Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A5

<u>Initial Sizing: *Wing Loading and Thrust Loading Estimation*</u>

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AOE 4065-4066:
Capstone Air Vehicle Design (AVD) Course Modules (CMs)

Overview of AVD Courses

I. Foundational Elements

F1. Design: *An Engineering Discipline*

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

A4. Initial Sizing: *Takeoff Weight Estimation*

A5. Initial Sizing: *Wing Loading and Thrust Loading Estimation*

A6. Cost Considerations

A7. Concept to Configuration: *Key Considerations*

A7A. Configuration Layout: *Drawings & Loft*

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

A10. Preliminary Design: *Baseline Design Refinement & Validation*

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

P4. Project Execution: *Teamwork for Success*

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

Prof. Pradeep Raj, Aerospace and Ocean Engineering, Virginia Tech, collected and compiled the material contained herein from publicly available sources solely for educational purposes.

Although a good-faith attempt is made to cite all sources of material, we regret any inadvertent omissions.

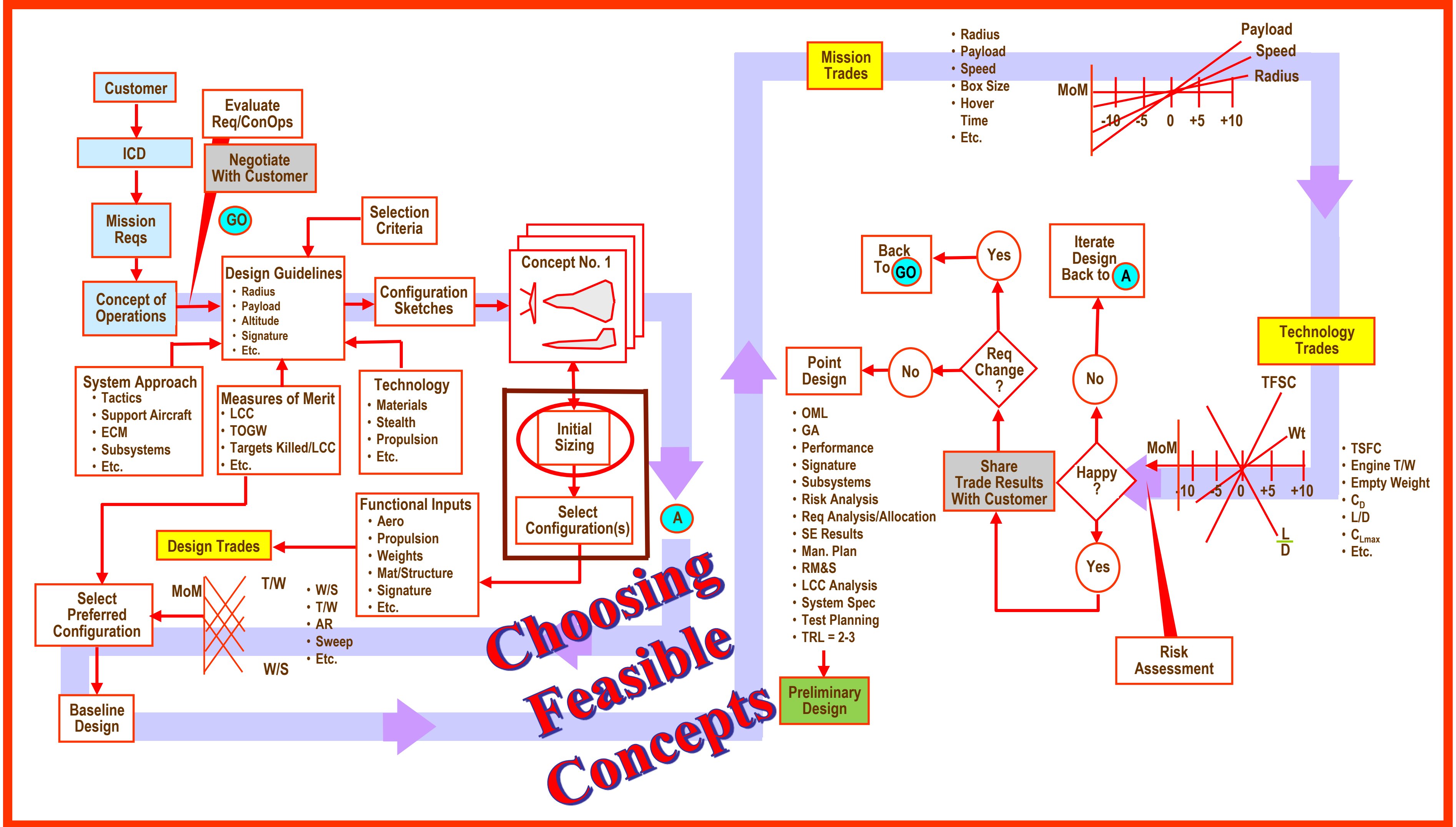
CRUCIALLY IMPORTANT

CMs only introduce key topics and highlight some important concepts and ideas…but without sufficient detail.

We must use lots of Reference Material* to add the necessary details!

(*see Appendix in the Overview CM)

Aircraft Conceptual Design (CD) Process



Courtesy of Lee Nicolai

Initial Sizing

Initial Weight Sizing (CM A4) is the first step.
It answers the question:
How heavy is the airplane concept as sketched?

But, it doesn't tell us anything about the physical size of the airplane.

Recall that *Initial Take-off Weight* estimation considers:

- Payload, and all phases of flight via a Mission Profile
- Design team makes assumptions about performance and geometric parameters, such as, cruise speed (V), cruise altitude (h), $(L/D)_{max}$, C_L, C_{D_0}, sfc, AR, etc.

The next step in *Initial Sizing (covered in this module)* is to estimate two parameters:

- **Wing loading, $(W/S)_{TO}$, which *gives wing area,* S_{ref}, to size the wing, and**
- **Thrust loading, $(T/W)_{TO}$, which *gives thrust,* T_{TO}, *to size the engine(s).***

These two parameters, W/S and T/W, are the key design parameters as they appear in all equations that describe the vehicle performance in various mission phases!

Outline

A5. Initial Sizing: *Wing Loading* and *Thrust Loading Estimation*

A5.1 Wing Loading Estimation

A5.2 Thrust Loading Estimation

A5.3 Constraint Plot*

***Defines Feasible Design Space or Design Domain in terms of** *W/S* **and** *T/W*

Wing Loading: $(W/S)_{TO}$

- $(W/S)_{TO}$ is the parameter used to size the wing (estimate wing area)
- Note that W is takeoff gross weight, W_{TO}, and S is wing reference area, S_{ref}
- "Wing Rules!" *Wing affects the performance, efficiency, and handling qualities more than any other single aircraft feature*.
- $(W/S)_{TO}$ is determined by considering all required flight missions to ensure that the aircraft will be able to meet all requirements and regulatory constraints.
- Example mission requirements include:
  - Range (Cruise Efficiency)
  - Endurance (Loiter Efficiency)
  - Take-off and Landing
  - Air-to-air combat (Maneuverability)
  - High altitude
  - High altitude, long endurance
  - Low-altitude ride quality
- Constraints include Government Regulations, such as Federal Air Regulations (FARs) and Military Specifications and Standard (MIL-SPEC or MIL-STD), which impose *safety requirements* that must be met.
- Different mission requirements drive W/S in opposite directions, i.e., high vs. low values! **We must strike the right balance in choosing initial** $(W/S)_{TO}$.

Wing Loading, W/S, Considerations

Range

- For a jet aircraft, *Best Specific Range (distance traveled per unit weight of fuel or miles per pound of fuel)* may be expressed as:

$$\frac{1.07}{sfc}\left\{\frac{(W/S)}{\rho}\right\}^{1/2}\frac{\{AR\cdot e\}^{1/4}}{\left\{C_{D_0}\right\}^{3/4}}\frac{1}{W}$$

HIGH Wing Loading is Good!

(SMALL Wing Area)

- High values of aspect ratio, AR, and wing efficiency, e, are desirable.

- Low values of specific fuel consumption, sfc, air density, ρ (higher altitude), zero-lift drag, C_{D_0}, and weight, W, are desirable.

Wing Loading, *W/S*, Considerations

Take-off

- For conventional take-off and landing (CTOL) aircraft, take-off distance,* s_{TO}, may be estimated using an approximate expression:

$$s_{TO} = \frac{1.44\,(TOP)}{(g\,\rho_{SL})\,(1-\omega)} + 3.394\sqrt{\frac{(TOP)\,(T/W)}{\rho_{SL}}}$$

Note: ρ_{SL} is sea level air density, and ω is the ratio of ground-run retardation force to takeoff thrust; ω may be assumed to be 0.1 or 0.15.

Where *TOP, Take-off Parameter,* is:

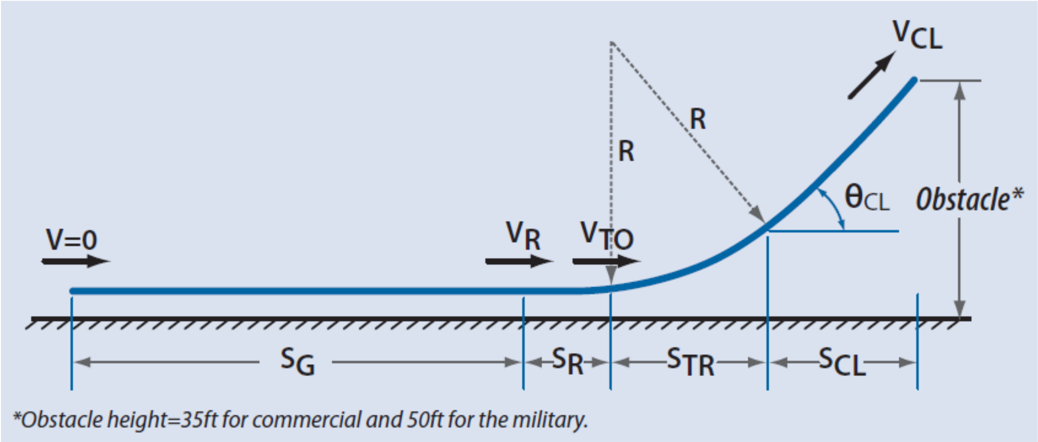
$$TOP = \frac{(W/S)_{TO}}{\sigma\,\left(C_{Lmax}\right)_{TO}\,\left(T/W\right)}$$

$$\sigma = \rho/\rho_{SL}$$

**Take-off distance is the sum of ground distance, rotation distance, transition distance, and climb distance to clear specified obstacle height.*

LOW Wing Loading is Good!

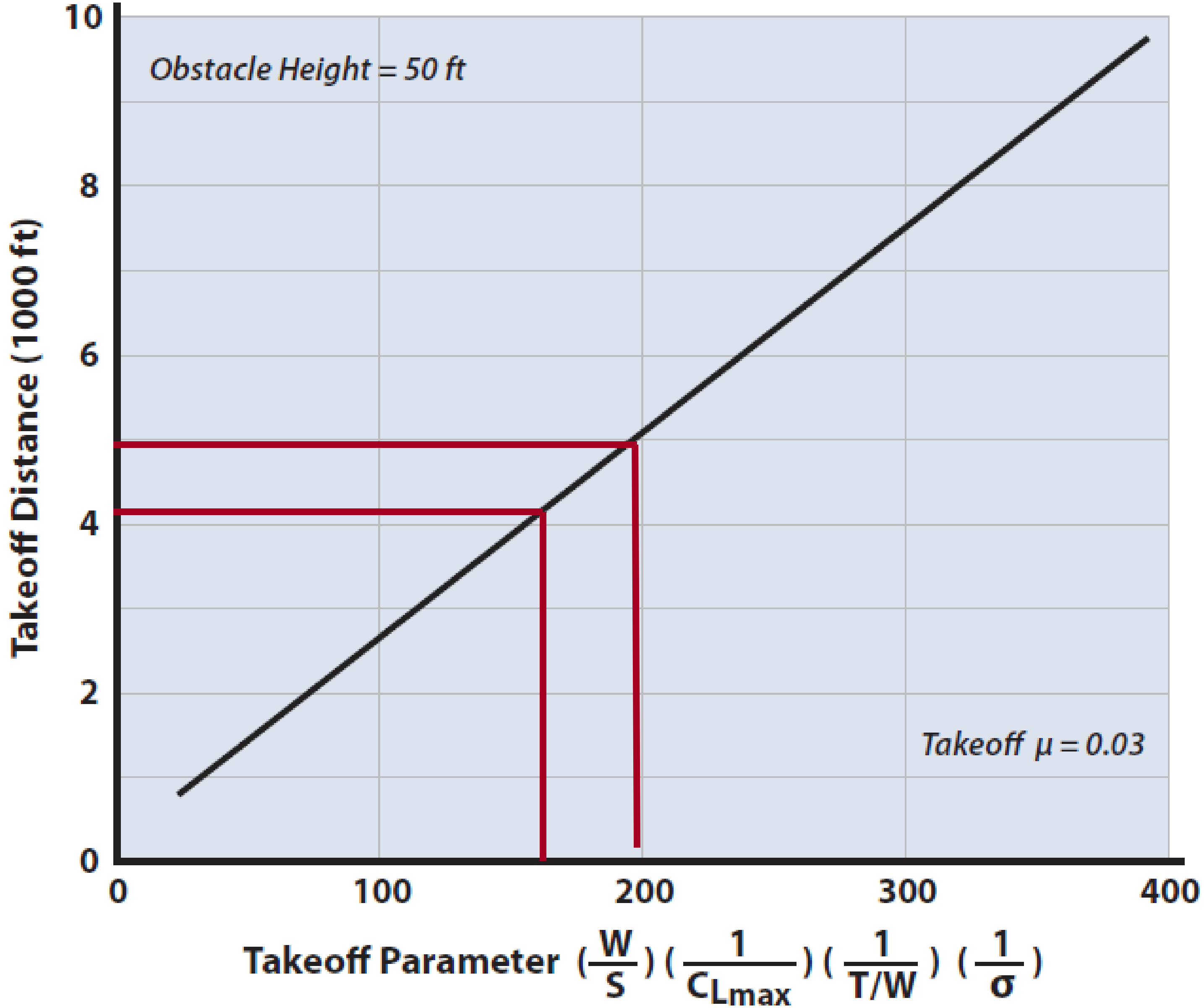
LARGE Wing Area



- For low take-off distance, it's good to have HIGH values of maximum lift coefficient, $C_{L_{max}}$; thrust-to-weight ratio, *T/W;* and air density (lower altitudes)…but beware of the downsides!

Source: Sec. 6.4, Ref. AVD 1 (Nicolai and Carichner)

Take-off Distance vs. TOP



Source: Fig. 6.3, Ref. AVD 1 (Nicolai and Carichner)

Wing Loading, W/S, Considerations

Landing

- Landing distance, s_L, for conventional takeoff and landing (CTOL) aircraft may be estimated from the *approximate* expression:

$$s_L = \frac{2.645\,(LP)}{(\mu\,\rho_{SL}\,g)} + \frac{h_{obstacle}}{\tan\theta_{approach}}$$

Note: ρ_{SL} is sea level air density

Where LP, *Landing Parameter,* is

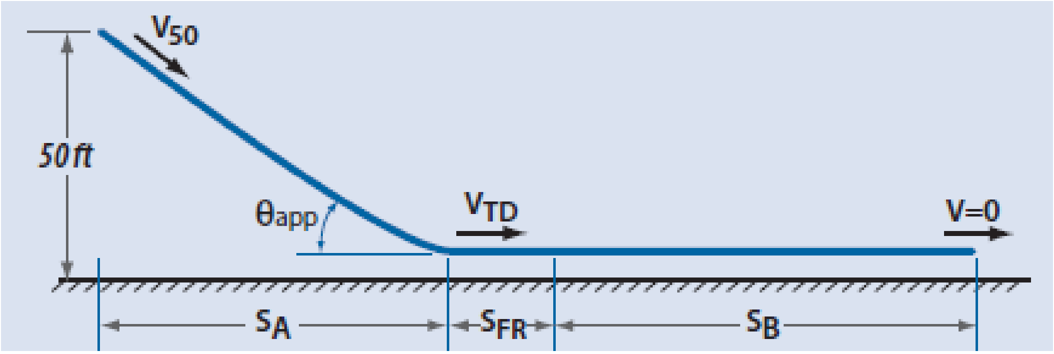
$$LP = \frac{(W/S)_L}{\sigma\,(C_{Lmax})_L}$$

$$\sigma = \rho/\rho_{SL}$$

LOW Wing Loading is Good!

LARGE Wing Area

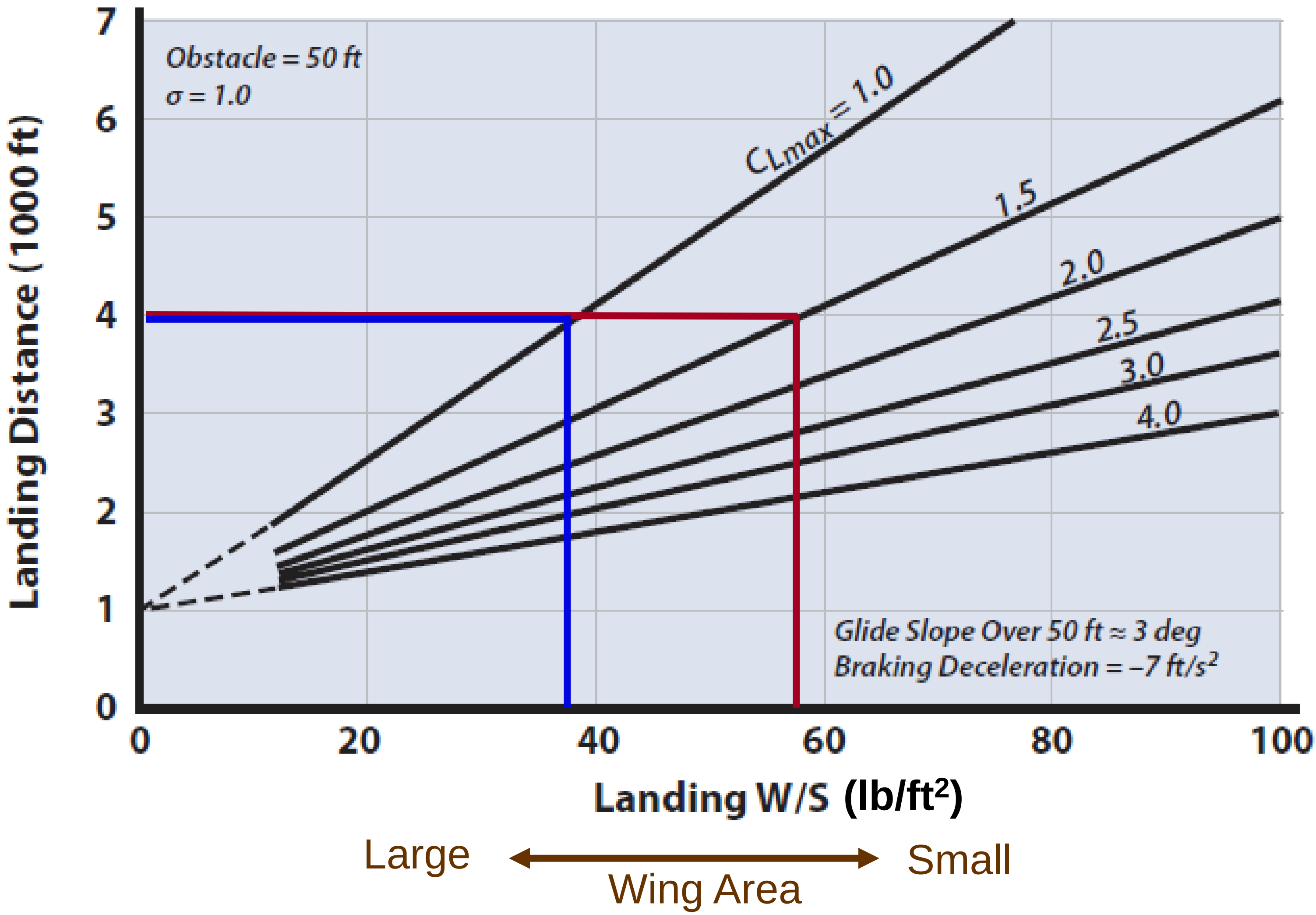
**Landing distance is the air distance (horizontal distance required to clear a specified obstacle height), free roll distance, and braking distance.*



- HIGH values of maximum lift coefficient, $C_{L_{max}}$, and air density (lower altitudes) are desirable...but beware of the downsides.
- Note: *No impact of thrust-to-weight ratio, T/W* !

Source: Sec. 6.4, Ref. AVD 1 (Nicolai and Carichner)

Landing Distance for CTOL Aircraft



NOTE: $W_{landing} = 0.85\ W_{TO}$ *for civil aircraft*

$= W_{TO} - 0.5\ W_{fuel}$ *for military aircraft*

Source: Fig. 6.4, Ref. AVD 1 (Nicolai and Carichner)

Wing Loading, *W/S*, Considerations

Coefficient of Friction, μ

Table 10.3 Coefficients of Friction for Various Takeoff and Landing Surfaces

Type of Surface	Brakes Off, Average Ground Resistance Coefficient	Brakes Fully Applied, Average Wheel-Braking Coefficient
Concrete or macadam	0.015–0.04	0.3–0.6
Hard turf	0.05	0.4
Firm and dry dirt	0.04	0.30
Soft turf	0.07	0.5
Wet concrete	0.05	0.2
Wet grass	0.10	0.2
Snow- or ice-covered field	0.01	0.07–0.10

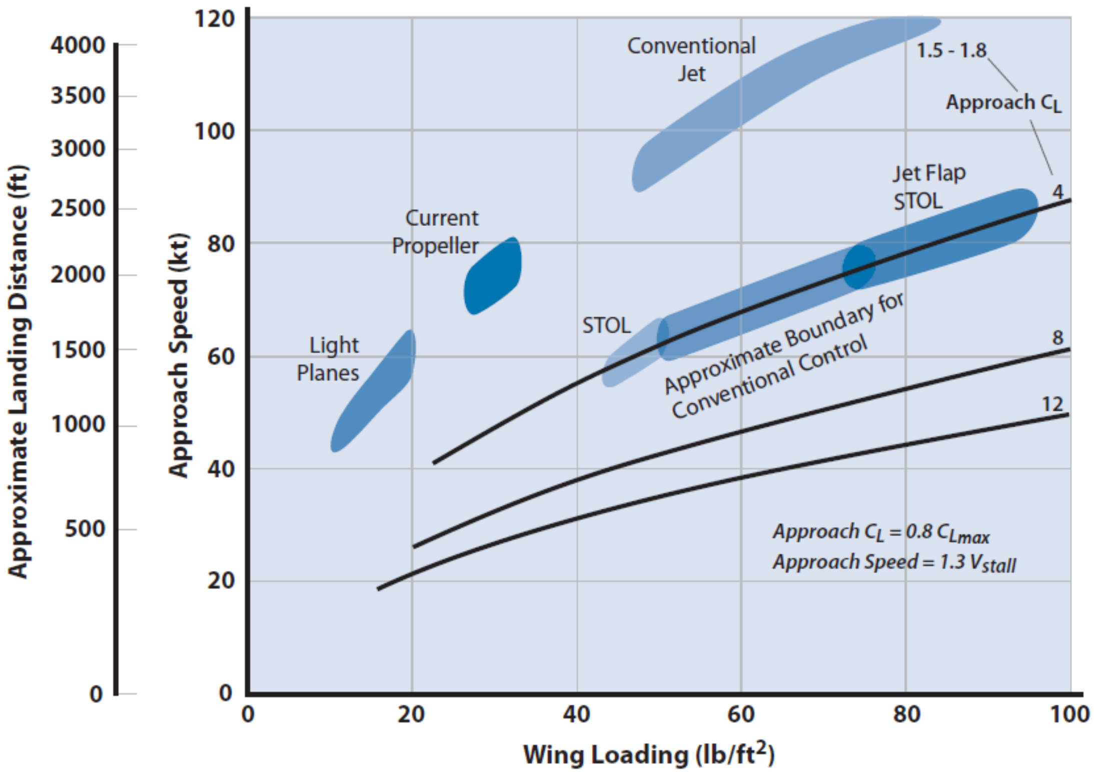
These may be used for estimating landing distance, s_L

Source: Table 10.3, Ref. AVD 1 (Nicolai and Carichner)

Wing Loading, W/S, Considerations

Take-off and Landing

- W/S and $C_{L_{max}}$ are partners in the landing and takeoff performance
- Selecting a takeoff W/S without proper consideration of $C_{L_{max}}$ and T/W may lead to an impossible design later—especially true for short take-off and landing (STOL) aircraft

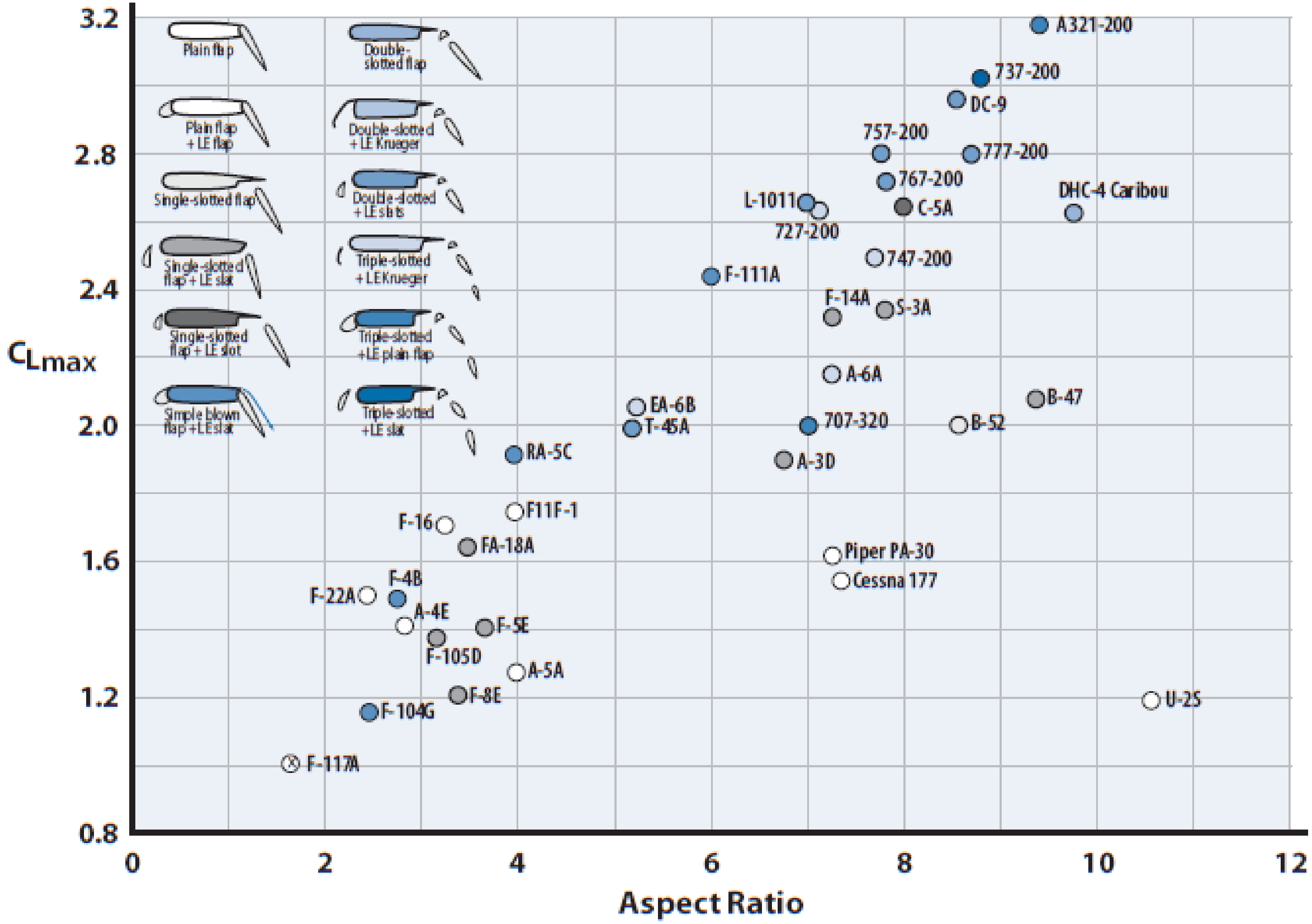


- High-lift devices are key to balancing conflicting Cruise and Take-off & Landing wing loading, W/S, requirements by producing desired $C_{L_{max}}$
- Mechanical high-lift devices have an upper $C_{L_{max}}$ limit of about 4.0, with powered lift devices extending up to about 12.0

Source: Fig. 6.5, Ref. AVD 1 (Nicolai and Carichner)

Wing Loading, *W/S*, Considerations

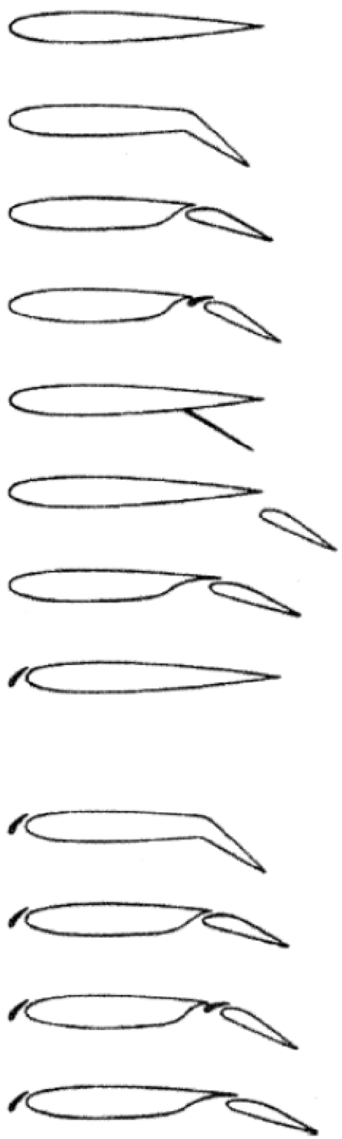
Practical Limits of Mechanical High-Lift Devices for $C_{L_{max}}$



See Tables 9.1 & 9.2 in Ref. AVD 1 (Nicolai) for additional relevant data

Source: Fig. 9.7, Ref. AVD 1 (Nicolai and Carichner)

Mechanical High-lift Devices for Higher C_{Lmax}



	$C_{L,max}$	$\Delta C_{L,max}$
Clean Airfoil	1,45	-
Plain Flap	2,25	0,80
Single-Slotted Flap	2,60	1,15
Double-Slotted Flap	2,80	1,35
Split Flap	2,40	0,95
Double-Wing (Junkers)	2,25	0,80
Fowler Flap	2,80	1,35
Slat	2,00	0,55
Combinations:		
Plain Flap and Slat	2,45	1,00
Single-Slotted Flap and Slat	2,70	1,25
Double-Slotted Flap and Slat	2,90	1,45
Fowler Flap and Slat	3,00	1,55

Table 5.15 Lift coefficient increment by various types of high-lift device (when deflected 60 deg)

No.	High-lift device	ΔC_L
1	Plain flap	0.7–0.9
2	Split flap	0.7–0.9
3	Fowler flap	1–1.3
4	Slotted flap	1.3 C_f/C
5	Double-slotted flap	1.6 C_f/C
6	Triple-slotted flap	1.9 C_f/C
7	Leading edge flap	0.2–0.3
8	Leading edge slat	0.3–0.4
9	Kruger flap	0.3–0.4

NOTE: $C_{Lmax} \cong 0.9\ C_{lmax}$ is typically realized for wings, i.e., max C_L for a wing is less than max C_l for an airfoil

Wing Loading, *W/S*, Considerations

Acceleration and Maneuver

- Maximize excess power, P_S, for critical mission phases:
  - Acceleration for load factor $n = 1$
  - Maneuver for $n > 1$

$$P_S = V\left[\frac{T}{W} - \frac{D}{W}\right]$$

- Excess power, P_S, is maximized by minimizing D/W
  - W/S for minimum D/W can be estimated using

$$\frac{W}{S} = \frac{q}{n}\sqrt{\frac{C_{D0}}{K}}$$

- Note that $\sqrt{(C_{D_0}/K)}$ is the C_L value for $(L/D)_{max}$ (or minimum drag)

Acceleration: HIGH Wing Loading is Good ⇨ SMALL Wing Area

Maneuver: LOW Wing Loading is Good ⇨ LARGE Wing Area

- Air combat aircraft have low wing loading for good maneuverability and high thrust loading for acceleration!

Source: Sec 6.5, Ref. AVD 1 (Nicolai and Carichner)

Use $(W/S)_{TO}$ *Trends* for Sanity Check of Your Estimate Based on All Considerations

Dominant Mission Requirement	$(W/S)_{TO}$	Example
High-altitude long-endurance solar-powered ISR[a]	0.5-3.0	Helios
Competition sailplanes	7-12	ASW 17
Light civil aircraft with short range and field length	10-30	C-172
High-altitude long-endurance hydrocarbon-powered ISR	25-50	RQ-4A
STOL[b] and utility transports	40-90	C-130
Short or intermediate range with moderate field length	50-90	Learjet 35
Long-range transports and bombers (>3000 n mile)	110-150	B 747
Fighter, high-altitude	30-60	F-106
Fighter, air-to-air	50-80	F-15A
Fighter, close air support	65-90	A-10A
Fighter, strike interdiction	90-130	F-4E
Fighter, interceptor	120-150	F-104G
Low-altitude subsonic cruise missile	200-240	AGM-109

[a] Intelligence, Surveillance and Reconnaissance [b] Short Take-Off and Landing

Source: Table 6.1, Ref. AVD 1 (Nicolai and Carichner)

Outline

A5. Initial Sizing: *Wing Loading* and *Thrust Loading Estimation*

A5.1 Wing Loading Estimation

A5.2 Thrust Loading Estimation

A5.3 Constraint Plot*

*Defines Feasible Design Space or Design Domain in terms of W/S and T/W

Thrust–to–Weight Ratio, $(T/W)_{TO}$

- $(T/W)_{TO}$ is the parameter for sizing the propulsion system. Note that T is T_{TO}, takeoff thrust, and W is W_{TO}, takeoff gross weight. T_{TO} is typically the maximum available thrust at takeoff conditions
- $(T/W)_{TO}$ is determined by considering various required mission phases subject to regulatory constraints
  - Cruise/ Loiter
  - Takeoff
  - Air Combat (Energy Maneuverability)
  - Acceleration time and fuel burned during acceleration
  - Maximum speed
- $(T/W)_{TO}$ for different mission phases typically conflict with one another forcing designers to <u>establish priorities and strike a reasonable compromise in choosing an initial</u> $(T/W)_{TO}$
- *Make sure to adjust estimated T/W for various mission phases back to the takeoff conditions for consistent comparison*. For example, for cruise segment,

$$(T/W)_{TO} = (T/W)_{cruise}\,(W_{cruise}/W_{TO})\,(T_{TO}/T_{cruise})$$

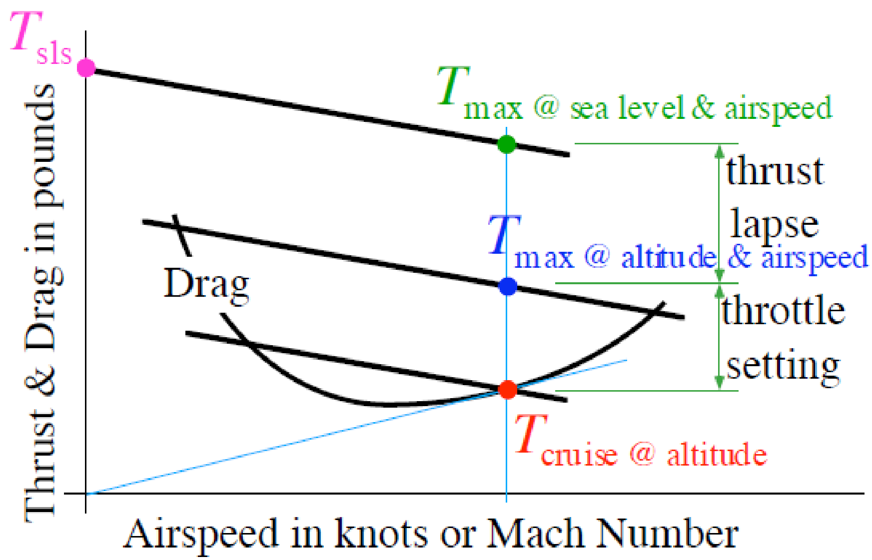
Typically, T_{cruise}/T_{TO} is ~ 0.2 – 0.25 for HBPR turbofan, and
~ 0.4 – 0.7 for LBPR turbofan or turbojet

Cruise Thrust and Cruise Weight

- Cruise thrust is related to takeoff thrust as a function of engine cycle, cruise altitude, cruise airspeed, engine thrust lapse rate, and thrust lever setting (or throttle setting)

$$T_{\text{cruise}} = \sigma\, f_{\text{throttle setting}}\, T_{\text{sea level}}$$

- Maximum engine thrust at any altitude *is less than its sea-level value* by the ratio of air densities, σ
- At cruise altitude, available engine thrust (*which is less than its sea-level value*) is adjusted to exactly match drag by the pilot via throttle setting



- Instead of assuming $W_{\text{cruise}} = (W_{takeoff\_end}/\,W_{\text{TO}})(W_{climb\_end}/\,W_{takeoff\_end})\,W_{\text{TO}}$

  we could use a mid-cruise value, $W_{\text{mid\_cruise}}$, estimated as

$$W_{\text{mid\_cruise}} = \tfrac{1}{2}\,(W_{takeoff\_end}/\,W_{\text{TO}})(W_{climb\_end}/\,W_{takeoff\_end})(1 + W_{cruise\_end}/\,W_{climb\_end})\,W_{\text{TO}}$$

Source: Courtesy of D.W. Hall, Personal Communication

Initial Estimate of $(T/W)_{TO}$

- Use available data based on *dominant mission requirement* of the aircraft being designed

Dominant Mission Requirement	$(T/W)_{TO}$ (uninstalled)
Long range	0.2-0.35
Short & intermediate range with moderate field length	0.3-0.45
STOL and utility transport	0.4-0.6
Fighter—close air support	0.4-0.6
Fighter—strike interdiction	0.45-0.7
Fighter—air-to-air	0.8-1.3
Fighter—interceptor	0.55-0.8

- Note that installed thrust will be less (3-10%) due to inlet losses, and *sfc* values will be higher (~20%), than the uninstalled values.

Source: Table 18.1, Ref. AVD 1 (Nicolai and Carichner)

Initial Estimate of $(T/W)_{TO}$

- Typical installed values for jet aircraft shown in the table; ***use installed values whenever available***

Aircraft Type	**$(T/W)_{TO}$ Installed**
Jet Trainer	0.4
Jet fighter (dogfighter)	0.9
Jet fighter (other)	0.6
Military cargo/bomber	0.25
Jet transport (higher values for fewer engines)	0.25-0.4

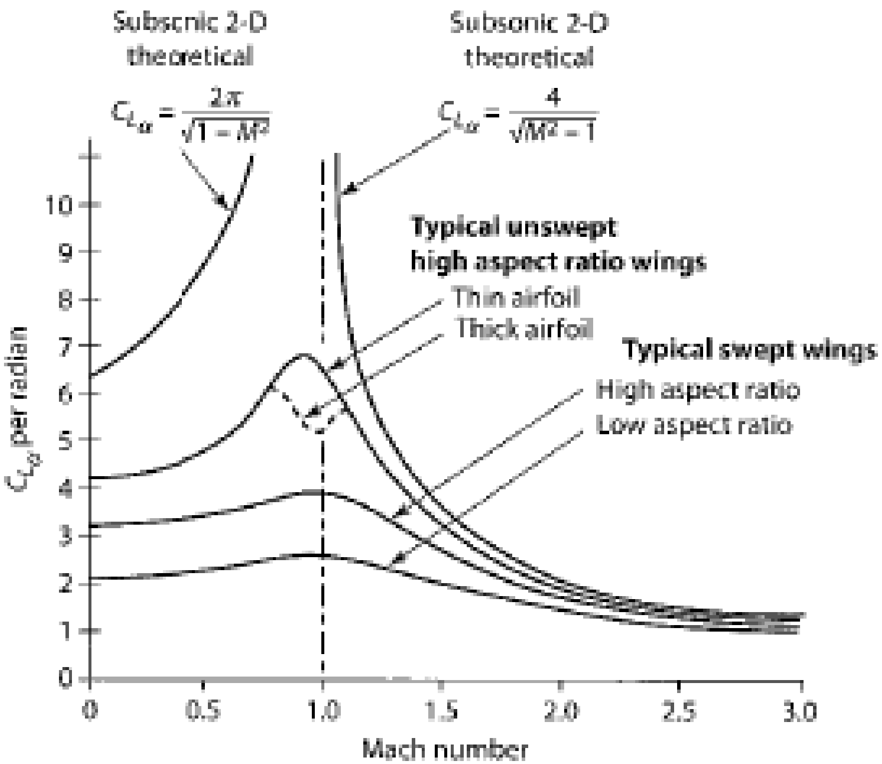
- Statistical estimation based on maximum Mach number

$T/W_0 = a\, M_{max}^{C}$	a	C
Jet trainer	0.488	0.728
Jet fighter (dogfighter)	0.648	0.594
Jet fighter (other)	0.514	0.141
Military cargo/bomber	0.244	0.341
Jet transport	0.267	0.363

Source: Table 5.1 & 5.3, Ref. AVD 2 (Raymer)

Sanity Check of Estimated Wing Area and Thrust Requirements

- We know Weight, hence Lift. Use C_{L_α} charts or formulas to compute angle of attack, α
- Ensure that cruise α is reasonable, between 3º and 6º. If not, consider decreasing W/S (increasing S)
- We know estimated L/D and Weight, W, hence L. We can, therefore, determine drag, D, and check if the estimated thrust, T, is adequate.



Source: Fig. 12.6, Ref. AVD 2 (Raymer)

- Check to see that the estimated Thrust value makes sense

Wing area is the starting point for wing design, and thrust estimate is needed to select a propulsion system

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Words of Wisdom from Experts about Initial Values of *T/W* and *W/S*

"A low wing loading makes a bigger wing which will always increase weight and cost. If a very low wing loading is driven by only one of the requirements, it might make sense to reconsider that requirement."

"…selected values of W/S and T/W are used only for the initial design layout. Once it is completed, a detailed optimization of those parameters will be done and the design will be revised accordingly. The initial values are just to get the design started and are never used again."

-- Dan Raymer

"…range-dominated aircraft always have high wing loadings." **[Except when they don't]**

"There are two rules that must be learned in the design of aircraft:

1. *There are no right answers, only a best answer.*
2. *There are no rules."*

-- Lee Nicolai

Source: Ch. 6, Ref. AVD 1 (Nicolai & Carichner); Ch. 5, Ref. AVD 2 (Raymer)

Outline

A5. Initial Sizing: *Wing Loading* and *Thrust Loading Estimation*

A5.1 Wing Loading Estimation

A5.2 Thrust Loading Estimation

A5.3 Constraint Plot*

***Defines Feasible Design Space or Design Domain in terms of W/S and T/W**

Constraint Plot

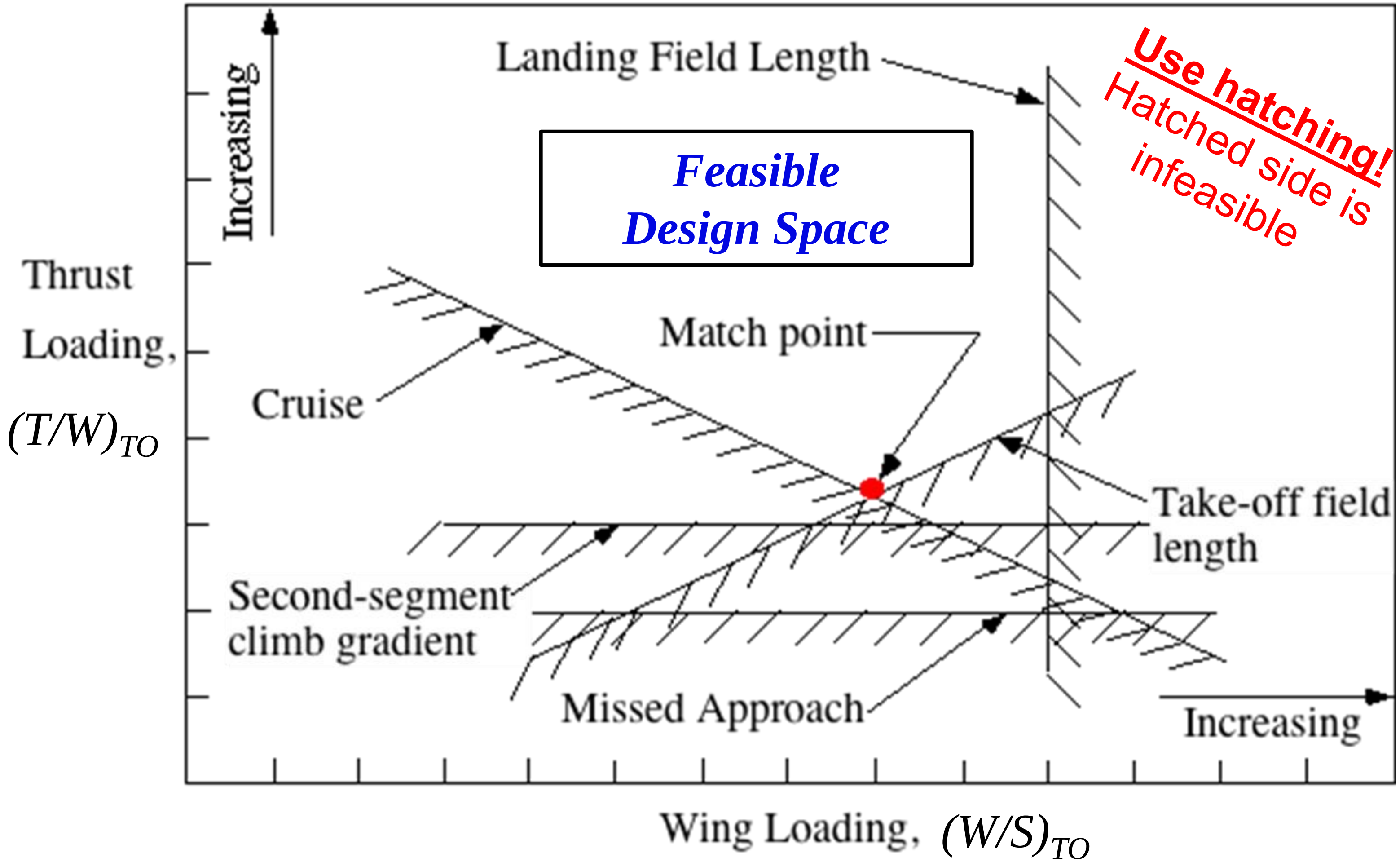
Constraint Plot is a technique to define a *Design Space* or *Design Domain* within which a designer can choose a combination of two universal design parameters, $(W/S)_{TO}$ and $(T/W)_{TO}$, and have reasonable confidence that a design based on this combination is feasible.

The design domain represents a region where any design will meet all mission requirements including, but not limited to,

- *Cruise Range*
- *Takeoff and Landing Field Lengths*
- *Rate of Climb*
- *Sustained Turn Rates*
- *Service Ceiling*
- *Maximum Speed*
- *Etc.*

Constraint Plot for Jet Aircraft

(*Notional, for illustrative purpose only*)



Note: **In an actual plot, all curves are NOT straight lines.**

How do we generate the curves?

Source: Adapted from Fig. 3.19, Ref. AVD 10 (Loftin)

Generating Curves for Constraint Plot

- **Select flight segments that together define the mission profile**
- **For each flight segment, choose the appropriate performance equation**
- **Manipulate the performance equation to express it in the form of**

$$T/W = f\,(W/S)$$

- **Choose a representative set of** W/S **values, and compute the corresponding** T/W **values**
- **Plot the values on a graph with** W/S **on the abscissa and** T/W **on the ordinate**
- ***For consistent comparison, convert all values to takeoff conditions before plotting***

The following slides show a few examples. Readers can find others in one of the references or derive themselves.

Thrust Loading *(T/W)* as a function of Wing Loading *(W/S)*
(for turbofan or turbojet aircraft)

Takeoff

$$\left(\frac{T}{W}\right)_{TO} \geq \frac{1.44\,(W/S)_{TO}}{(1-\omega)(\rho_{SL}\,g\,\sigma)\,(C_{Lmax})_{TO}\left\{s_{TO} - 3.394\sqrt{\dfrac{(W/S)_{TO}}{\sigma\,\rho_{SL}\,(C_{Lmax})_{TO}}}\right\}}$$

Here, ω is the ratio of the ground-run retardation force to the takeoff thrust. The retardation force, which decreases the ground run acceleration, is a function of the aircraft drag and the coefficient of friction with brakes off.
At this stage of design, a value of ω between 0.1 and 0.15 may be assumed.

Note that this expression is based on an updated approximate form of the full equation for takeoff distance, s_{TO}, given by Eq. (10.4b) in *Ref. AVD 1 (Nicolai & Carichner)*. The updated one differs from Eq. (6.3) in the same reference in one key aspect: unlike Eq. (6.3), the ***updated one is not restricted to FPS units.***
Eq. (10.4b) is the source of both Eq. (6.3) and its updated form.

See the two slides in the Appendix for the underlying assumptions used to derive the approximate form of the equations.

Thrust Loading *(T/W)* as a function of Wing Loading *(W/S)*

(for turbofan or turbojet aircraft)

2nd Segment Climb: 35 ft. to 400 ft. (OEI)

$$\left(\frac{T}{W}\right)_{OEI} \geq \left(\frac{n_{engines}}{n_{engines}-1}\right)\left[\frac{1}{(L/D)} + \sin\gamma\right]$$

L/D is evaluated at $V_2 \geq 1.2\,(V_{stall})$; V_2 is the speed at the 35 ft. height point

$$C_L = C_{L_{max}}/(1.2)^2 \qquad C_D = C_{Do} + K\,C_L^2$$

It is assumed that landing gear is retracted and flaps are in takeoff position, therefore,

(i) increase C_{Do} by adding incremental take-off flap drag* estimate, and

(ii) reduce e for estimating K

Climb gradient is typically given as a percentage *(see slide 33, CM A2)* from which the climb angle, γ, can be calculated using

$$\gamma = \tan^{-1}\frac{climb\ gradient}{100}$$

*Fig. 9.25, AVD 1, Nicolai & Carichner

Thrust Loading *(T/W)* as a function of Wing Loading *(W/S)*

(for turbofan or turbojet aircraft)

Rate of Climb

$$\left(\frac{T}{W}\right)_{ROC_{max}} \geq \left[\frac{ROC_{max}}{\sqrt{\frac{2(W/S)}{\rho C_{Lopt}}}} + 2\sqrt{K\,C_{Do}}\right] \qquad C_{L_{opt}} = \sqrt{\frac{C_{D0}}{K}}$$

Note: Maximum (T/W) and maximum (L/D) gives maximum ROC

1. **Absolute ceiling (*h_{ac}*)**. The altitude at which the ***ROC is zero***. It is the absolute maximum altitude that an aircraft can maintain level flight.
2. **Service ceiling (*h_{sc}*)**. The highest altitude at which aircraft ***ROC is 100 ft/min*** (i.e., 0.5 m/s).
3. **Cruise ceiling (*h_{cc}*)**. The cruise ceiling is defined as the altitude at which the aircraft can ***climb with a rate of 300 ft/min*** (i.e., 1.5 m/s).
4. **Combat ceiling (*h_{cc}*)**. The combat ceiling is defined as the altitude at which a fighter can climb with a rate of 500 ft/min (i.e., 5 m/s). This ceiling is defined only for fighter aircraft.

Source: Ref. AVD 5 (Sadraey)

Thrust Loading *(T/W)* as a function of Wing Loading *(W/S)* (contd.)

(for turbofan or turbojet aircraft)

Cruise Speed

$$\left(\frac{T}{W}\right)_{V_{cr}} \geq \left\{\frac{\rho V_{cr}^2}{2(W/S)} C_{D0} + \frac{2(W/S)}{\rho V_{cr}^2 (\pi ARe)}\right\}$$

Note: $V_{cr} = aM_{cr}$ where a is the speed of sound at the cruise altitude

Max Speed

$$\left(\frac{T}{W}\right)_{V_{max}} \geq \left\{\frac{\rho V_{max}^2}{2(W/S)} C_{D0} + \frac{2(W/S)}{\rho V_{max}^2 (\pi ARe)}\right\}$$

Note: $V_{max} = aM_{max}$ where a is the speed of sound at the cruise altitude

Thrust Loading *(T/W)* as a function of Wing Loading *(W/S)* (contd.)

(for turbofan or turbojet aircraft)

Range

$$\left(\frac{T}{W}\right)_{range} \geq \sqrt{\left(\frac{W}{S}\right)} \left[\frac{\sqrt{2/(\rho\, C_{L_{cr}})}}{tsfc\ \cdot R} \ln\left\{\frac{W_{initial}}{W_{final}}\right\}\right]$$

$tsfc, R, \rho$, and $C_{L_{cr}}$: Use estimates from Initial Take-off Weight Estimation

Note that $\frac{W_{final}}{W_{initial}} = 1 - \frac{W_{fuel}}{W_{initial}}$

- Use fuel fraction estimate from Initial Take-off Weight Estimation
- As a first approximation, fuel fraction, $W_{fuel}/W_{initial}$, may be considered to be independent of the aircraft weight assuming the fuel consumption to be proportional to the aircraft weight; see *Ref. AVD 2 (Raymer)*

CAUTION: Beware that varying *(W/S)* while keeping $C_{L_{cr}}$ fixed implies varying cruise velocity!

Thrust Loading (T/W) as a function of Wing Loading (W/S)

(for turbofan or turbojet aircraft)

Landing

$$\left(\frac{W}{S}\right)_L = \frac{(\mu\,\rho_{SL}\,g)\,\sigma\,(C_{Lmax})_L}{2.645}\left[s_L - \frac{h_{obstacle}}{\tan\theta_{approach}}\right]$$

Civil aircraft: $\theta_{approach} = 3^o$ *(4.5^o for General Aviation aircraft)*

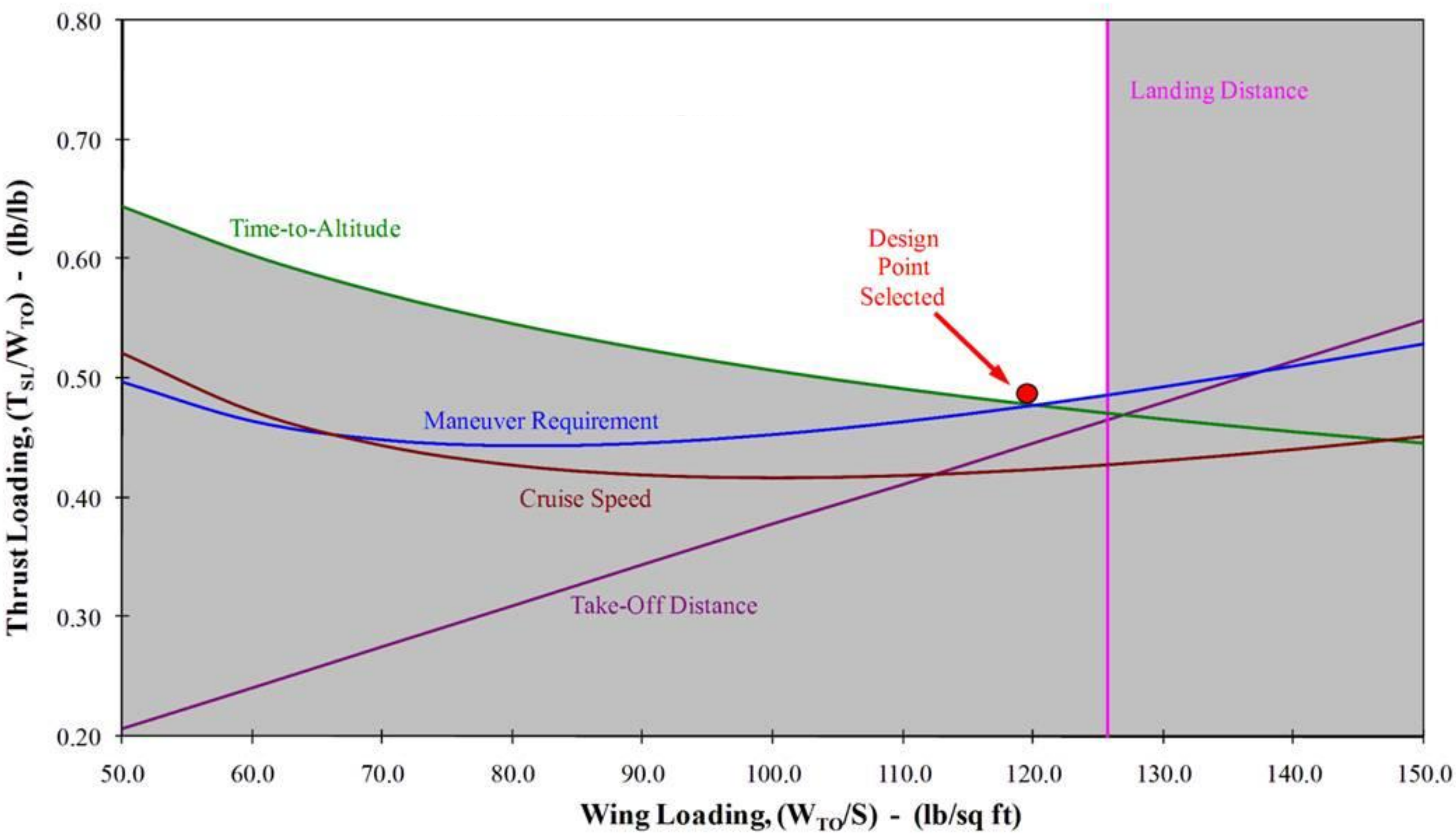
Civil aircraft: $W_L = 0.85\, W_{TO}$

Military aircraft: $W_L = W_{TO} - 0.5\, W_{fuel}$

Evaluated at $V = 1.5\,(V_{\text{stall}})_{\text{landing}}$

Remember to convert $(T/W)_{range}$ and $(W/S)_L$ to takeoff conditions

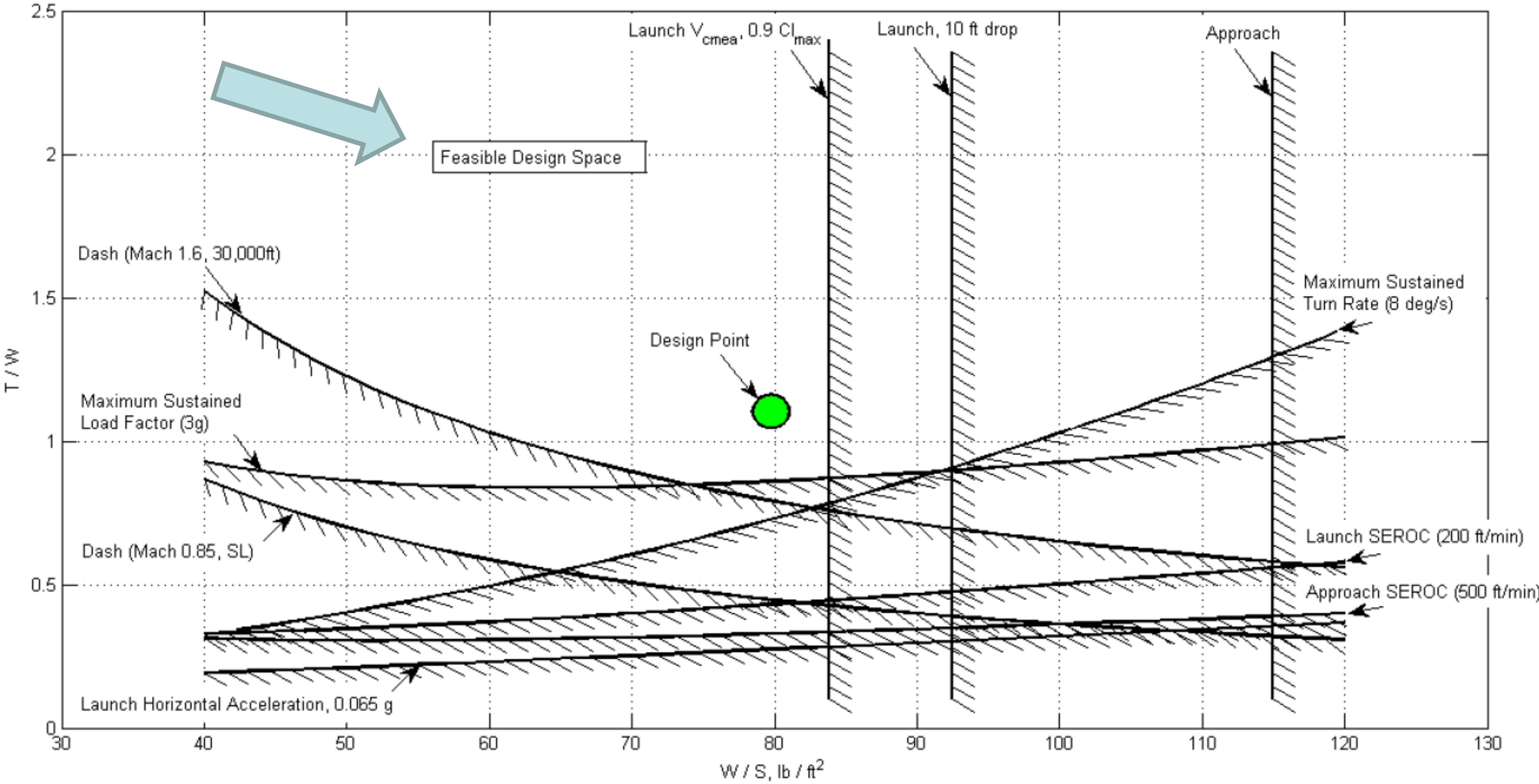
Constraint Plot Example



Source: http://john-golan.blogspot.com/2015/07/aircraft-performance-part-1-design.html

Constraint Plot: *F/A-36*

Student Design Project



Source: 2013-14 NAVAIR Carrier-based Tactical Fighter, VT Team, Lead: Williams

Power Loading *(W/P or P/W)* as a function of Wing Loading *(W/S)* *(for propeller-driven aircraft)*

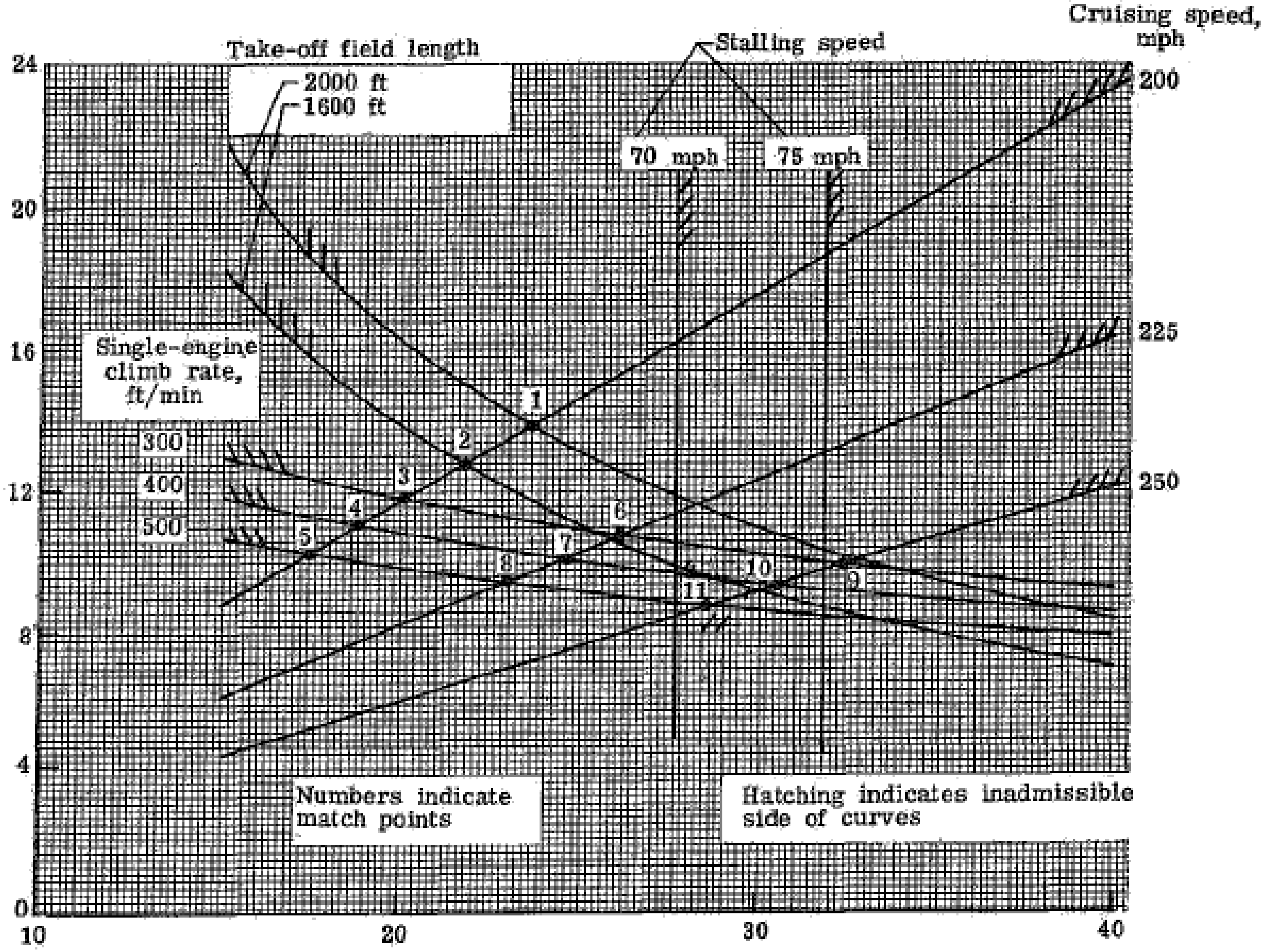
- **Use of Power Loading, *W/P* or *P/W*, instead of *T/W*, is preferred for propeller aircraft because piston or turboprop engines are rated in terms of shaft horsepower (*SHP*) or brake horsepower (*BHP*).**
- **Note that thrust, *T*, in lb_f and power, *P*, in *BHP* are related as**

$$P = T \times V / (\eta_p \times 550)$$

  where speed, *V*, is in *ft/s* and η_p is propeller efficiency.
- **This relationship can be used to convert *T/W* to *P/W***
- **More details can be found in**
  - **Section 3.2, Ref. AVD 4 (Gudmundsson)**
  - **Section 4.3, Ref. AVD 5 (Sadraey)**

Constraint Plot for Propeller Aircraft
An Example

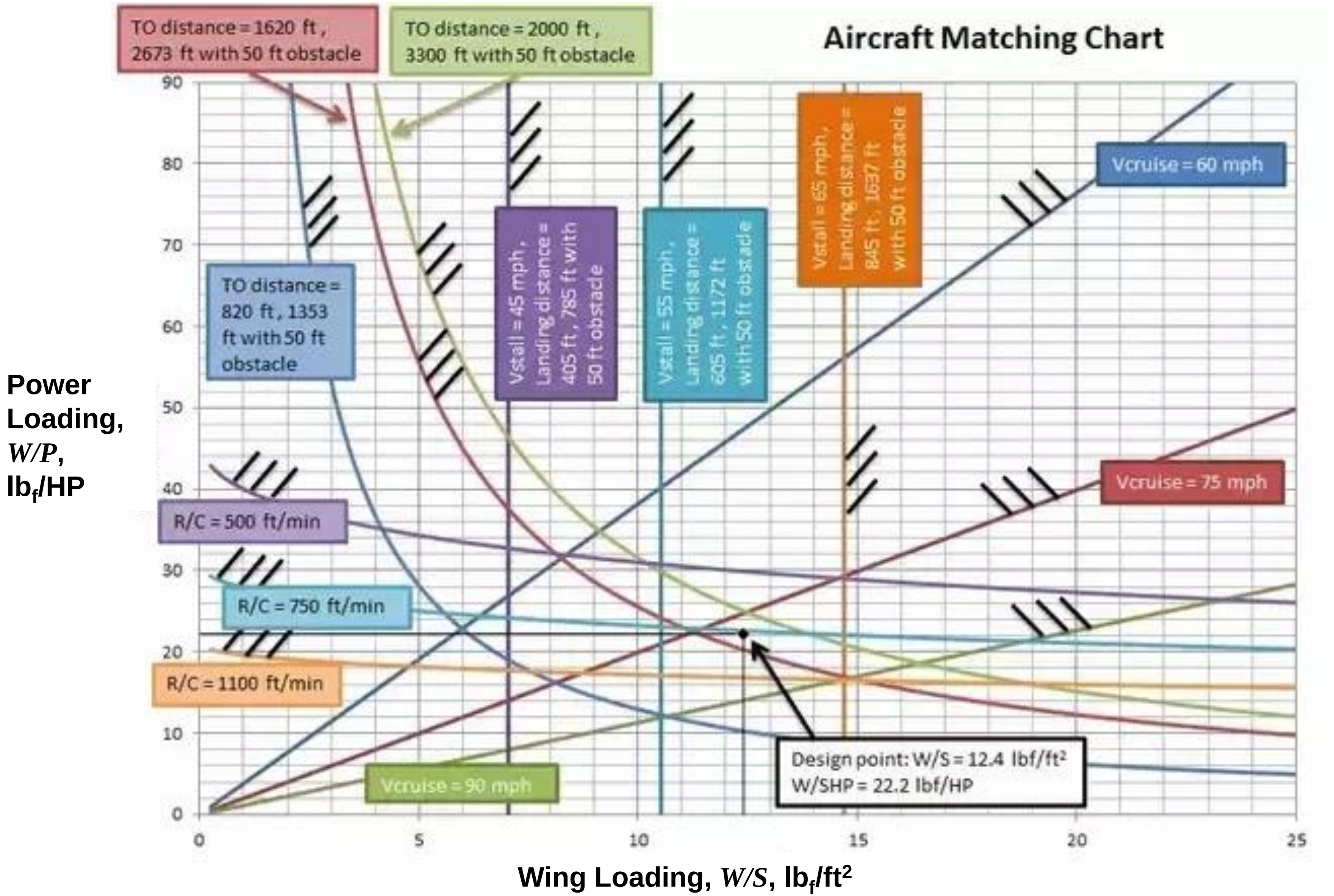
Power Loading, *W/P*, lb_f/HP



Wing Loading, *W/S*, lb_f/ft^2

Source: Fig. 7.1, Ref. AVD 10 (Loftin)

Constraint Plot:
Propeller-Driven Aircraft Example



Source: Internet

Epilogue

Where we are, and where we go next

- **Having completed *Initial Sizing*, we now know**
  - What the payload or fixed weight is (from customer requirements)
  - How heavy the airplane is ($TOGW$ as the sum of empty weight, fuel weight, and fixed weight)
  - How big the wing is (wing reference area, S)
  - How many, and how big, the engines are (based on thrust or power value)
  - How many phases the mission has (and the corresponding assumed values of L/D, speeds, sfc, etc.)

Each Team's Challenge

"INTEGRATE all…geometrical and dimensional requirements, equipment, structural components…into a vehicle that is BALANCED with respect to flight in all phases of its flight envelope and ground operations…Satisfy the DESIRED requirements with the lightest weight (or least cost) vehicle."

-- Nathan Kirschbaum

Recommended Readings

Ref. No.	Chapter	Author(s)	Title
AVD 1	**Chapters 6, 10, 18**	Nicolai, L.M. and Carichner, G.E.	***Fundamentals of Aircraft and Airship Design , Volume I—Aircraft Design ,*** AIAA Education Series, AIAA, Reston, VA, 2010.
AVD 2	**Chapter 5**	Raymer, D.P.	***Aircraft Design* : *A Conceptual Approach ,*** AIAA Education Series, AIAA, Reston, VA, 2012.
AVD 4	**Chapter 3.2**	Gudmundsson, S.	***General Aviation Aircraft Design: Applied Methods and Procedures ,*** 1st Ed., Butterworth-Heinemann, September 2013.
AVD 5	**Chapter 4.3**	Sadrey, M.H.	***Aircraft Design: A Systems Engineering Approach*** , John Wiley & Sons, Inc., 2013.

NOTE: See Appendix in the Overview CM

Appendix

Approximate Equation of Takeoff Distance

My Correspondence with Lee Nicolai

Nov 29, 2020 (PR: I have a problem)

"In attempting to reconcile the first term of Eq. (6.3) on page 158 with Eq. (10.4b) on page 265, I seem to get the multiplier to be 18.8 instead of 20.9. So my multiplier is off by about 10%. I wonder what I am missing--probably making an incorrect assumption somewhere? Any insight you can provide will be much appreciated."

An approximate expression of *takeoff distance* (valid only for FPS system)

$$S_{TO} = 20.9\frac{W/S}{\sigma C_{L\max}(T/W)} + 69.6\sqrt{\frac{W/S}{\sigma C_{L\max}}} \tag{6.3}$$

A more accurate, detailed and general expression for *ground distance*

$$S_G = \frac{1.44\left(W/S_{\text{ref}}\right)_{\text{TO}}}{g\rho C_{L\max}\left[(T/W)-(D/W)-\mu(1-L/W)\right]} \tag{10.4b}$$

Nov 30, 2020 (LMN: You're kidding me; you want me to remember details?)

"Where did the factor 20.9 come from? You are asking me to remember back 50 years when I wrote the first design text in 1970. The equation with the 20.9 was developed along with class notes for the design class at the USAF Academy and I do not remember the details. The 20.9 has served me well as you are the first to ask where did it come from. I suspect it came from some assumption that I made about the transition distance since it is neither ground distance or air/climb out distance. Sorry that I can't be of more help."

Me: Hmm…I am *the first one to ask*. Everyone else must have figured it out!

Approximate Equation of Takeoff Distance

My Correspondence with Lee Nicolai (contd.)

Dec 4, 2020 (PR: Bingo!)

"I think I got it! Will you mind taking a quick look at the equations and approximations in the one-page attachment, and let me know what you think?"

If we assume the retarding force term $\{(D/W) + \mu(1 - L/W)\}$ to be 0.1 (T/W), then Eq. (10.4b) can be reduced to the 1st term of Eq. (6.3)

$$S_G = \frac{1.44\left(W/S_{\text{ref}}\right)_{\text{TO}}}{g\rho C_{L\max}\left[\left(T/W\right)-\left(D/W\right)-\mu\left(1-L/W\right)\right]} \qquad (10.4\text{b})$$

$$S_{\text{TO}} = 20.9\frac{W/S}{\sigma C_{L\max}\left(T/W\right)} + 69.6\sqrt{\frac{W/S}{\sigma C_{L\max}}} \qquad (6.3)$$

If we assume that $V_{TO} = 1.2\,V_S$, then Eq. (10.5) can be reduced to the 2nd term of Eq. (6.3)

$$S_R = 2V_{\text{TO}} \qquad (10.5)$$

We can now derive an updated expression that is not restricted to FPS units!

Dec 6, 2020 (LMN: *humorous, kind and generous response*)

"I had it all the time. Just seeing if you could solve the mystery ....not really, you are the better man. See if your students could get it."

PR: You've got to be kidding me!