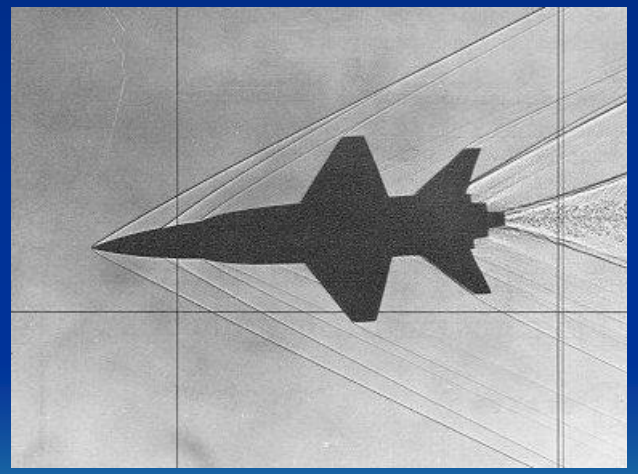
https://en.wikipedia.org/wiki/Ernst_Mach#/media/File:Ernst_Mach_01.jpg

Mach Number:

$$M = \frac{\text{Inertia Forces}}{\text{Elastic Forces}} = \frac{V}{a}$$

where

$a = \text{ambient speed of sound in air}$



Source: www.centenialloffflight.gov

Aerodynamic Forces and Moments in Plane of Symmetry

Lift Coefficient $C_L = \dfrac{L}{\left(\frac{1}{2}\right)\rho V^2 S}$

Drag Coefficient $C_D = \dfrac{D}{\left(\frac{1}{2}\right)\rho V^2 S}$

Pitching Moment Coefficient $C_M = \dfrac{M}{\left(\frac{1}{2}\right)\rho V^2 c\, S}$

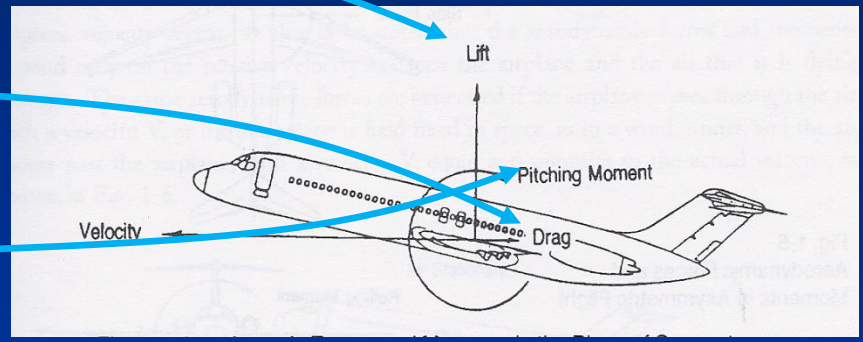
where

ρ = local air density

V = true airspeed

c = mean aerodynamic chord

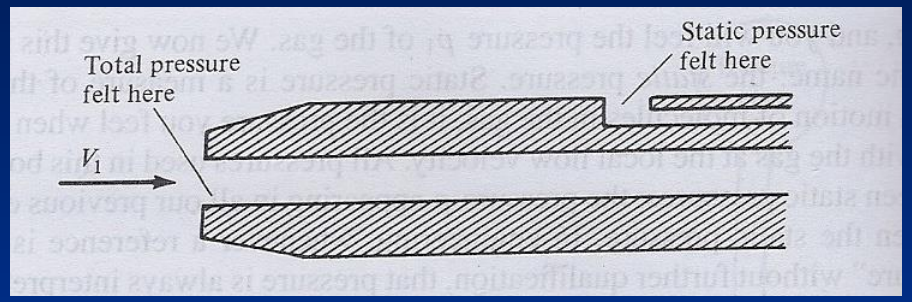
S = reference wing area



Source: Schaufele

By definition, lift is perpendicular to velocity vector and drag is along velocity vector. Pitching moment is positive nose-up.

Dynamic Pressure



Source: Anderson

Aerodynamic pressures are related by

$p_t = p_s + q$

where

p_t = total pressure

p_s = static pressure

q = dynamic pressure: measure of the air pressure due to motion of the aircraft through the air

We can write

$$C_L = \frac{L}{q\,S}$$

$$C_D = \frac{D}{q\,S}$$

$$C_M = \frac{M}{q\,c\,S}$$

where

$$\text{dynamic pressure } q = \left(\frac{1}{2}\right)\rho V^2$$

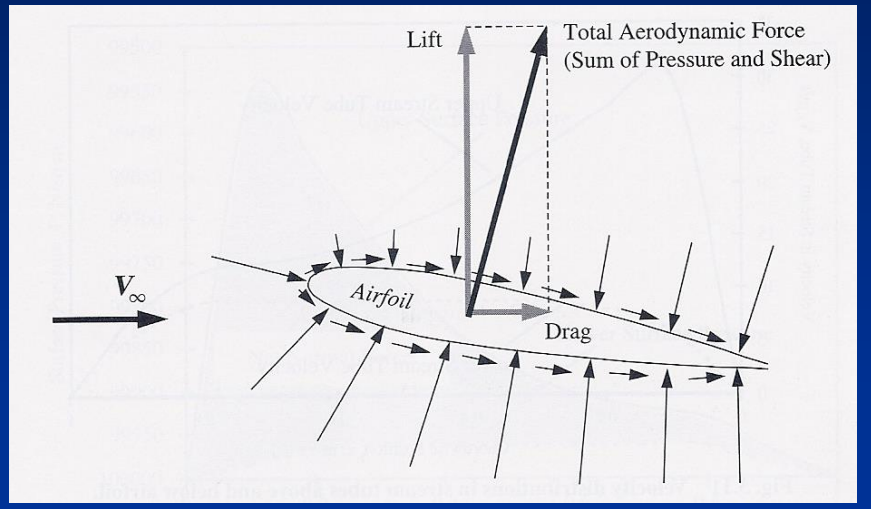
Forces and Moments on a 2-D Airfoil

On a two-dimensional section, forces and moments per unit width

$$C_l = \frac{L}{\left(\frac{1}{2}\right)\rho V^2 c}$$

$$C_d = \frac{D}{\left(\frac{1}{2}\right)\rho V^2 c}$$

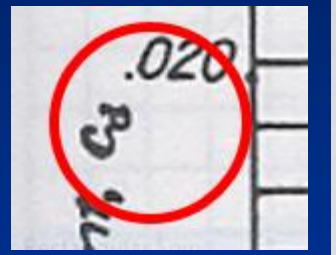
$$C_m = \frac{M}{\left(\frac{1}{2}\right)\rho V^2 c^2}$$

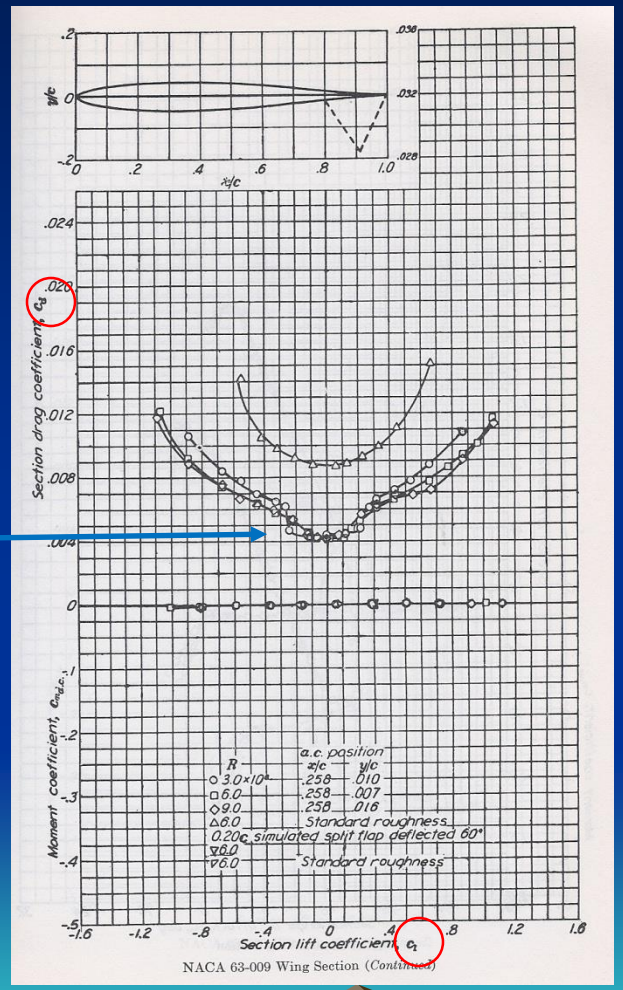


Source: Schaufele

Example of Forces on a 2-D Airfoil

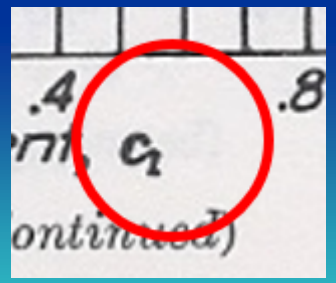
- Drag is due to shear and pressure forces only
- No induced drag
- Note drag bucket near α = +/-2^0





NACA 63-009 Wing Section (Continued)

Source: Abbott & Von Doenhoff



Lateral-Directional Forces and Moments

$$\text{Yawing moment } C_n = \frac{N}{qbS}$$

where

N = yawing moment

b = wingspan

$$\text{Side force coefficient } C_y = \frac{Y}{qS}$$

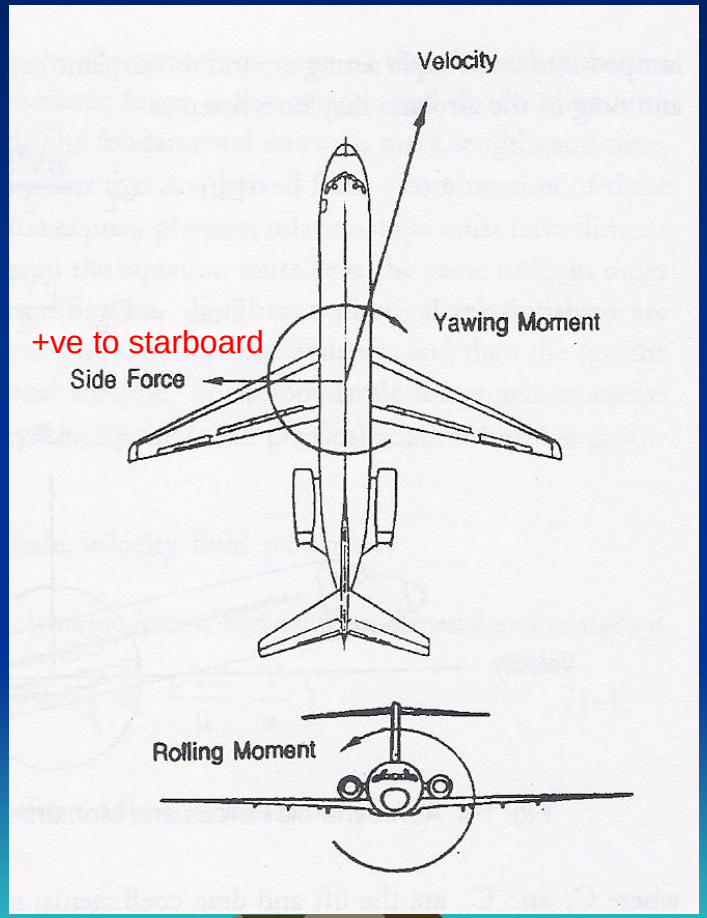
where

Y = side force $(+\text{ ve to starboard})$

$$\text{Rolling moment coefficient } C_l = \frac{L}{qbS}$$

where

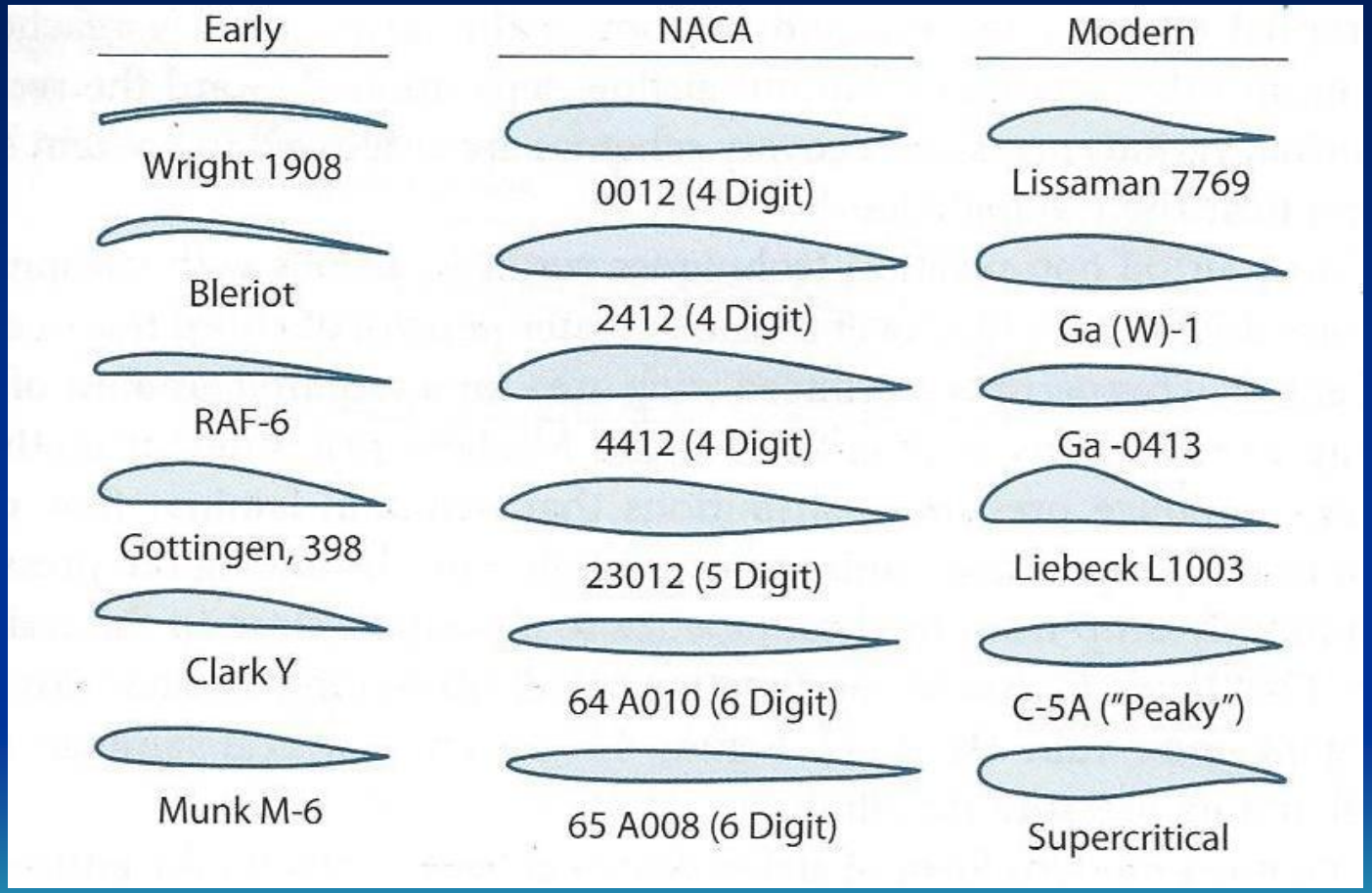
L = rolling moment (NOT lift force)



Source: Schaufele

Section 4.3
Wing Geometry

Airfoil Sections – Infinite Choice

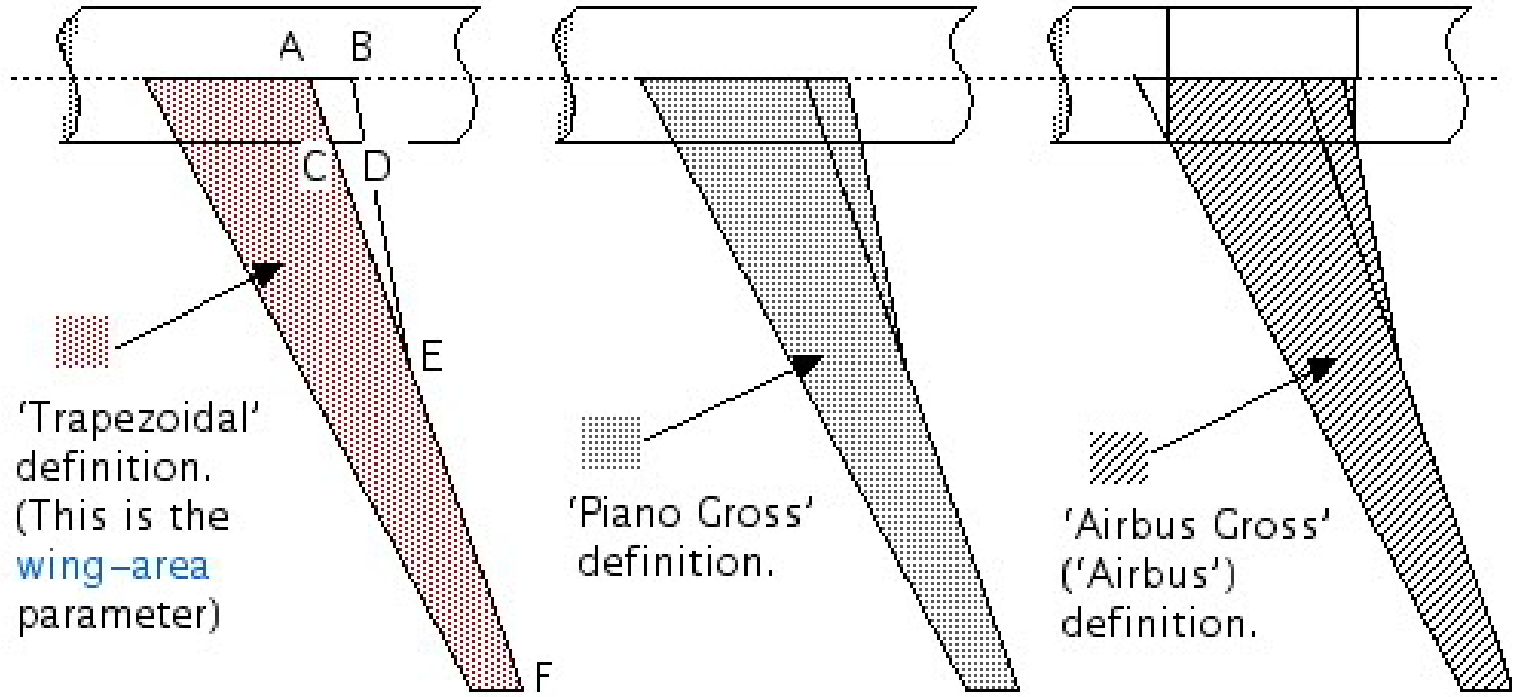


Source:Raymer

Mostly proprietary

Wing Reference Area Definitions

Wing Area definitions.

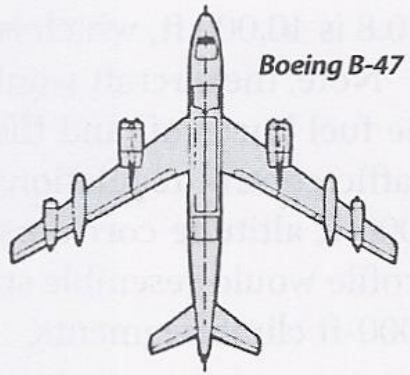


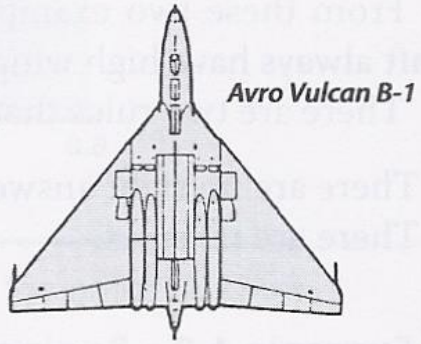
'Wimpress' definition = trapezoidal wing–area + area CDE + (area ABDC * CE/CF).

Source: http://www.lissys.demon.co.uk/

Comparison between B-47 and Avro Vulcan Aerodynamic Characteristics

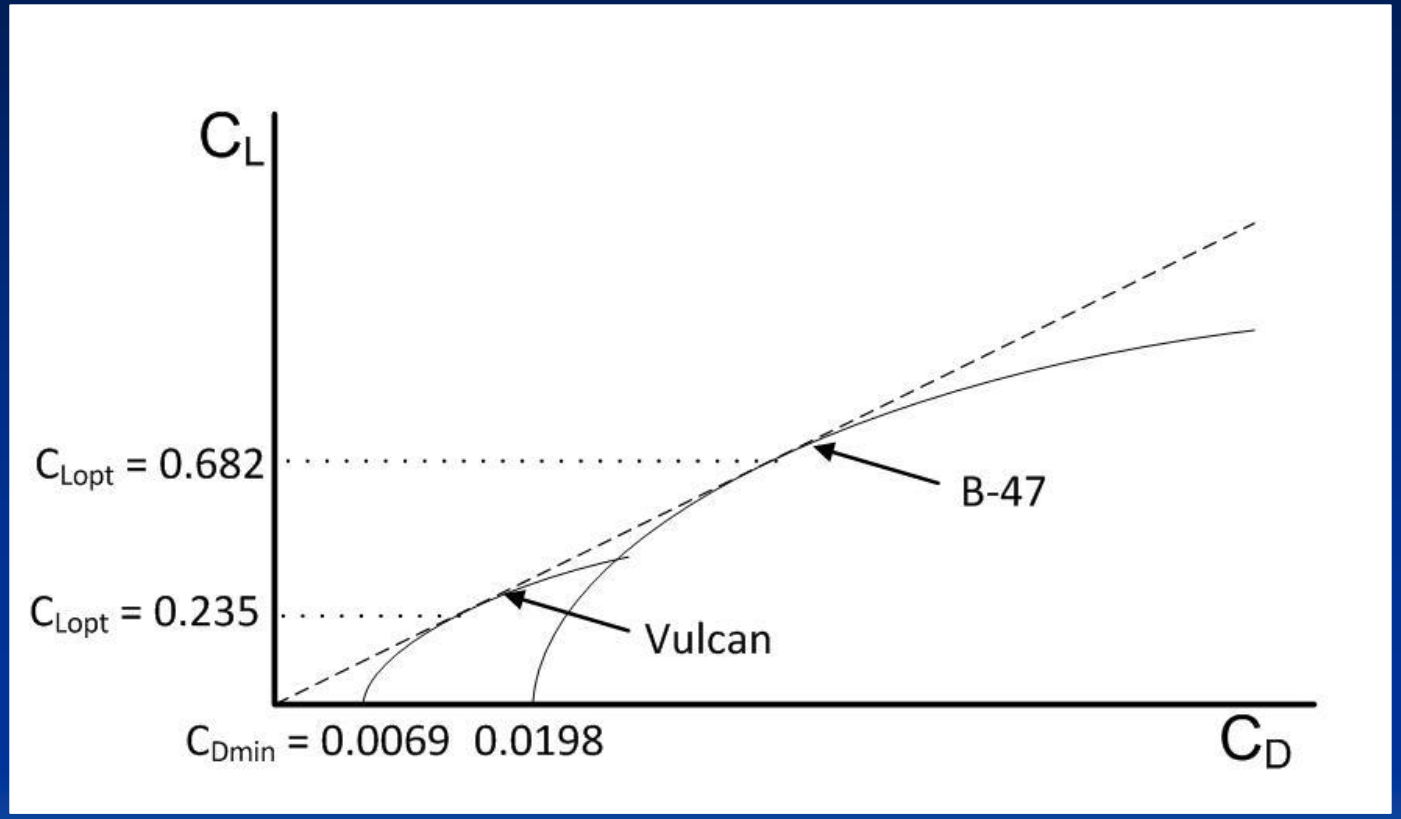
	Boeing B-47	Avro Vulcan
Wing Area (ft^2)	1430	3446
Total Wetted Area (ft^2)	11,300	9,500
Span (ft)	116	99
Wing Loading (lb/ft^2)	140	43
Span Loading (lb/ft)	1750	1520
Aspect Ratio	9.43	2.84
$C_{D_{min}}$	0.0198	0.0069
$K = 1/(\pi AR e)$	0.0425	0.125
Value of e	0.8	0.9
Max L/D	17.25	17.0
$C_{L_{opt}}$	0.682	0.235
Max Cruise C_L	0.48	0.167
$C_{D_{min}} S_{ref}$	28.3	23.8
Wetted Area / S_{ref}	7.9	2.8





Source: Raymer

B-47 and Avro Vulcan Drag Polar Comparison



Speeds:

- Vulcan M_{cruise} = 0.947 M_{max} = 0.977
- B-47 M_{combat} = 0.847 M_{max} = 0.910

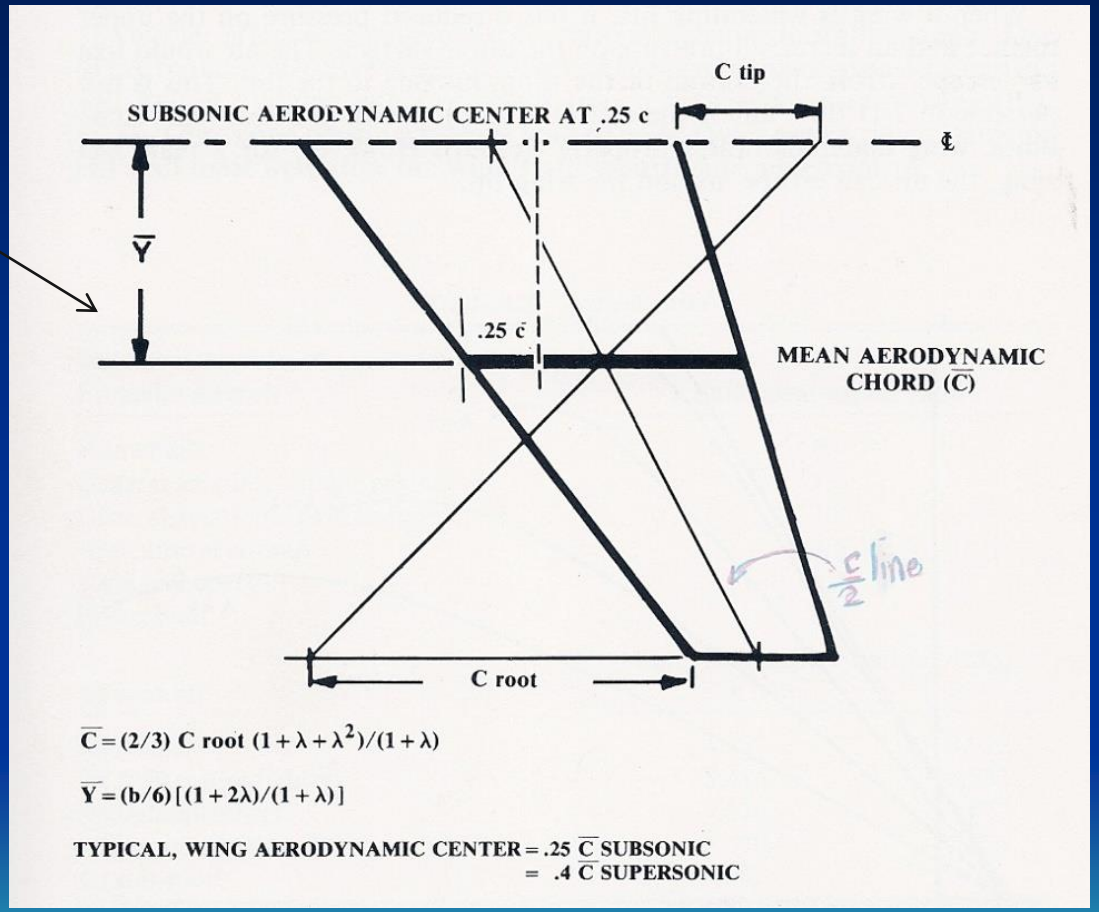
Mean Aerodynamic Chord

Two ways to determine MAC

1. Graphical
2. Algebraic

$$c = \begin{pmatrix} 2 \\ 3 \end{pmatrix} c_{root} \frac{1 + \lambda + \lambda^2}{1 + \lambda}$$

$$y = \begin{pmatrix} b \\ 6 \end{pmatrix} \frac{1 + 2\lambda}{1 + \lambda}$$



Source: Raymer

Planform with Minimum Induced Drag

Elliptical planform has minimum induced drag at all values of C_L

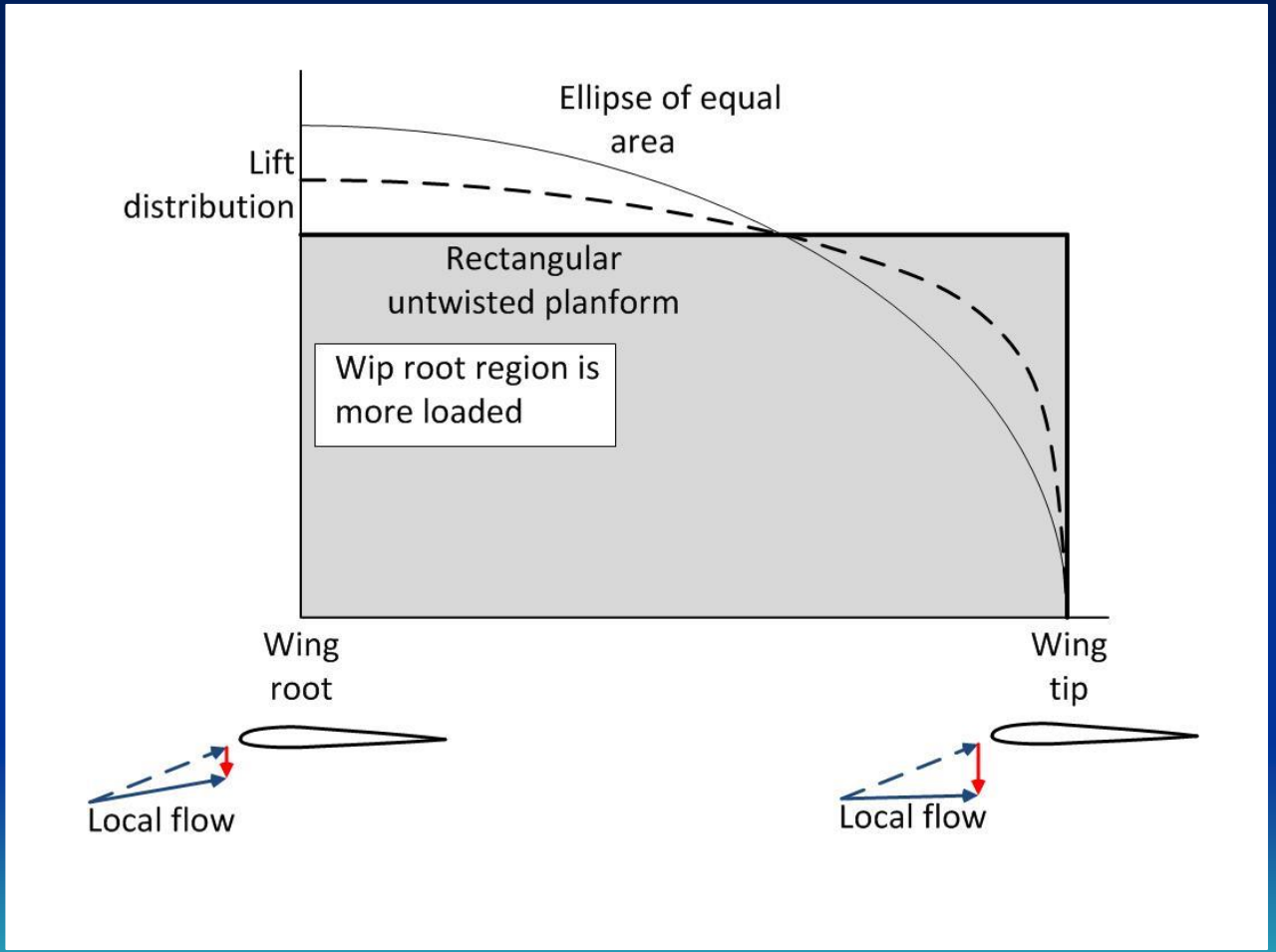
Trends in Wing Aspect Ratio and Taper Ratio

Aircraft Type	Aspect Ratio (AR)	Taper Ratio (λ)
Personal/Utility	5.0 – 8.0	0.6 – 1.0
Commuter Airliner	9.0 – 12.0	0.5 – 1.0
Regional Turboprop	11.0 – 12.8	0.4 – 0.6
Business Jet	5.0 – 8.8	0.4 – 0.6
Jet Transport	7.0 – 9.5	0.2 – 0.4
Military Fighter/Attack	2.4 – 5.0	0.2 – 0.5

Source: Schaufele

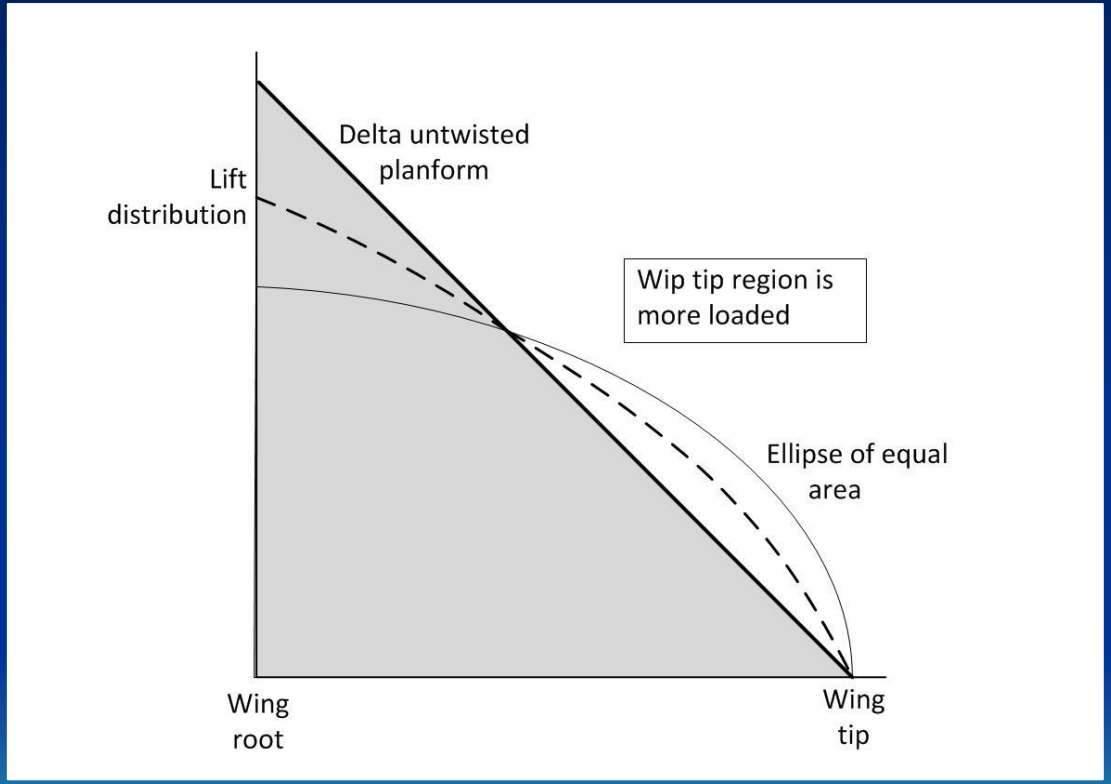
Schrenk's Approximation for Rectangular Planform

- Wing section aerodynamic load = (lift per unit span)/chord
- For an unswept, untwisted wing, lift distribution is represented by line midway between planform chord distribution and ellipse of equal area

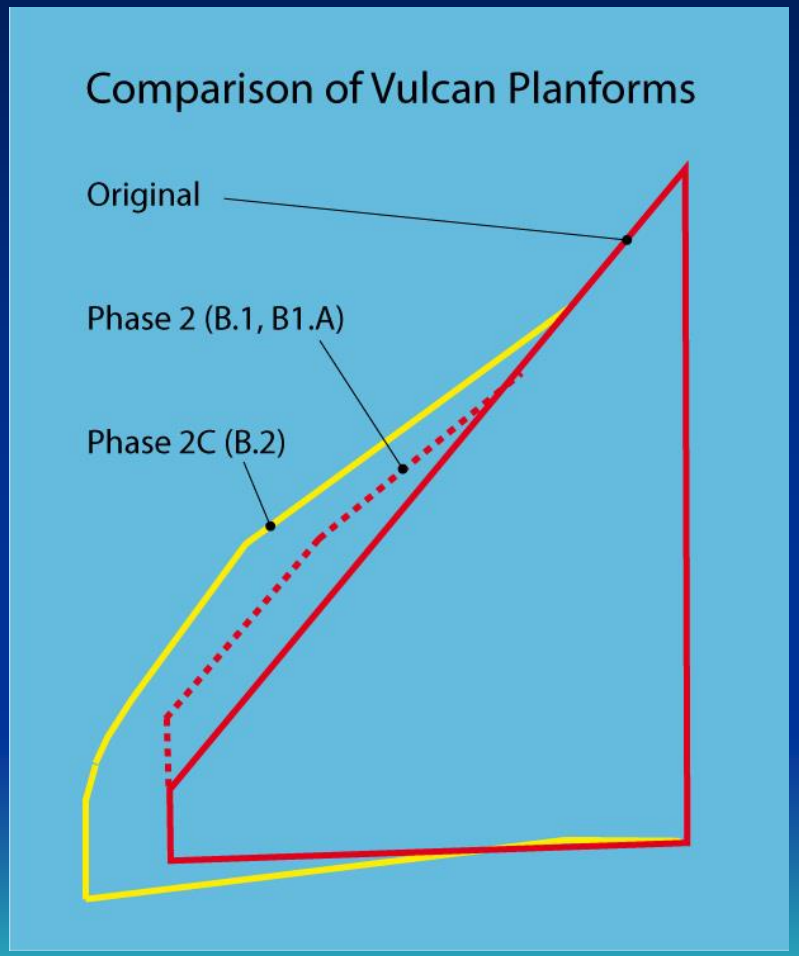


Schrenk's Rule for Delta Planform

- Likelihood of asymmetric stall
- Increased transonic drag



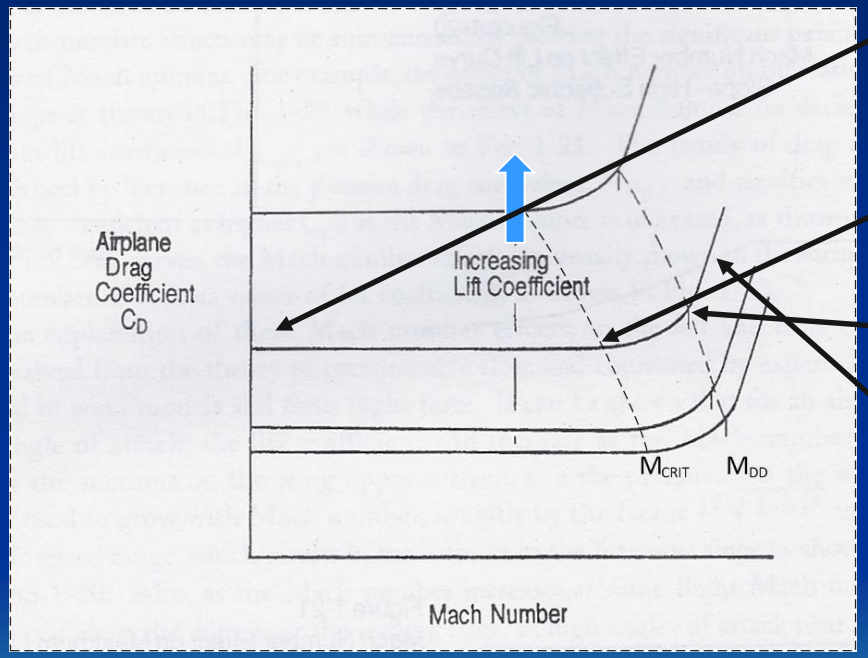
Development of Avro Vulcan Planform



Source (all images): commons.wikipedia.org

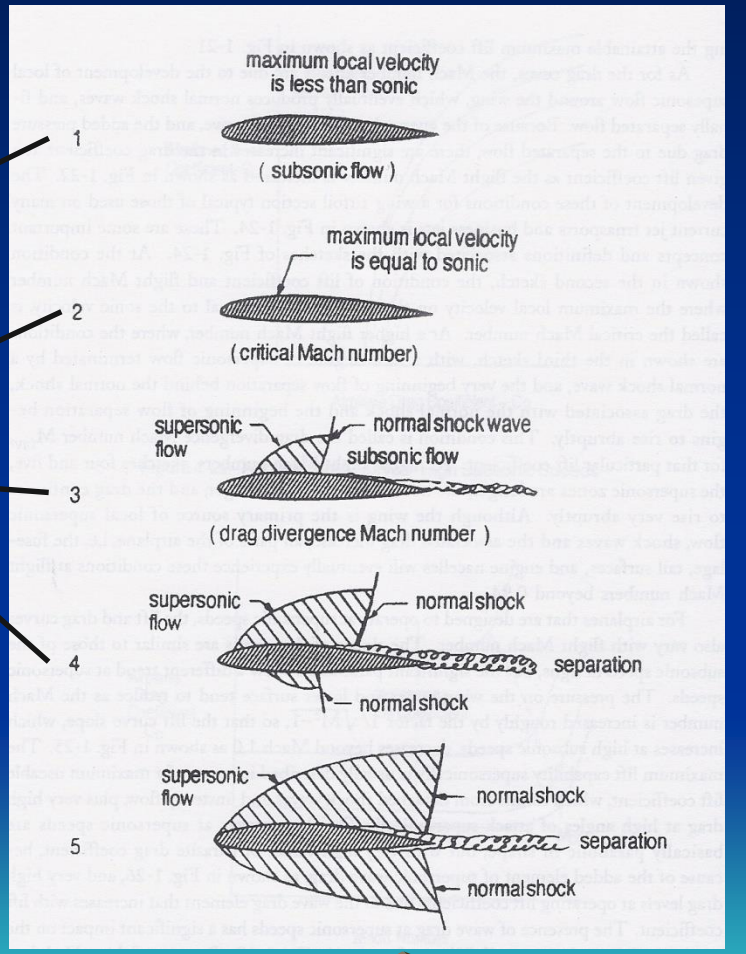
Flow Over Wing At Increasing Mach Number

M_{CRIT} and M_{DD} are a function of C_L (shown here), Λ and t/c



Source: Schaufele (modified)

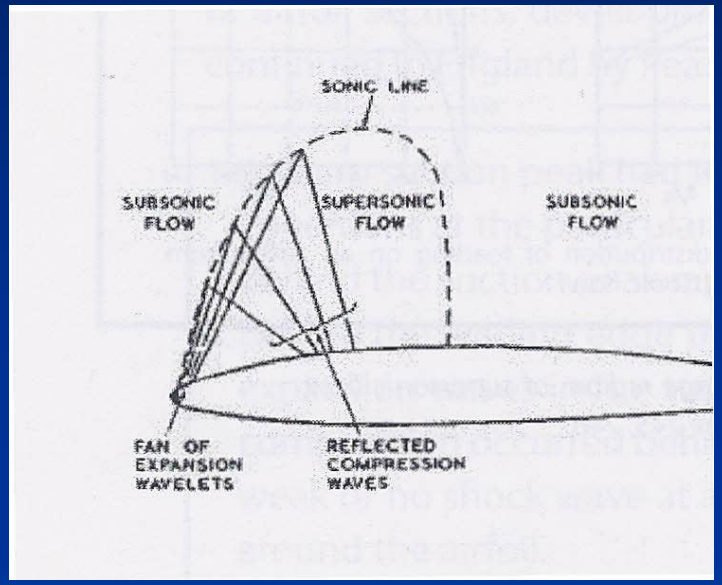
Note: this is not a supercritical airfoil section



Source: Schaufele

Flow within Supersonic Region

- System of expansion and compression waves exist within supersonic flow region



Source: Obert

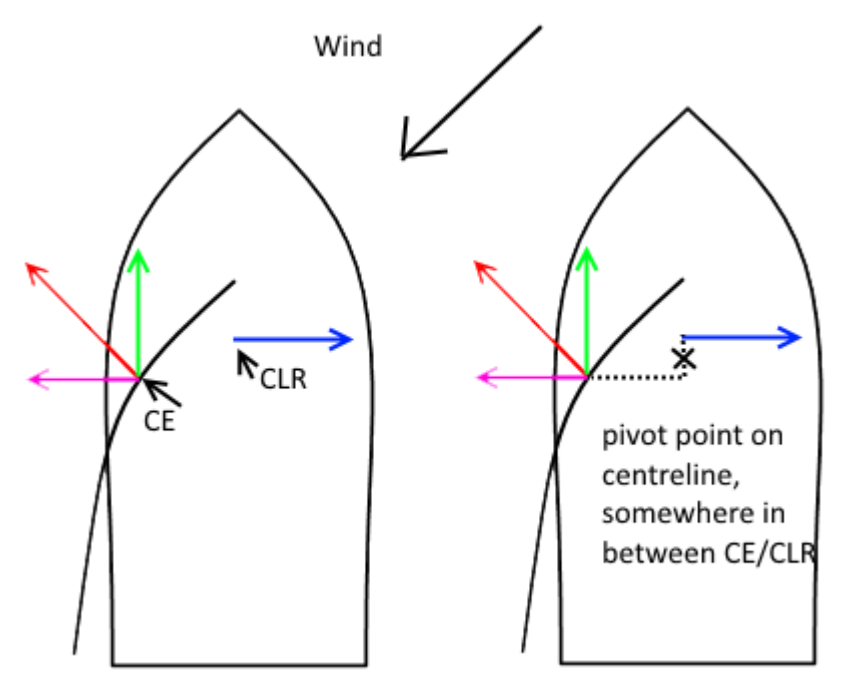
Source: Schaufele

Winglet Design

Source: Aviation Week advertisement

- Take advantage of crossflows near wingtips due to tip vortices

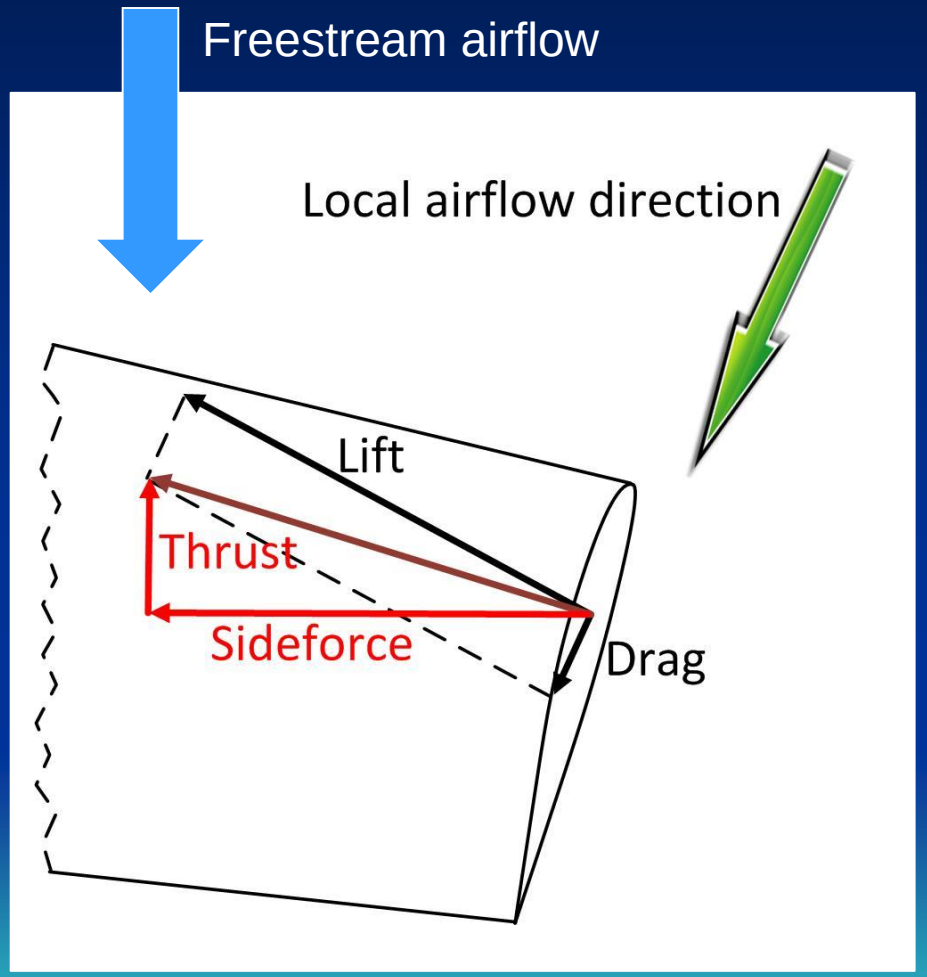
Winglet Action



- Similar to that of sailing boat sailing into the wind.

Plan View of Winglet

- Exaggerated inflow angle on upper surface
- Inflow angle is a function of wing C_L
- If winglet incidence is incorrect, then thrust may become drag



Winglet Installation on Existing Wing Design

- Smooth transition to minimize mutual interference
- Installation of B.757 winglet for UAL shown

Winglet Installation on 737 MAX

Source: www.boeing.com

- Integrated wingtip/winglet design can use smaller radius fillet

High Wing

- Advantages
  - Continuous wing upper surface (high L/D)
  - Clean propeller nacelle
  - Short airstairs
  - Easy baggage loading

High Wing

- Disadvantages
  - For jets, MLG on fuselage (more drag, narrow track)
  - For jets, landing wing inertia loads carried through wing root
  - Main spar passes through cabin
  - Pax view impaired

Source: John Wright

Low Wing

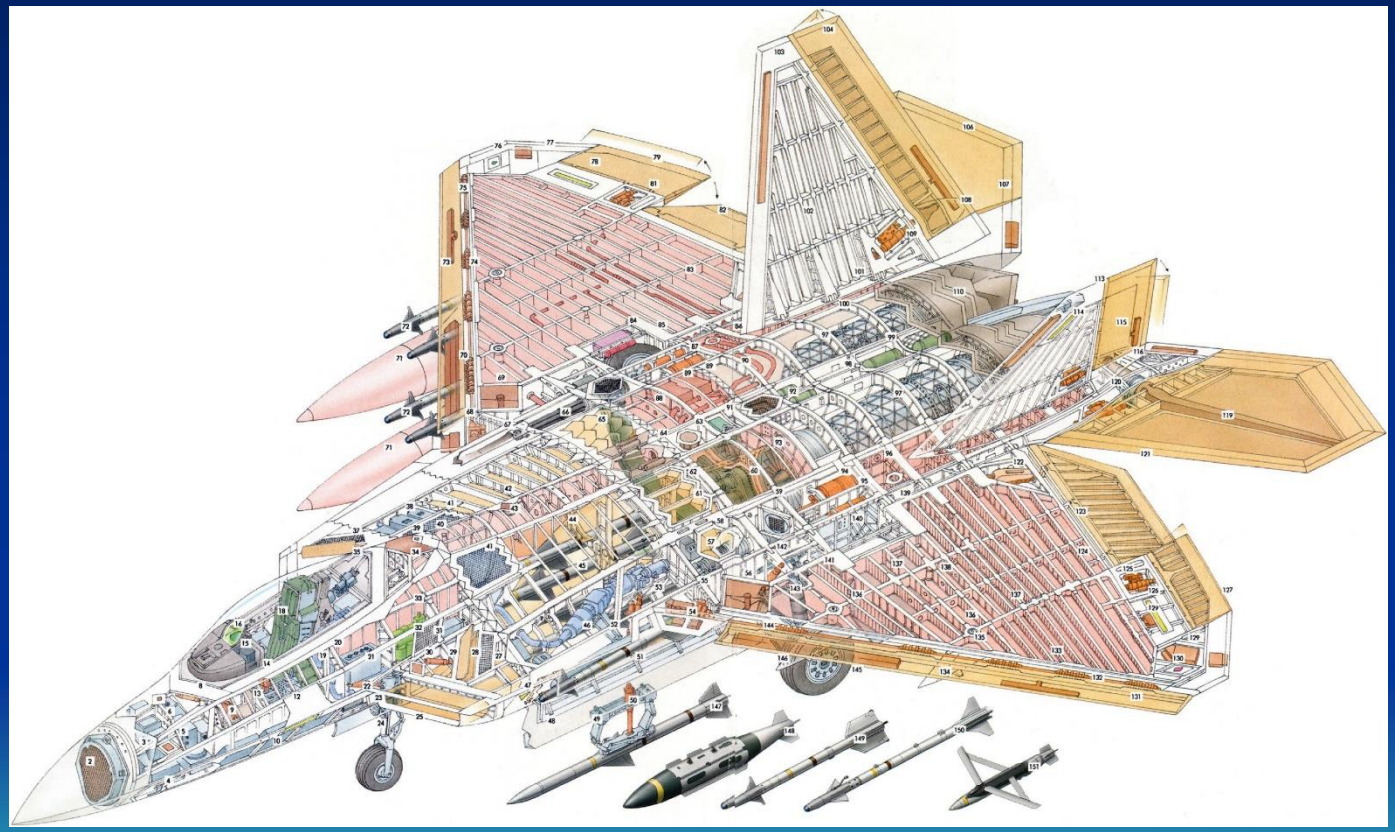
- Advantages
  - Wing box under cabin floor
  - Easier landing gear installation (esp. for large transport aircraft)
  - Good visibility for pax

Low Wing

- Disadvantages
  - Difficult to install high BPR engines under wing
  - Interference drag between wing and fuselage
  - Difficult to install airstairs

https://www.ndtv.com/world-news/boeing-says-its-open-to-changing-the-name-of-grounded-737-max-jet-2054867

F-22



https://conceptbunny.com/lockheed-martin-f-22-raptor/

https://retireenews.org/2016/10/25/f-22-raptor/

F-117

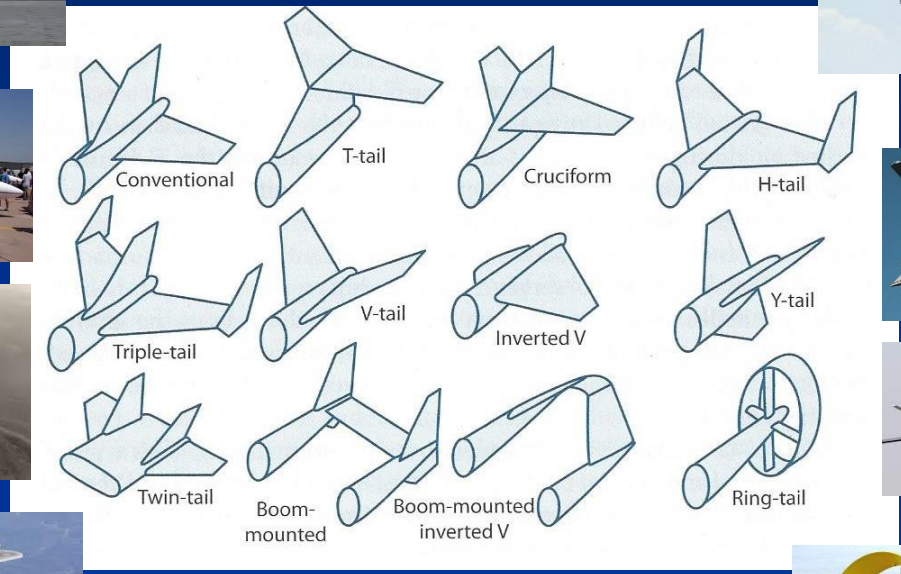
- Shield inlet and nozzle from ground-based missiles
- Minimize reflections from ground radar

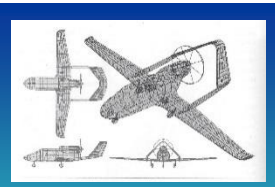
F-35A

- Requirements for air superiority not as stringent as for F-22

Section 4.5
Tail Geometry and Arrangement

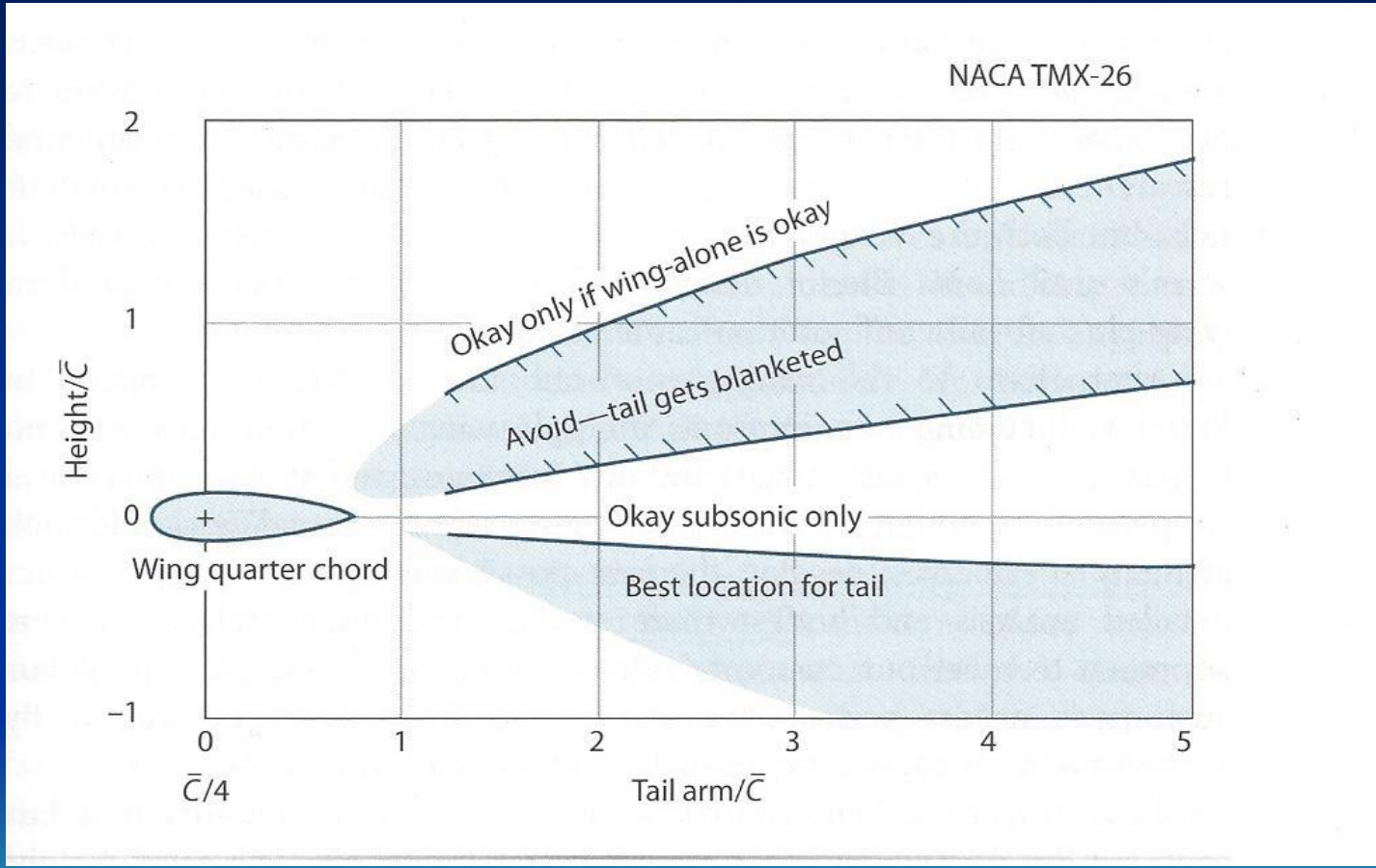
Tail Layout Options





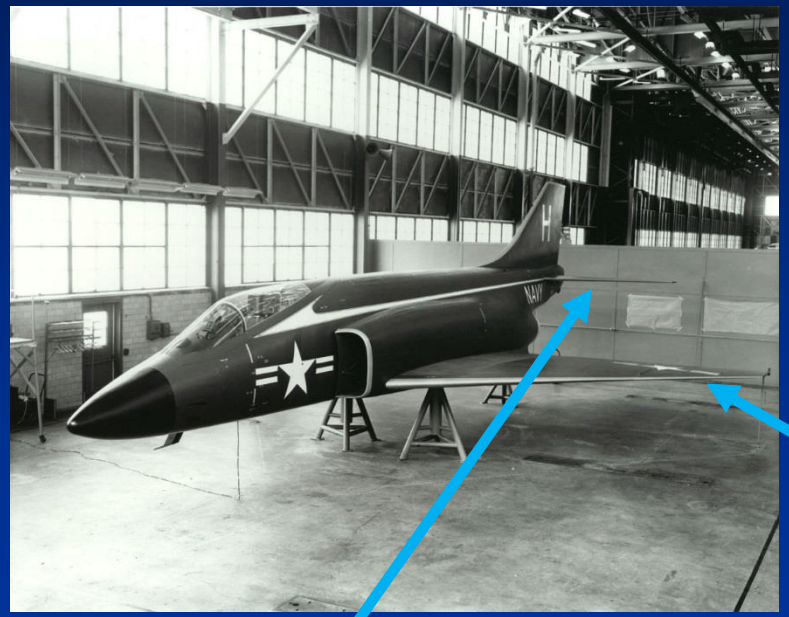
- Benefits of Inverted V or Y-tail
  - Offers appropriate stability and control
  - Clean air (not disturbed by wing or fuselage) over high range of α
  - Lightweight
  - Protects pusher propeller
  - Can get inside hangar

Preferred HT Location



Source: Raymer

McDonnell Douglas F-3H



Source: commons.Wikipedia.com

No anhedral on horizontal tail

No dihedral on outer wing panel

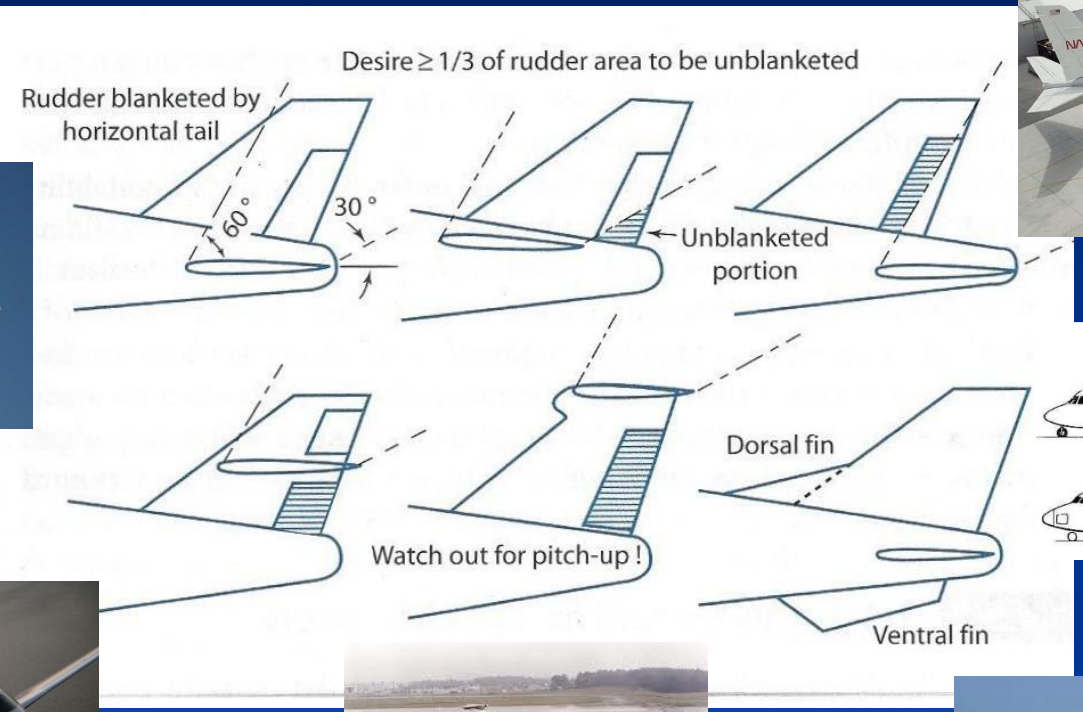
McDonnell Douglas F-4E

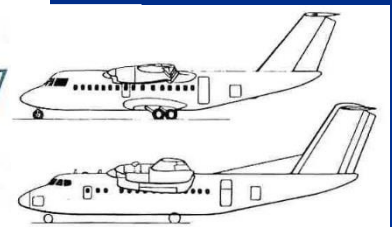
Source: commons.Wikipedia.com

Avoids blanketing of tail at high α

Outer wing panel dihedral adds roll stability lost when setting anhedral on horizontal tail

Tail Geometry for Spin Recovery





Source: Raymer

Horizontal and Vertical Tail Volume Coefficients

Aircraft Category	V_{HT}	V_{VT}
Sailplane	0.50	0.02
Homebuilt	0.50	0.04
GA – single engine	0.70	0.04
GA – twin engine	0.80	0.07
Agricultural	0.50	0.04
Twin turboprop	0.90	0.08
Flying boat	0.70	0.06
Jet trainer	0.70	0.06
Jet fighter	0.40	0.07
Military cargo/bomber	1.00	0.08
Jet transport	1.00	0.09

Use these values for initial estimates. Tail areas will be determined by stability and control analysis

Source: Raymer

Airfoil and Wing/Tail Geometry Selection

The End