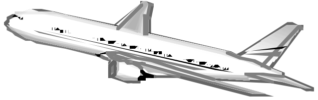
CEE 5614 - Analysis of Air Transportation Systems
Aircraft Performance Notes 1
Spring 2024

Virginia Tech - Air Transportation Systems Laboratory



Introductory Remarks

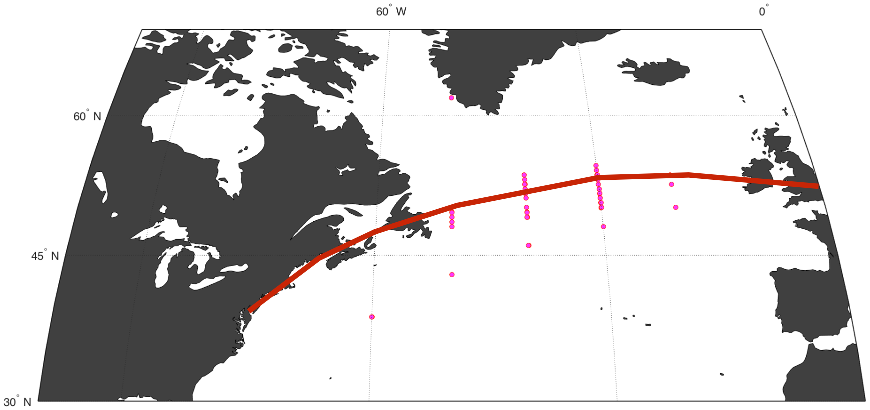
Air vehicles are significant different than their ground vehicle counterparts in three aspects:

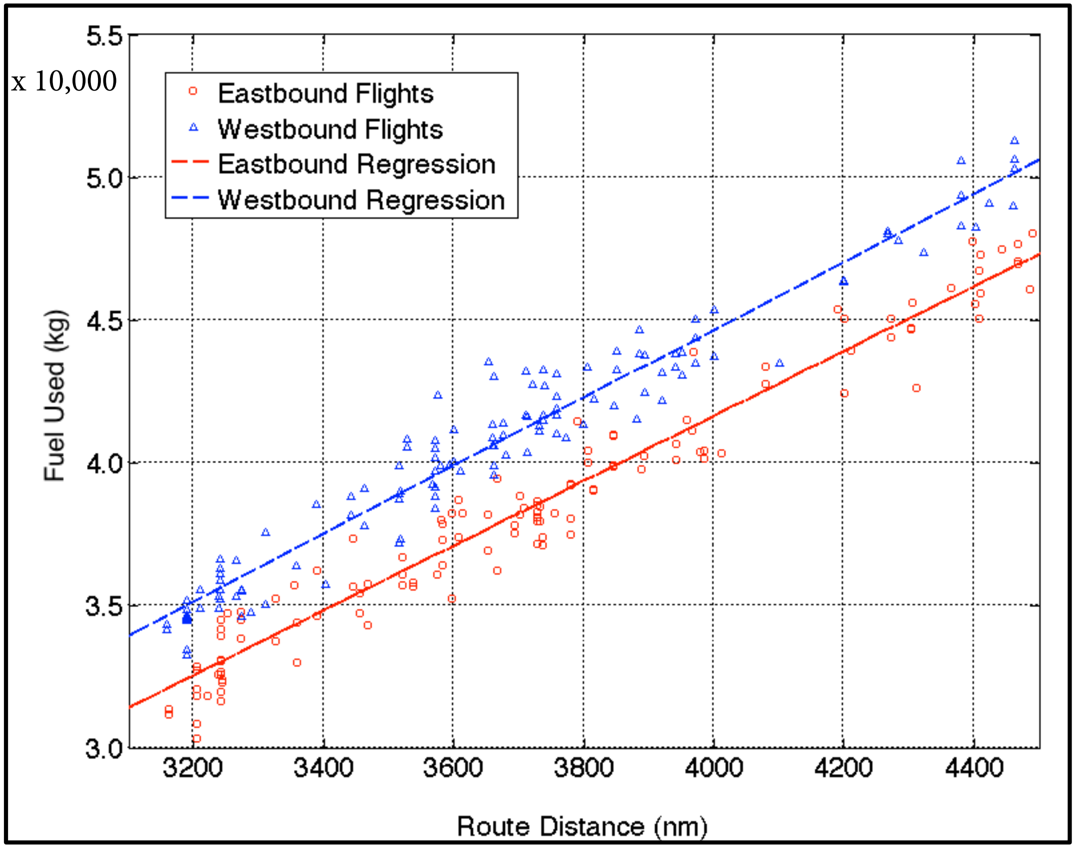
- Most aircraft require a prepared surface to operate from which affects the overall capability of the vehicle to carry useful payload
- Aircraft operate in a dynamic atmospheric environment where changes in temperature, density, and speed of sound are drastic and cannot be neglected
- Aircraft mass expenditures are significant and thus need to be accounted for in the air vehicle performance analysis. For example, a Boeing 747-400 can takeoff at near 390 metric tons and yet land at its destination at 220

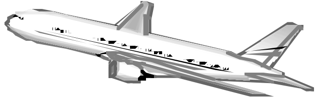
Fuel Used in Typical Transatlantic Flights

- The plot illustrates the typical fuel burn for a twin-engine wide body aircraft flown across the Atlantic
- Virginia Tech NATSAM 2 model developed for the FAA


Boeing 767-300

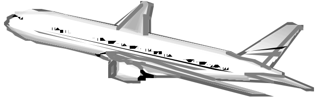




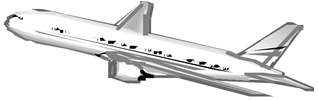


metric tons thus making the fuel expenditure a significant factor in how the vehicle performs along the flight path

- The analysis of NAS performance is related to the performance of the vehicles operating in it (i.e., airport runway and airspace sector capacity depends on aircraft characteristics)
- The analysis of airline operations requires a careful examination of the aircraft performance that matches a specific route segment (i.e., DOC, travel time, seating capacity, etc.)

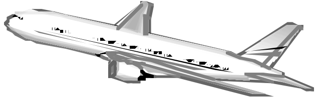


Aircraft Performance Basics (International Standard Atmosphere)



Assumptions of the International Standard Atmosphere

- Linear variation in temperature with altitude up to 11,000 meters (Troposphere)
- Constant temperature between 36,000 and 82,300 ft (25.1 kilometers) in the so-called stratosphere region
- Linearly increasing temperature from 82,300 ft. and above
- Most of the analysis we do in this class requires knowledge of temperature variations up to 15,600 meters (51,000 ft.) thus only the first two layers of the atmosphere are of interest to us



Basic Relationships to Uderstand the Atmosphere

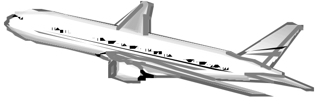
Equation of state:

$$p = \rho R T \tag{1}$$

where:

p is the air pressure (N/m^2), R is the universal gas constant (287 N-m/^oK), ρ is the air density (kg/m^3), and T is the absolute air temperature (^oK)

Basic Relationships (Hydrostatic Equation)



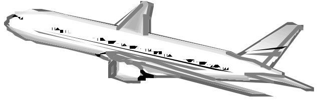
the hydrostatic equation that relates air pressure, density and height above sea level of a fluid is,

$$dp = -\rho g dh \qquad (2)$$

where: dp is rate of change in air pressure, g is the gravity constant (9.81 m/s^2), ρ is the air density (kg/m^3), and h is the altitude of the fluid element above sea level conditions (m)

Note: For derivations of these equations consult any fluid dynamics textbook or aerodynamics text

Atmosphere with Constant Temperature



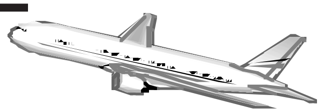
Using equations (1) and (2),

$$\frac{dp}{p} = \frac{-gdh}{RT} \tag{3}$$

This equation can be integrated to obtain a basic relationship between atmospheric pressures at various layers in the atmosphere as a function of altitude

$$\int_{p_0}^{p} \frac{dp}{p} = \int_{h_0}^{h} \frac{-gdh}{RT} \tag{4}$$

where the subindex 0 denotes a reference condition.



Atmosphere with Constant Temperature

$$\frac{p}{p_0} = e^{-\left(\frac{g}{RT}\right)(h-h_0)} \qquad (5)$$

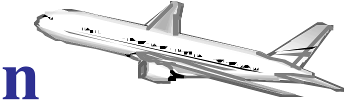
and

$$\frac{\rho}{\rho_0} = e^{-\left(\frac{g}{RT}\right)(h-h_0)} \qquad (6)$$

if the temperature is constant - isothermal layer (only true in the stratosphere).

In this analysis we have assumed a constant value for the gravity constant. This is a good approximation in the tropopause and stratosphere.

Atmosphere with Linear Temperature Variation



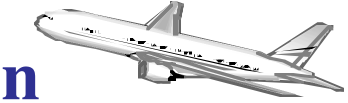
According to the International Standard Atmosphere (ISA), the variation of temperature is linear up to 11,000 meters. Then,

$$T = T_o + \lambda(h - h_o) = T_o + \frac{dT}{dh}(h - h_o) \qquad (7)$$

where: $\lambda = \frac{dT}{dh}$ is the temperature lapse rate with altitude (i.e., rate of change in temperature with altitude)

and T_0 is the reference temperature (typically sea level)

Atmosphere with Linear Temperature Variation

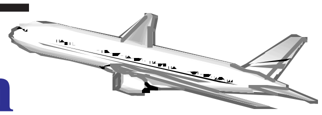


Since $dh = \frac{dT}{\lambda}$ using the equation (4) we find an expression to relate the change in pressure with altitude in a non-isothermal layer of the atmosphere,

$$\int_{p_0}^{p} \frac{dp}{p} = \int_{h_0}^{h} \frac{-g}{R\lambda} \frac{dT}{T} \tag{8}$$

$$\frac{p}{p_0} = \left(\frac{T}{T_0}\right)^{-\left(\frac{g}{R\lambda}\right)} \tag{9}$$

Atmosphere with Linear Temperature Variation

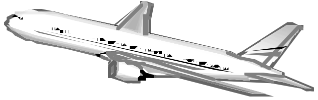


Using the equation of state for two refence points (sea level denoted by subidex zero and at altitude denoted by y a function of altitude:

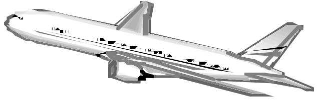
$$\frac{p}{p_0} = \frac{\rho}{\rho_0}\left(\frac{T}{T_o}\right) \qquad (10)$$

$$\frac{\rho}{\rho_0} = \left(\frac{T}{T_0}\right)^{\left[-\left(\frac{g}{R\lambda}\right) - 1\right]} \qquad (11)$$

Reference Values of Interest at ISA Conditions



Constant	Value
T_0 reference temperature	288.2 ^oK
λ temperature lapse rate	-0.0065 ^oK per meter
ρ_o air density	1.225 kg/m^3
p_o air pressure	101,325 N/m^2
a speed of sound	340.3 m/s
R universal gas constant	287 $N\text{-}m/^oK$

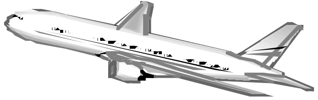


International Standard Atmosphere

Characteristics of the International Standard Atmosphere.

Geopotential Altitude (m.)	Temperature (^{o}K) T	Density (kg/m^3) ρ	Speed of Sound (m/s) a
0	288.2	1.225	340.3
1000	281.7	1.112	336.4
2000	275.2	1.007	332.5
3000	268.7	0.909	328.6
4000	262.2	0.819	324.6
5000	255.7	0.736	320.5
6000	249.2	0.660	316.4
7000	242.7	0.589	312.3
8000	236.2	0.525	308.1

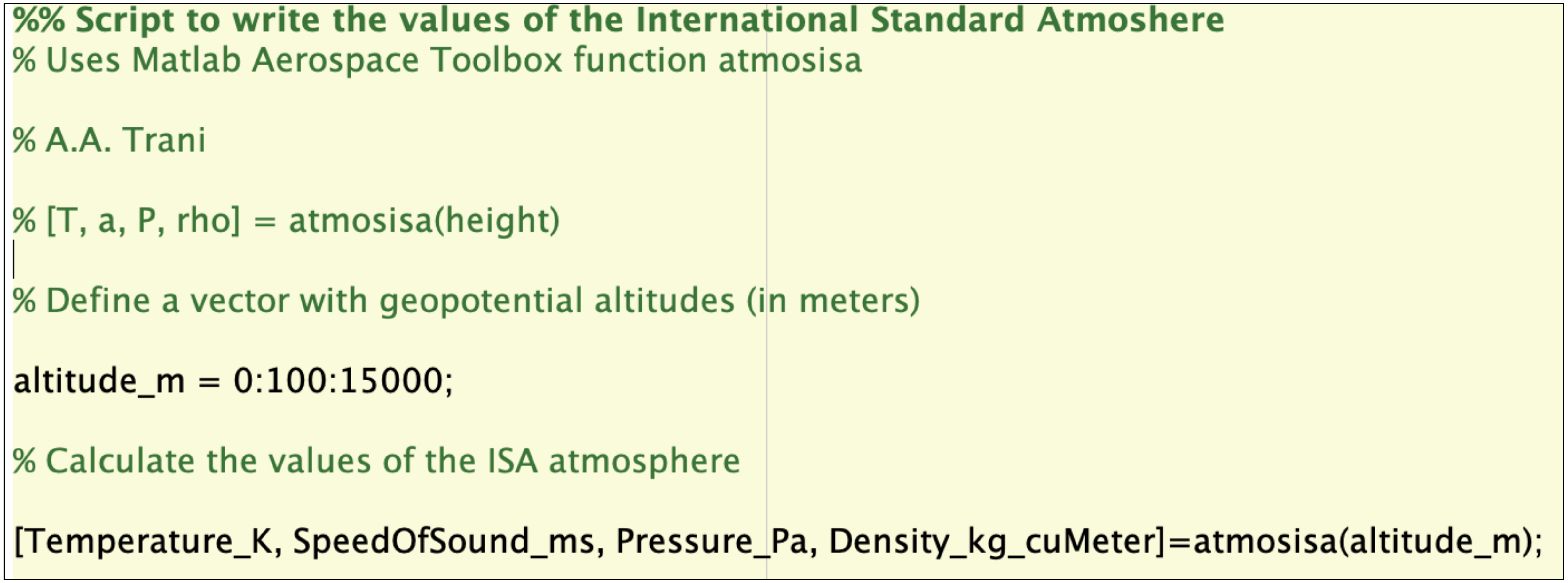
Characteristics of the International Standard Atmosphere.



Geopotential Altitude (m.)	Temperature (^oK) T	Density (kg/m^3) ρ	Speed of Sound (m/s) a
9000	229.7	0.466	303.8
10000	223.2	0.413	299.5
11000	216.7	0.364	295.1
12000	216.7	0.311	295.1
13000	216.7	0.266	295.1
14000	216.7	0.227	295.1
15000	216.7	0.194	295.1
16000	216.7	0.169	295.1

Graphical Depiction of the ISA Atmospheric Model

- Use the Matlab Aerospace Toolbox or the function ISAM provided in class to estimate the values of the International Atmosphere
- Function: **atmosisa**
- **Input = geopotential altitude (meters)**
- **Outputs = Temperature, Speed of sound, Pressure and Density)**



```
%% Script to write the values of the International Standard Atmoshere
% Uses Matlab Aerospace Toolbox function atmosisa

% A.A. Trani

% [T, a, P, rho] = atmosisa(height)

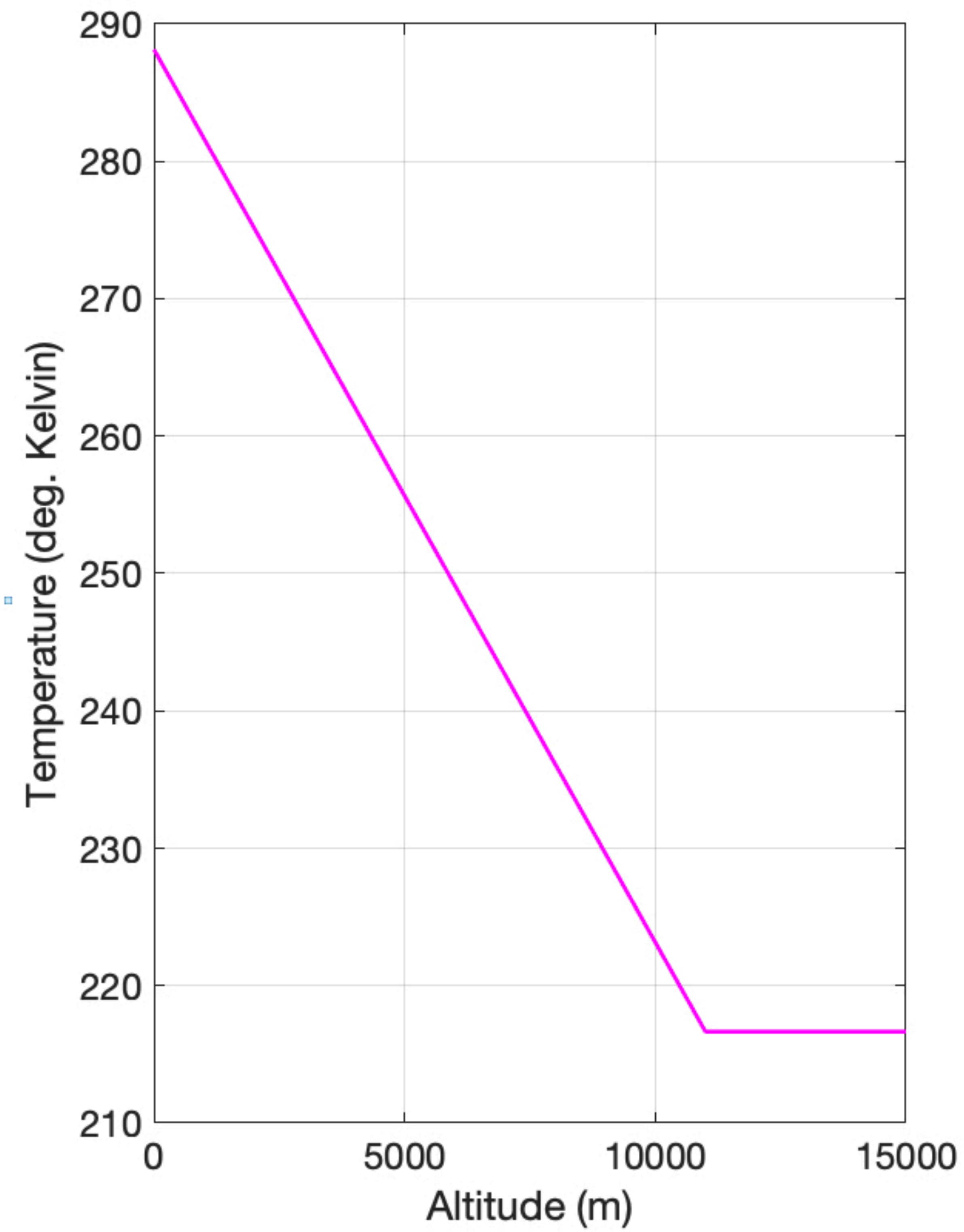
% Define a vector with geopotential altitudes (in meters)

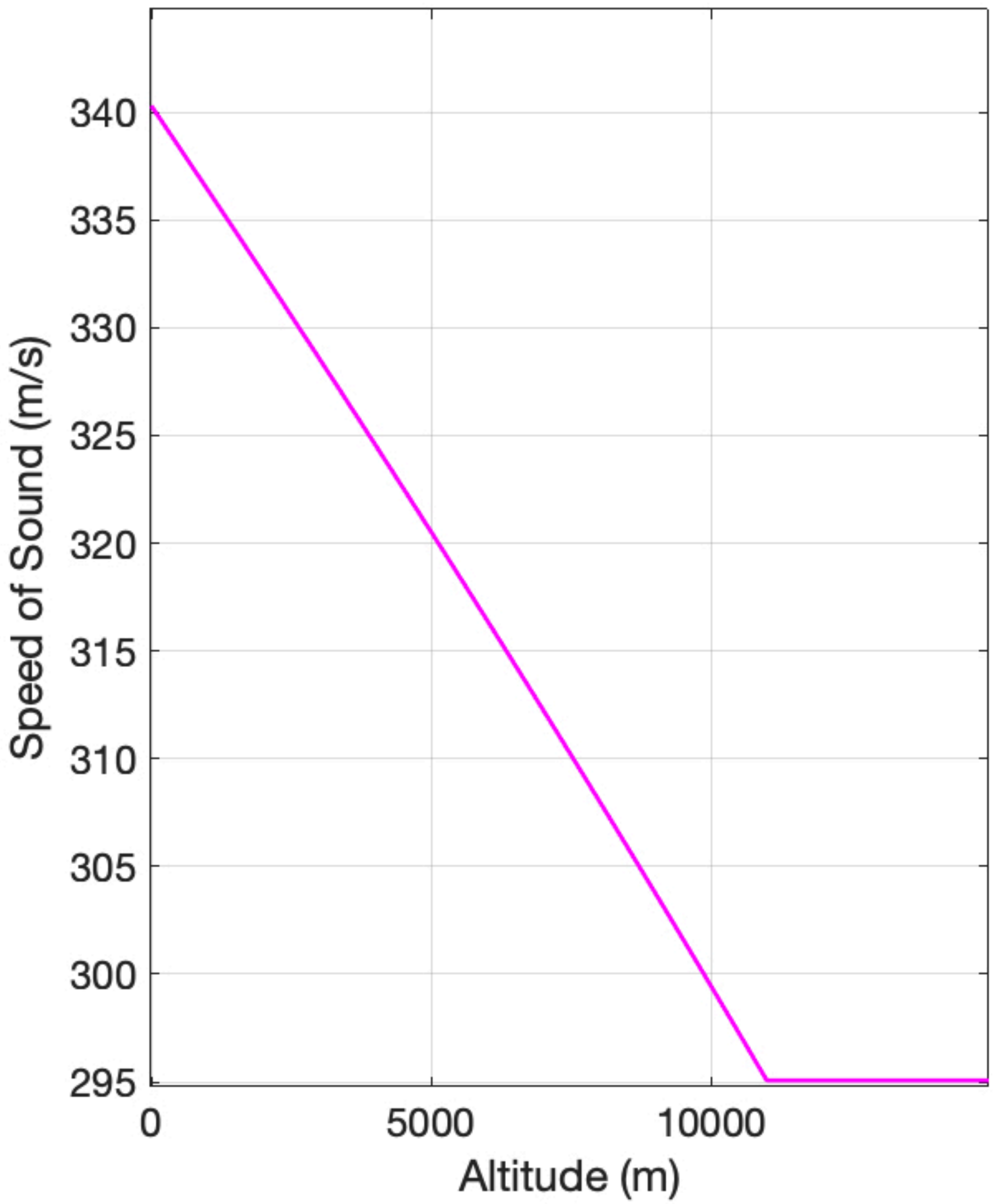
altitude_m = 0:100:15000;

% Calculate the values of the ISA atmosphere

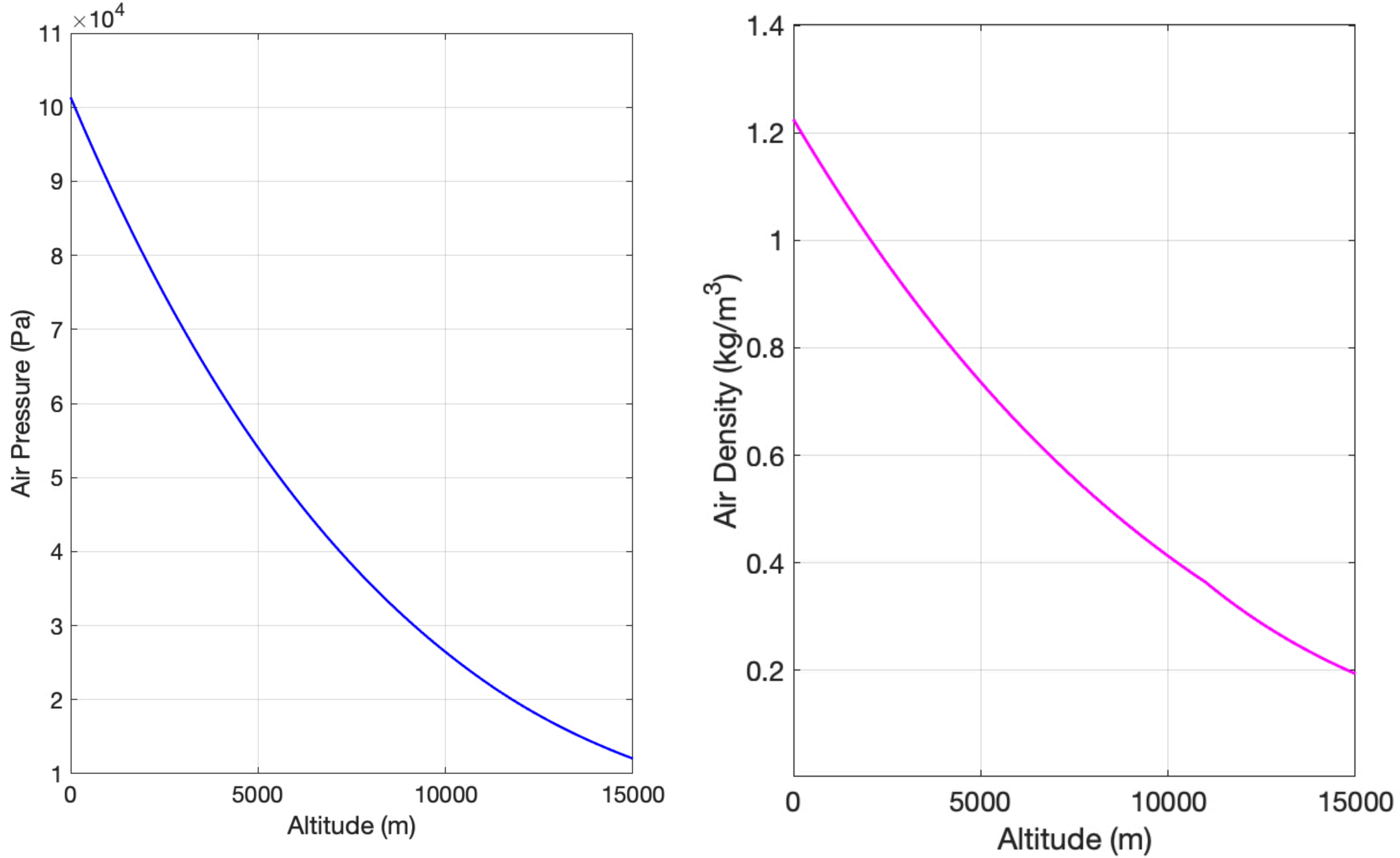
[Temperature_K, SpeedOfSound_ms, Pressure_Pa, Density_kg_cuMeter]=atmosisa(altitude_m);
```

International Standard Atmosphere

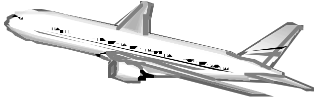




International Standard Atmosphere



Important Aircraft Speed Terms to Know



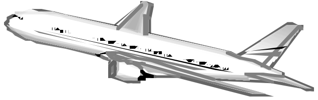
Indicated Airspeed (IAS) - is the speed registered in the cockpit instrument

True Airspeed (TAS) - is the actual speed of the vehicle with respect of the mass of air surrounding the aircraft (accounts for compressibility effects)

Calibrated Airspeed (CAS) - similar to IAS but corrected for instrument position errors (airflow problems outside the vehicle).

Ground speed (GS) - TAS corrected for wind

Stalling Speed (V_{stall}) - minimum speed for safe flight



Mach Number - ratio of the aircraft speed to the speed of sound, a (note a varies with altitude)

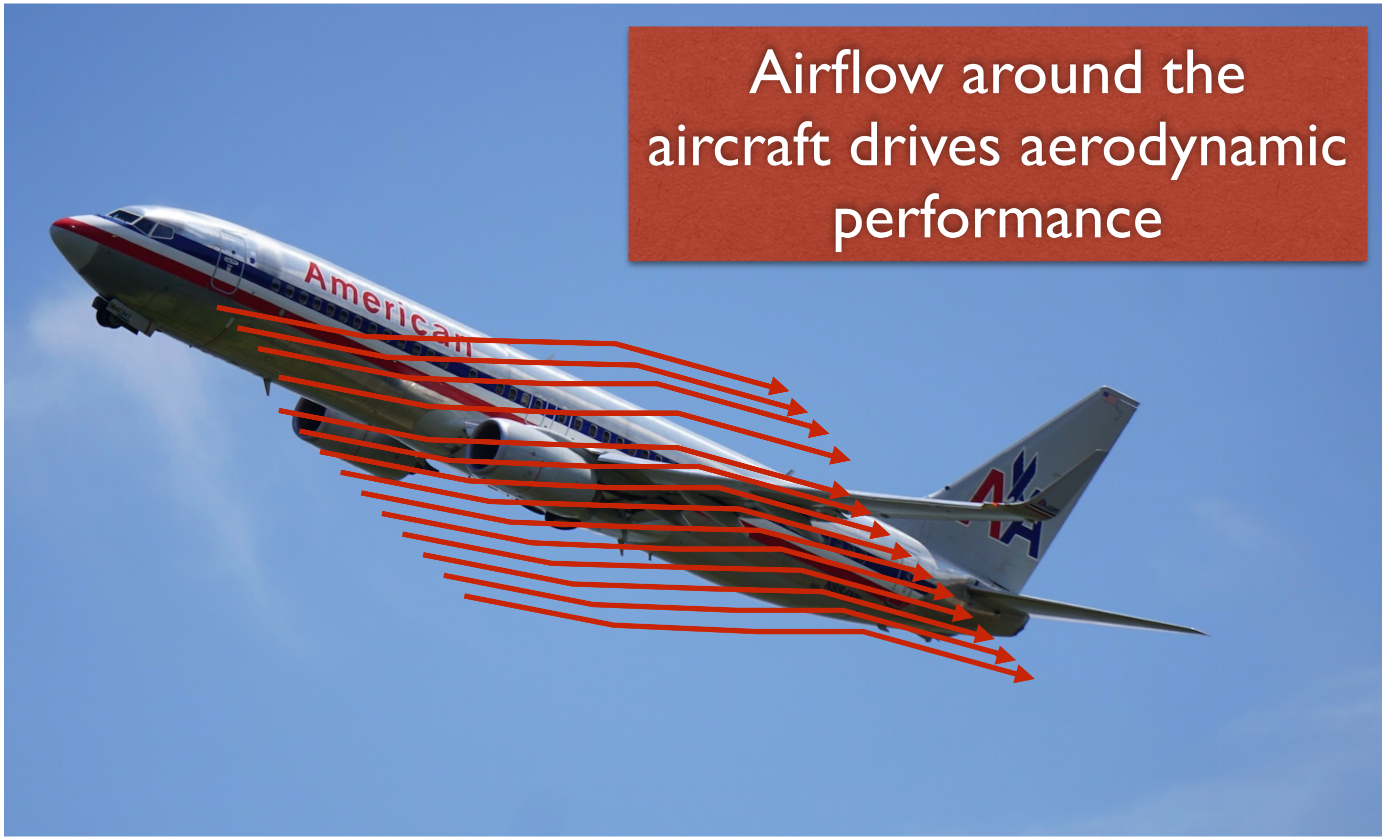
Mach number can be easily computed using the following equation,

$$a = \sqrt{\gamma R T} \tag{12}$$

where: R is the universal gas constant (287 N-m/^{o}K), T is the air temperature (^{o}K) and γ is the ratio of specific heat at constant volume ($\gamma = 1.4$ for air)

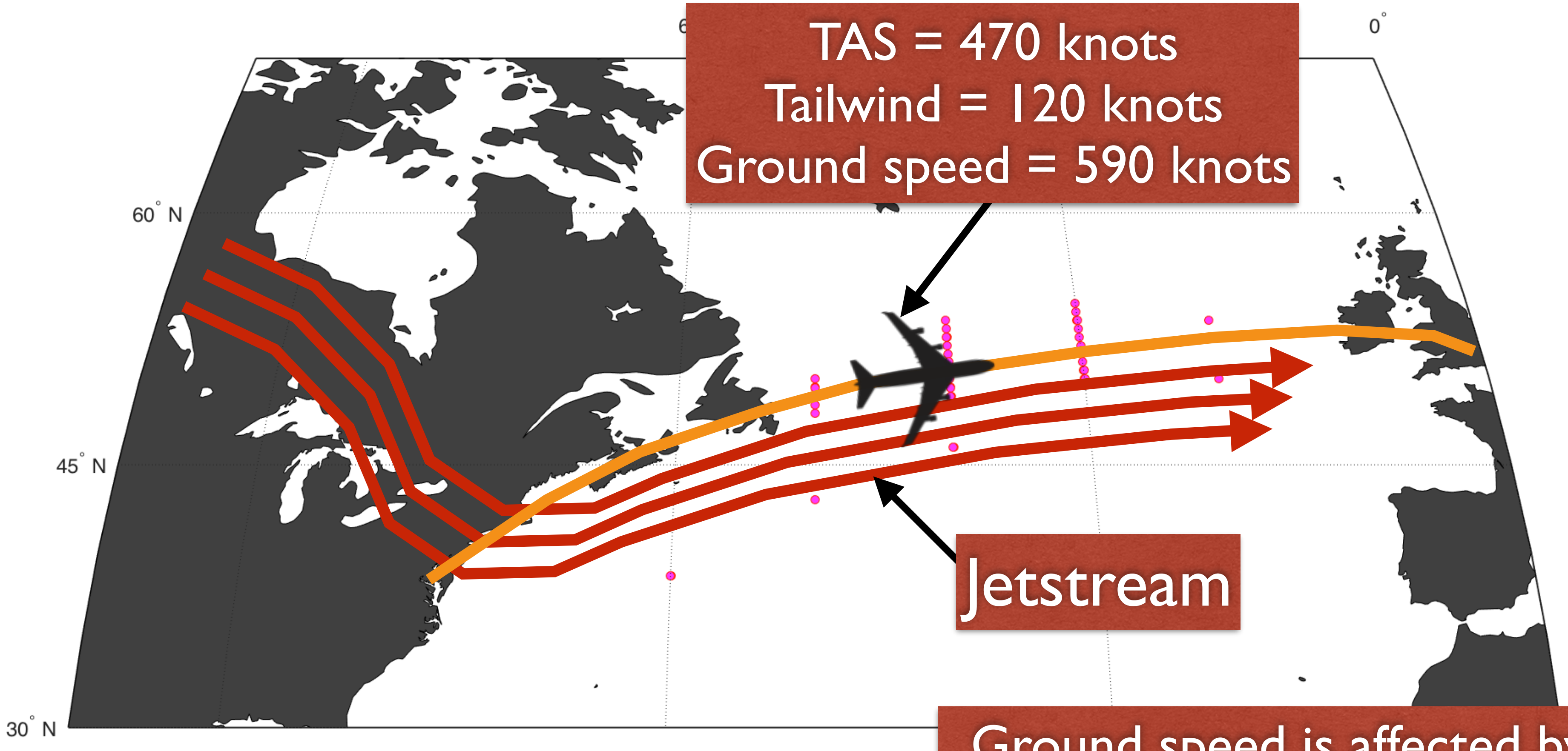
Significance of Aircraft Speeds

- True airspeed (TAS) is the speed that is used in measuring the aerodynamic performance of the aircraft in flight
- Aerodynamic forces are affected by the speed of the air surrounding the aircraft


Airflow around the aircraft drives aerodynamic performance

Significance of Aircraft Speeds (2)

- Ground speed (GS) is the speed that is used to measure travel time (an important factor in air transportation)



TAS = 470 knots
Tailwind = 120 knots
Ground speed = 590 knots

Jetstream

Ground speed is affected by winds aloft between the origin and destination airports

An Exceptional Flight

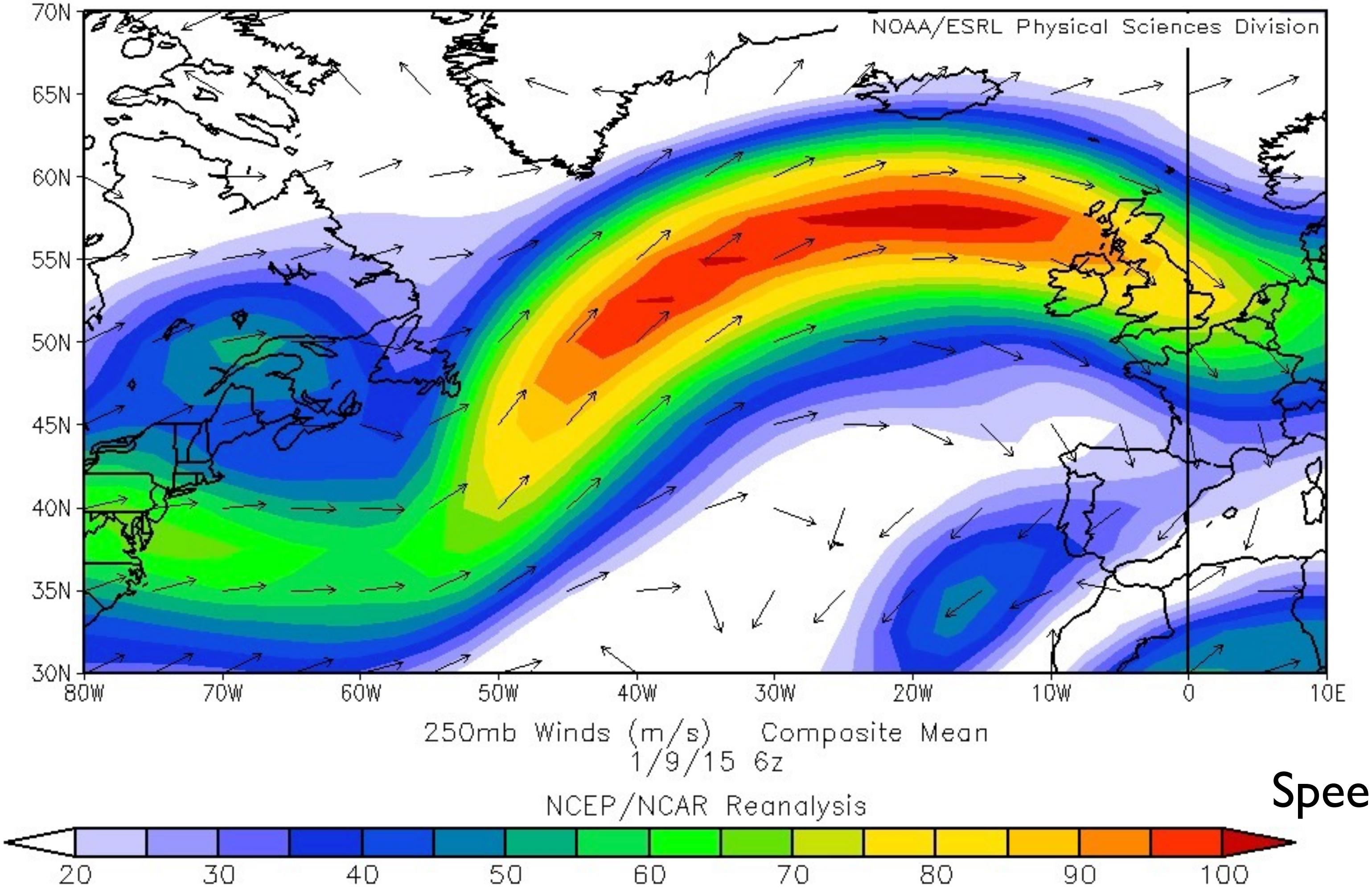
- A British Airways Boeing 777-200 flight from JFK to London LHR (Heathrow)
- 5 hours and 16 minutes across the Atlantic (typically a 7 hour flight)
- Aircraft took advantage of 170 knot tailwind Jetstream for most of the cruise flight

Jet stream blasts BA plane across Atlantic in record time

Boeing 777 reported at speeds of up to 745mph as it flies from New York to Heathrow in just 5 hours 16 minutes

An Exceptional Flight (2)

- Wind patterns over the North Atlantic on January 9, 2015
- Note the wind speeds over 90 m/s

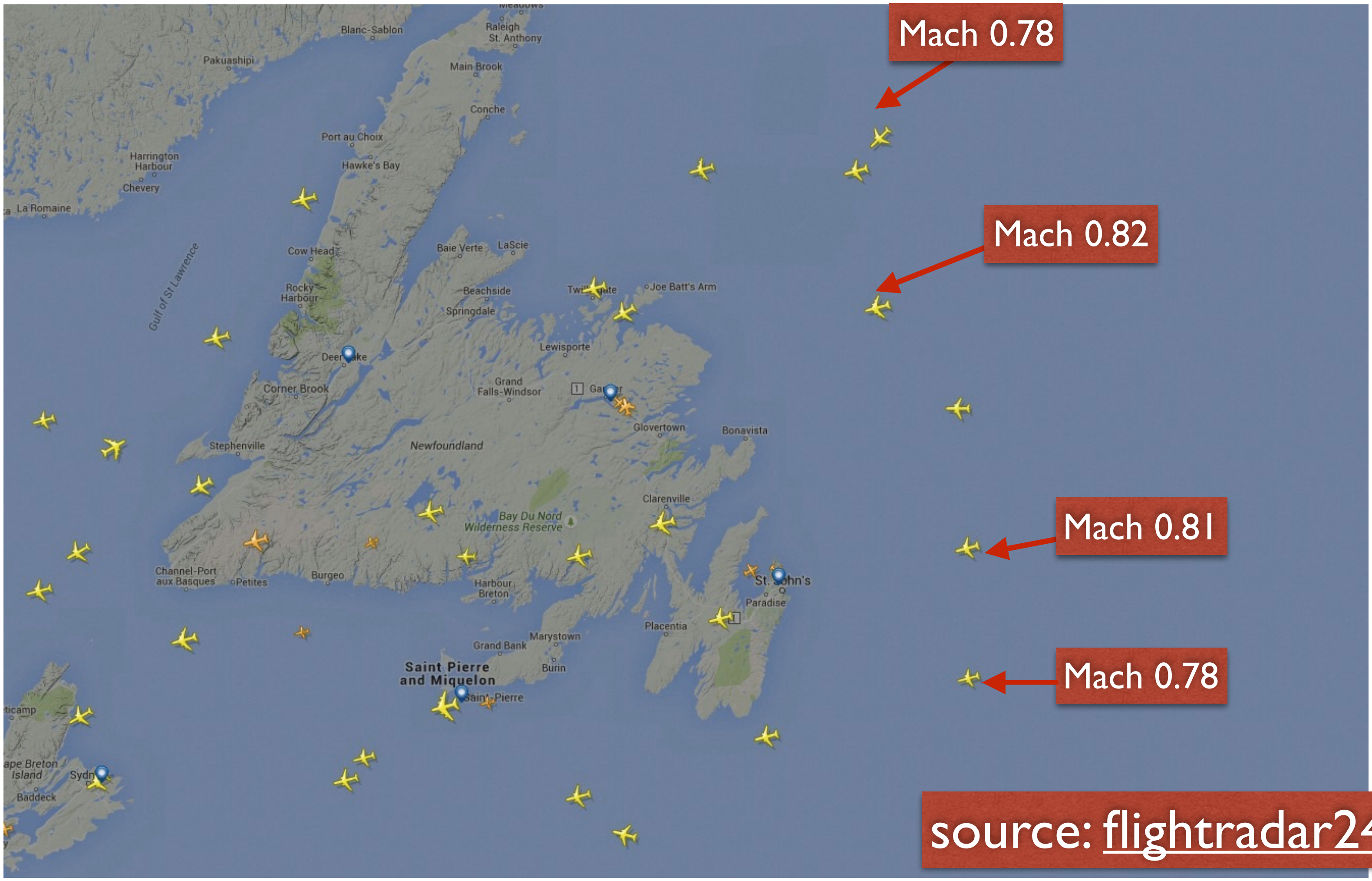


Speed in m/s

http://www.esrl.noaa.gov/psd/data/composites/hour/

Significance of Mach Number

- Most of the speed information shared between pilots and Air Traffic Controllers in the cruise segment of the flight is expressed in Mach number

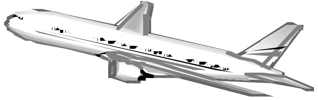


source: flightradar24.com

Typical Cruise Mach Numbers for Some Commercial Aircraft (ISA Conditions and 11,000 meters cruise altitude)

Aircraft	Typical Mach Number	True Airspeed (knots)
Boeing 737-800 and Airbus A320	0.78	445
Boeing 767-300	0.81	464
Boeing 777-200 and Airbus A330-300	0.83	476
Boeing 747-400, Airbus A380 and Airbus A350	0.84-0.85	482-488

Aircraft Recognition Quiz

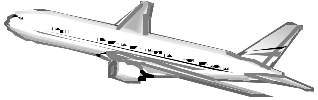


Air Compressibility Effects

A mathematical expression to estimate true airspeed (in terms of true Mach number) from CAS follows:

$$M_{true} = \sqrt{5\left[\left[\frac{\rho_0}{\rho}\left(\left[1+0.2\left(\frac{V_{CAS}}{661.5}\right)^2\right]^{3.5}-1\right)+1\right]^{0.286}-1\right]} \qquad (13)$$

where: M_{true} is the true mach number, V_{CAS} is the calibrated airspeed in knots (CAS = IAS) in our analysis, ρ_0 is the atmospheric density at sea level, ρ is the density at the altitude the aircraft is flying, and the constants 0.2 and 661.5 account for the specific heat of the air and the speed of sound at sea level (in knots), respectively.



Defining true mach number (M_{true}) as the ratio of the true aircraft speed (V_{TAS}) and the speed of sound (a) at the flight level in question we have,

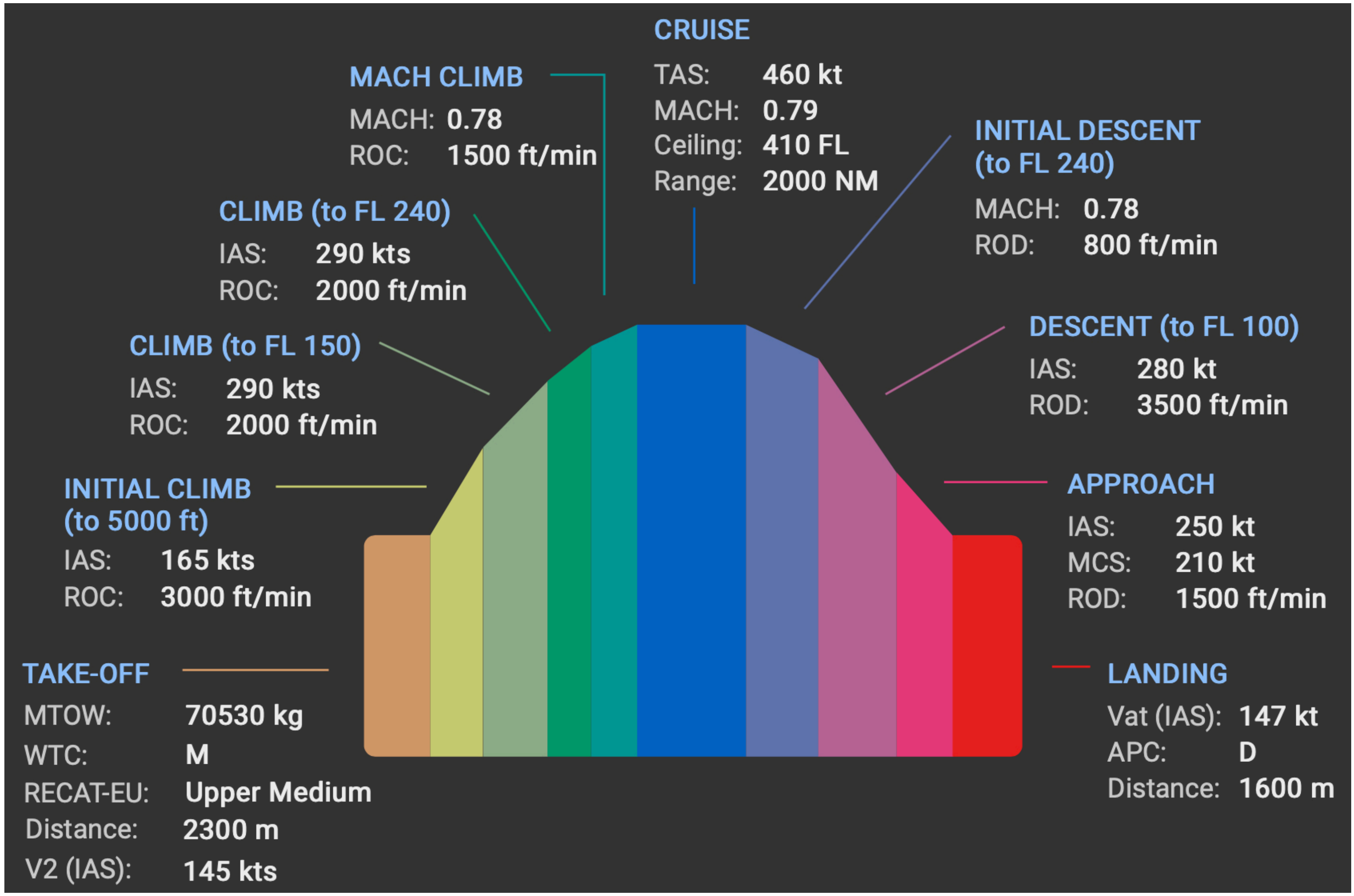
$$V_{TAS} = aM_{true} \tag{14}$$

Example Problem to Estimate True Airspeed

A pilot of a Boeing 737-800 (a medium size jet transport) reports flying at **290 knots (IAS)** at an altitude of **15,000 feet (4,572 meters)** under standard atmospheric conditions

Find the True Airspeed (TAS) and the aircraft Mach number at the flight conditions reported

source: A. A. Trani



CRUISE
TAS: 460 kt
MACH: 0.79
Ceiling: 410 FL
Range: 2000 NM

MACH CLIMB
MACH: 0.78
ROC: 1500 ft/min

INITIAL DESCENT (to FL 240)
MACH: 0.78
ROD: 800 ft/min

CLIMB (to FL 240)
IAS: 290 kts
ROC: 2000 ft/min

CLIMB (to FL 150)
IAS: 290 kts
ROC: 2000 ft/min

DESCENT (to FL 100)
IAS: 280 kt
ROD: 3500 ft/min

INITIAL CLIMB (to 5000 ft)
IAS: 165 kts
ROC: 3000 ft/min

APPROACH
IAS: 250 kt
MCS: 210 kt
ROD: 1500 ft/min

TAKE-OFF
MTOW: 70530 kg
WTC: M
RECAT-EU: Upper Medium
Distance: 2300 m
V2 (IAS): 145 kts

LANDING
Vat (IAS): 147 kt
APC: D
Distance: 1600 m

Example Problem to Estimate True Airspeed

Flight conditions are: **290 knots (IAS)** at an altitude of **15,000 feet (4,572 meters)** under standard atmospheric conditions

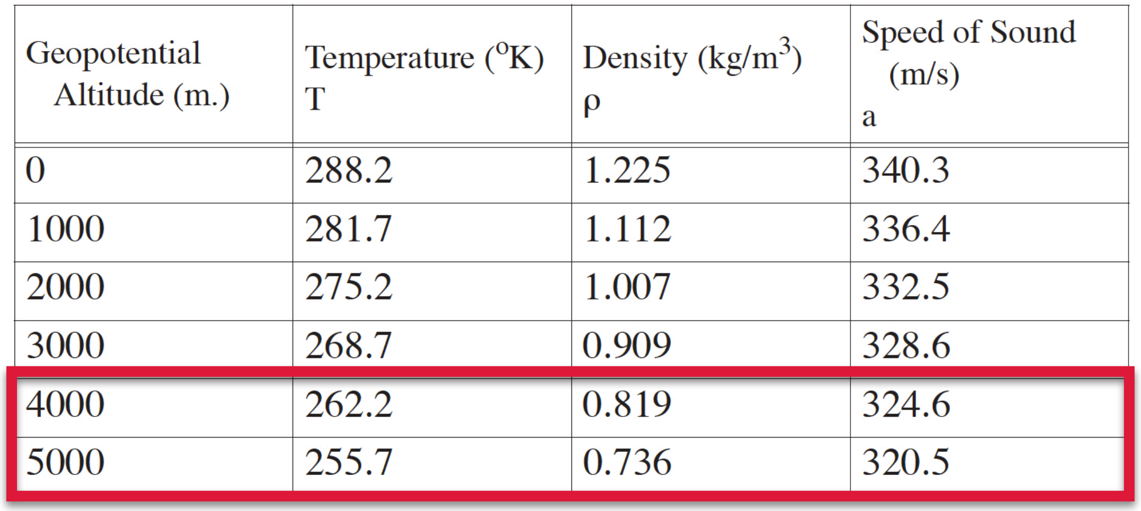
Solution : Use the ISA Table to estimate the following parameters at 4,572 meters:

Density = 0.7707 kg/m³

Mach number of 0.5459 (use Equation 13)

$$M_{true} = \sqrt{5\left[\left[\frac{\rho_0}{\rho}\left(\left[1+0.2\boxed{\left(\frac{V_{CAS}}{661.5}\right)}^2\right]^{3.5}-1\right)+1\right]^{0.286}-1\right]}$$

Assume calibrated airspeed and indicated airspeeds are the same



Geopotential Altitude (m.)	Temperature (°K) T	Density (kg/m³) ρ	Speed of Sound (m/s) a
0	288.2	1.225	340.3
1000	281.7	1.112	336.4
2000	275.2	1.007	332.5
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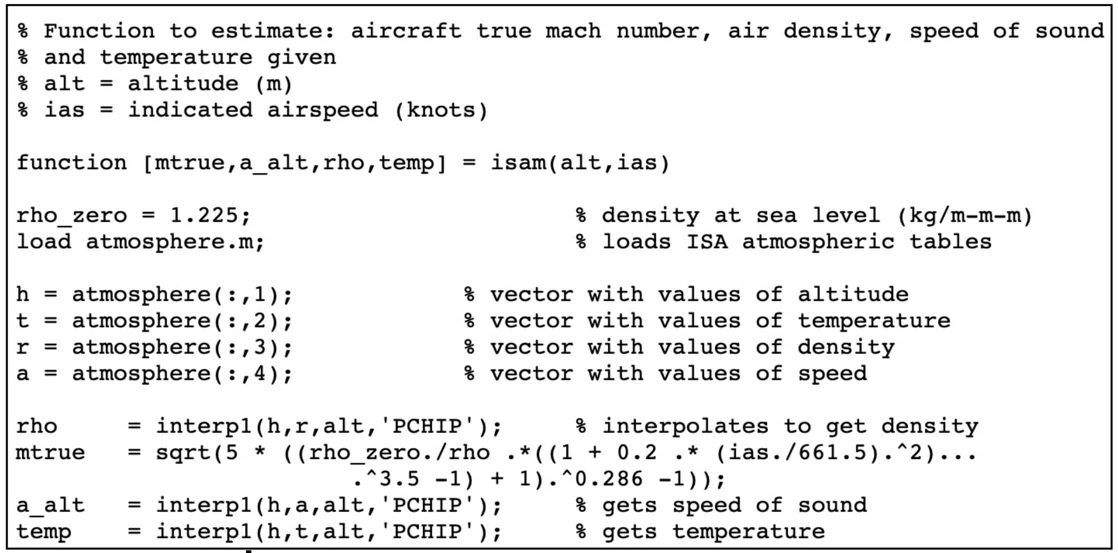
ISAM function



```
% Function to estimate: aircraft true mach number, air density, speed of sound
% and temperature given
% alt = altitude (m)
% ias = indicated airspeed (knots)

function [mtrue,a_alt,rho,temp] = isam(alt,ias)

rho_zero = 1.225;                          % density at sea level (kg/m-m-m)
load atmosphere.m;                         % loads ISA atmospheric tables

h = atmosphere(:,1);               % vector with values of altitude
t = atmosphere(:,2);               % vector with values of temperature
r = atmosphere(:,3);               % vector with values of density
a = atmosphere(:,4);               % vector with values of speed

rho     = interp1(h,r,alt,'PCHIP');    % interpolates to get density
mtrue   = sqrt(5 * ((rho_zero./rho .*((1 + 0.2 .* (ias./661.5).^2)...
                        .^3.5 -1) + 1).^0.286 -1));
a_alt   = interp1(h,a,alt,'PCHIP');    % gets speed of sound
temp    = interp1(h,t,alt,'PCHIP');    % gets temperature
```

T = 258.4 deg. Kelvin
a = 322.28 m/s
p = 0.7707 kg/m³

Example Problem to Estimate True Airspeed

Flight conditions are: **290 knots (IAS)** at an altitude of **15,000 feet (4,572 meters)** under standard atmospheric conditions

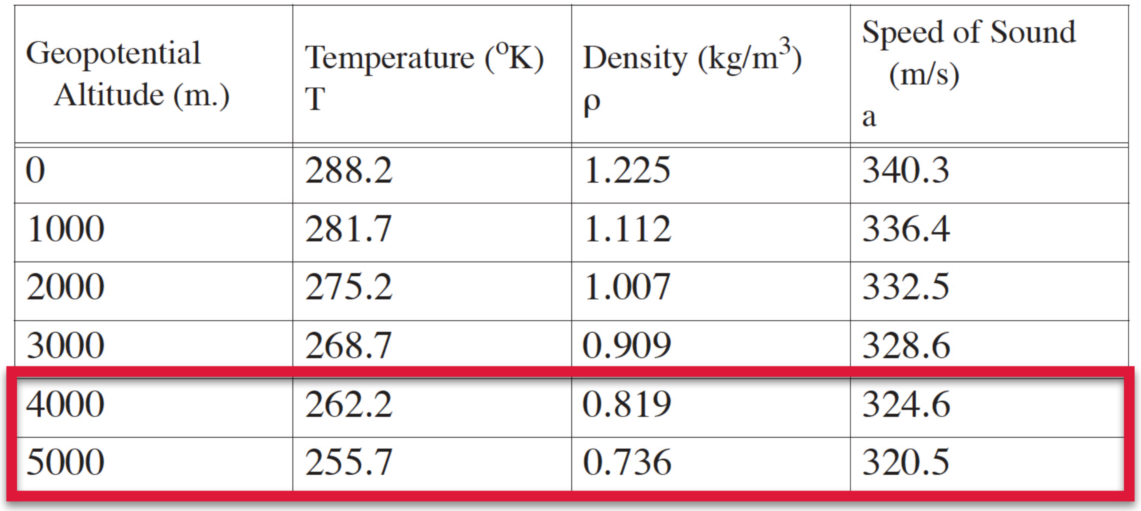
Use ISAM to find the remaining parameters of the atmosphere at 4,572 meters:

Speed of sound (a) is 322.3 m/s

Mach number (mtrue) is 0.5459 (dim)

$$\mathbf{V_{TAS} = a\,(M_{true})}$$

True airspeed of the aircraft is 175.91 m/s or **342 knots.**



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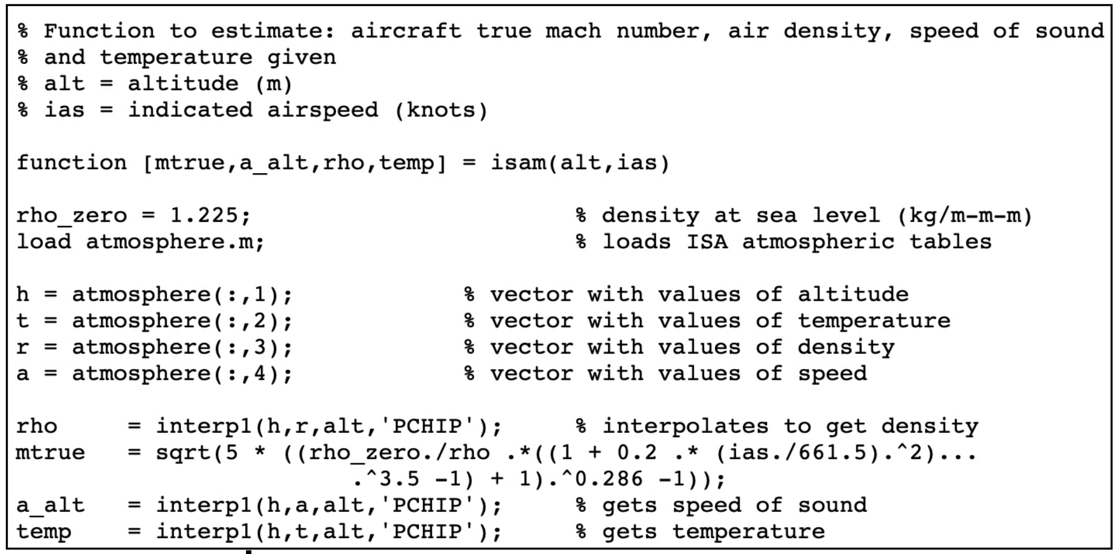
ISAM function



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rho     = interp1(h,r,alt,'PCHIP');      % interpolates to get density
mtrue   = sqrt(5 * ((rho_zero./rho .*((1 + 0.2 .* (ias./661.5).^2)...
                        .^3.5 -1) + 1).^0.286 -1));
a_alt   = interp1(h,a,alt,'PCHIP');      % gets speed of sound
temp    = interp1(h,t,alt,'PCHIP');      % gets temperature
```

T = 258.4 deg. Kelvin
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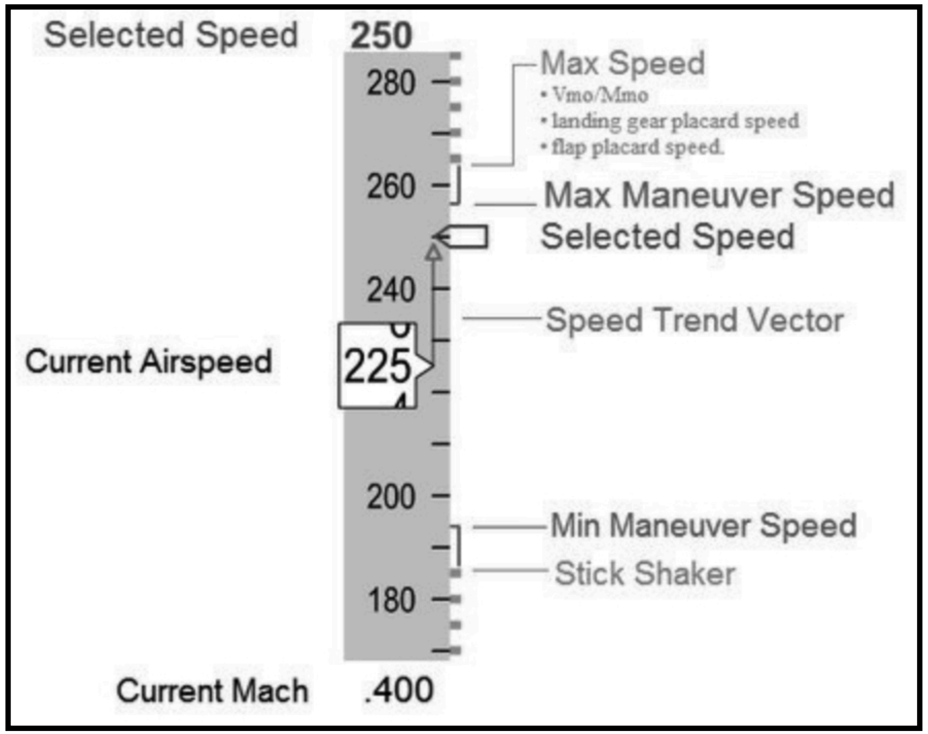
p = 0.7707 kg/m^3

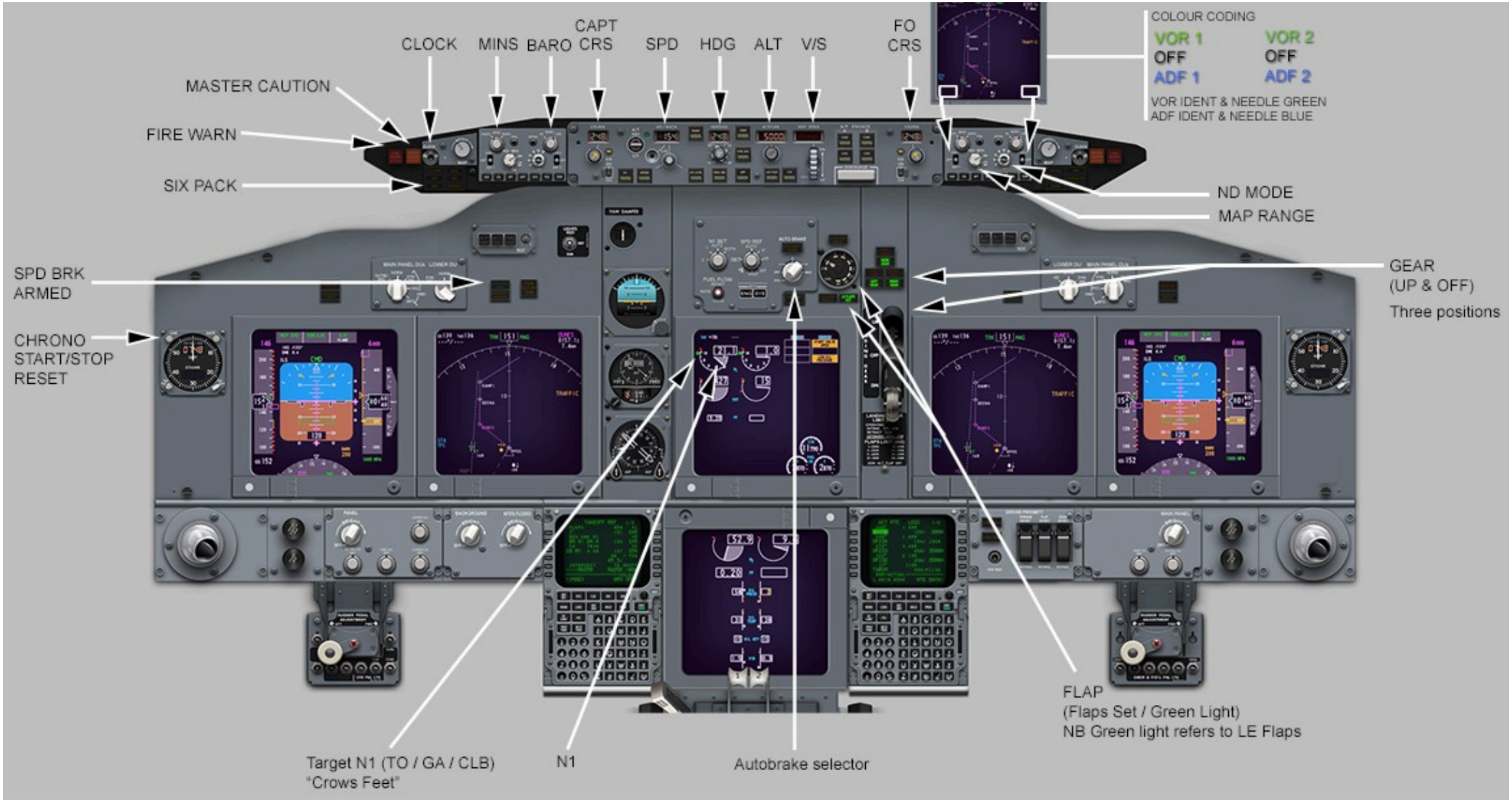
Important Observations

- At 4,572 meters (290 knots IAS) the difference between IAS and TAS is **52 knots**
- At sea level ISA conditions IAS and TAS are the same
- The difference between IAS and TAS is larger as the aircraft climbs to higher altitudes
- Ground Speed (GS) is the value of true airspeed adjusted by wind (GS is used to estimate travel time)

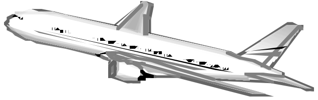


Boeing 737-800 Primary Flight Display
Source: https://pmflight.co.uk/737-simulator-pfd/

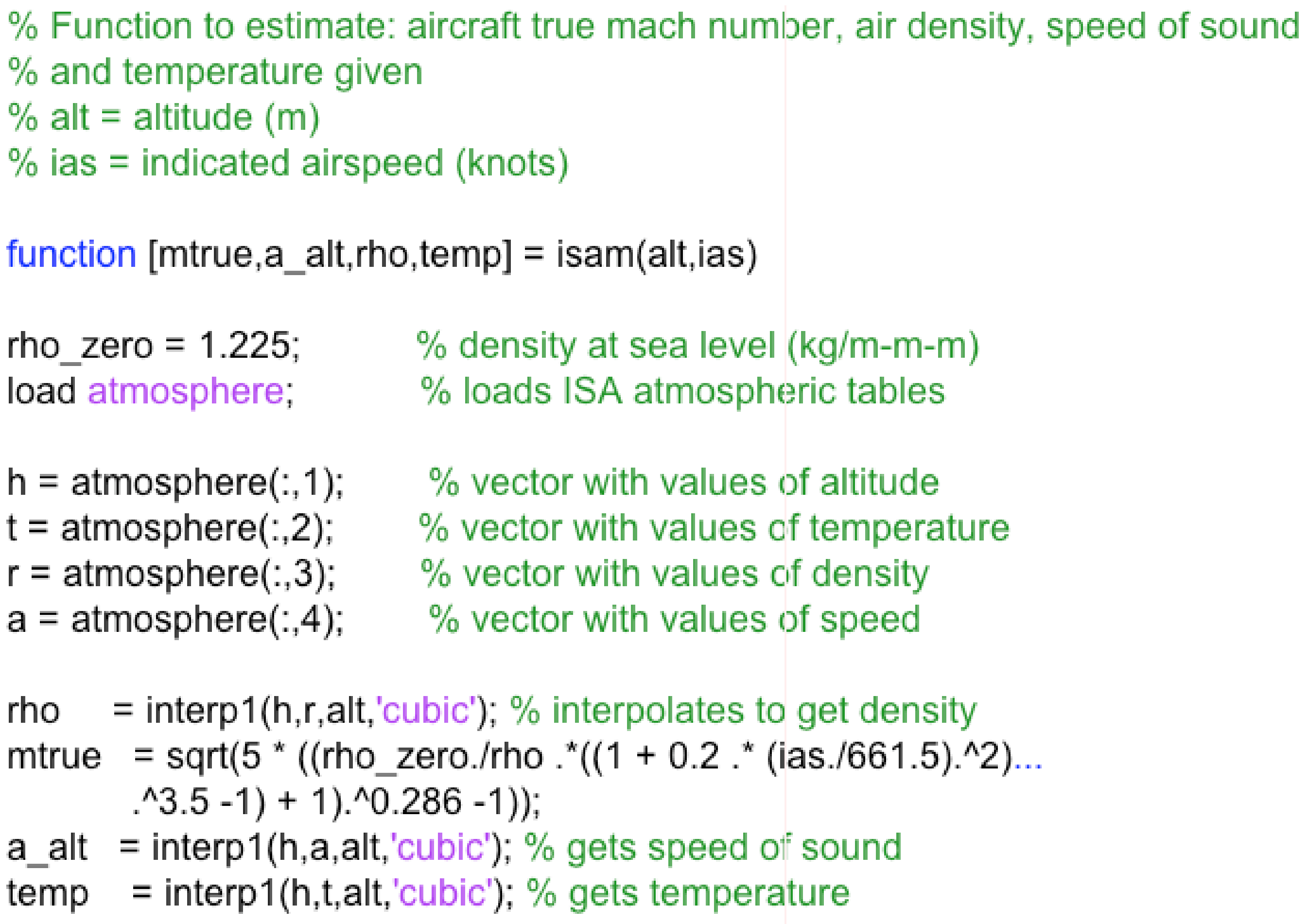
Typical Flight Deck Instrumentation



Boeing 737-800 Instrument Panel
Source: https://pmflight.co.uk/737-simulator-pfd/



Sample Matlab Code Used (ISAM.m)



```
% Function to estimate: aircraft true mach number, air density, speed of sound
% and temperature given
% alt = altitude (m)
% ias = indicated airspeed (knots)

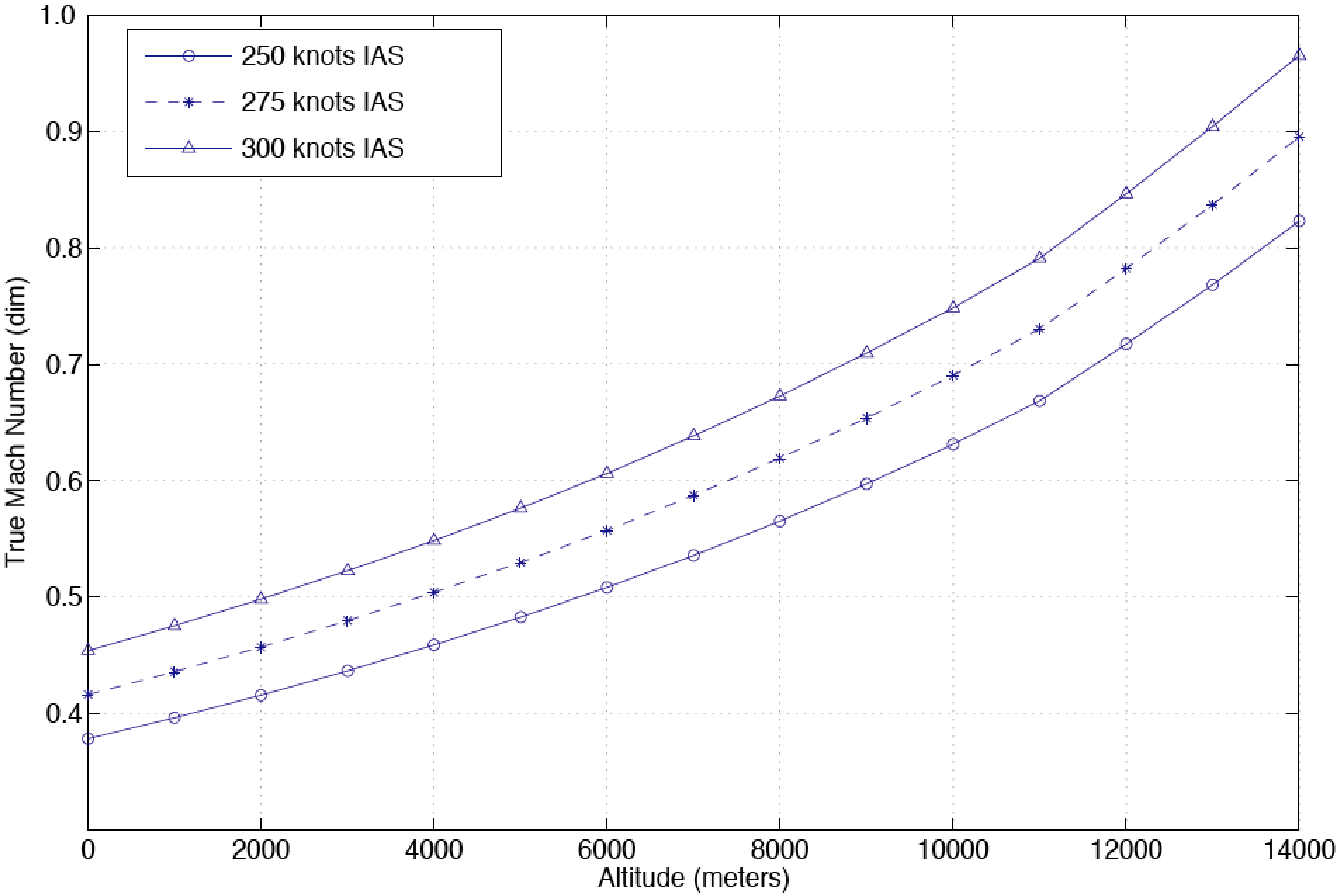
function [mtrue,a_alt,rho,temp] = isam(alt,ias)

rho_zero = 1.225;          % density at sea level (kg/m-m-m)
load atmosphere;           % loads ISA atmospheric tables

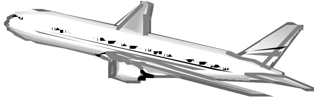
h = atmosphere(:,1);        % vector with values of altitude
t = atmosphere(:,2);        % vector with values of temperature
r = atmosphere(:,3);        % vector with values of density
a = atmosphere(:,4);        % vector with values of speed

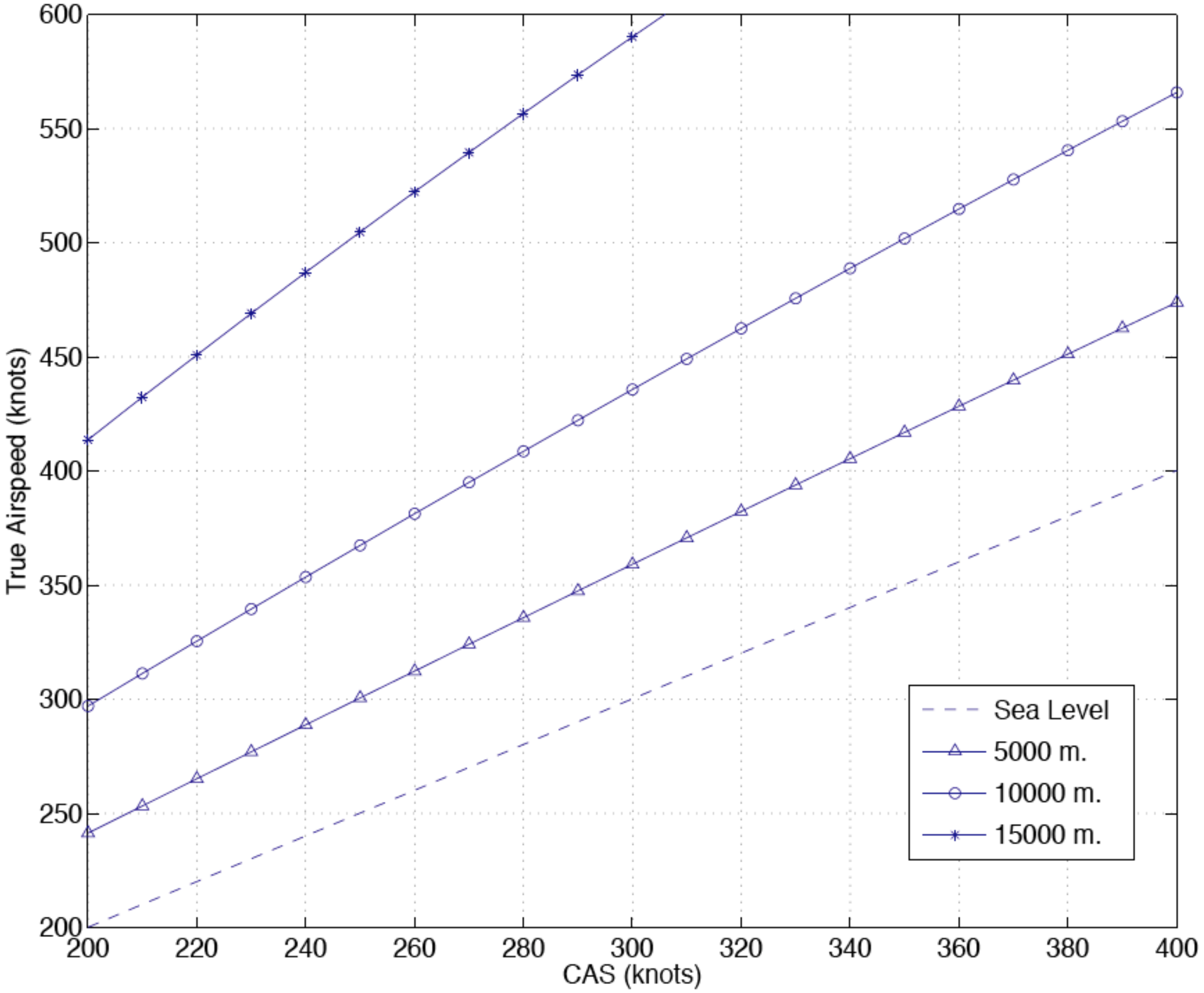
rho     = interp1(h,r,alt,'cubic'); % interpolates to get density
mtrue   = sqrt(5 * ((rho_zero./rho .*((1 + 0.2 .* (ias./661.5).^2)...
          .^3.5 -1) + 1).^0.286 -1));
a_alt   = interp1(h,a,alt,'cubic'); % gets speed of sound
temp    = interp1(h,t,alt,'cubic'); % gets temperature
```

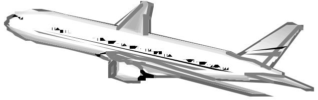
Plot of True Mach Number vs. Altitude



Plot of CAS vs. TAS (Subsonic Aircraft)







Aircraft Performance Estimation (Runway Length)

Aircraft Runway Length Performance Estimation

Critical issue in airport engineering and planning (errors in runway length are costly to the operator and perhaps unsafe)

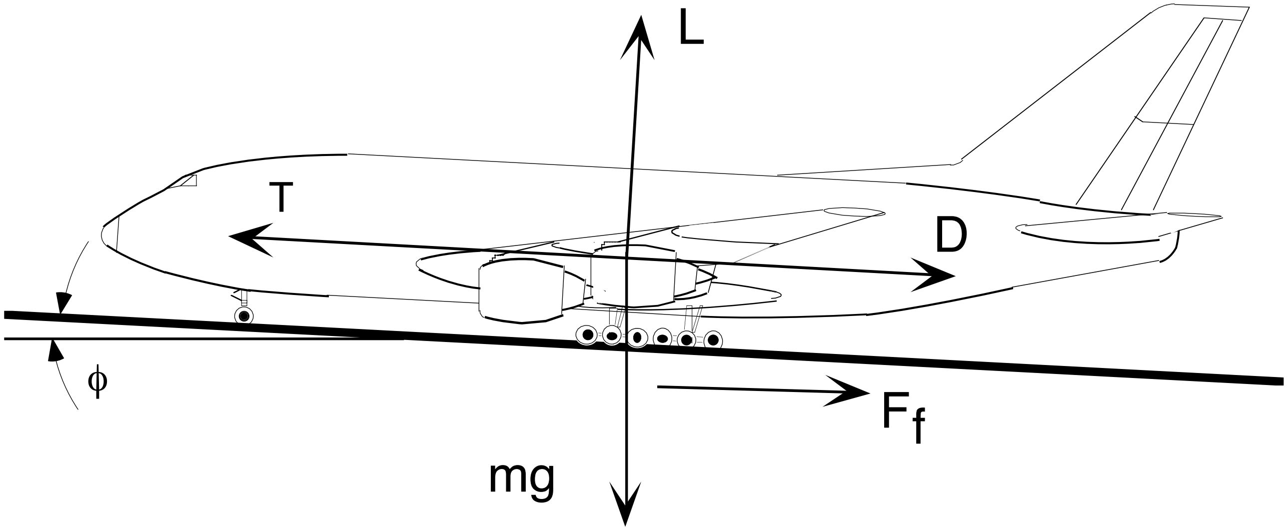
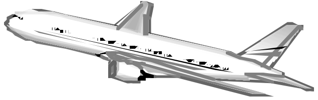


Figure 1. Forces Acting in the Aircraft During Takeoff.



Nomenclature

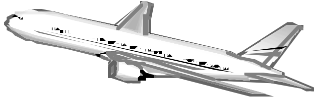
T - thrust force (also called tractive effort) provided by the vehicle powerplant

L - lifting force provided by the wing-body of the vehicle

D - drag force to the vehicle body, nacelle(s), landing gears, etc.,

F_f - friction force due to rolling resistance

The functional form of these forces has been derived from dimensional analysis (review your math course notes) and from extensive knowledge of fluid mechanics (wind tunnels and water tank experiments)



Functional Forms of the Forces

The functional form of these forces is as follows:

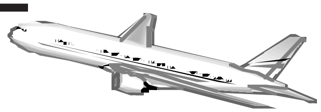
$$L = \frac{1}{2}\rho V^2 S C_L \tag{15}$$

$$D = \frac{1}{2}\rho V^2 S C_D \tag{16}$$

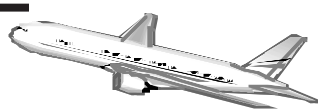
$$T = f(V, \rho) \tag{17}$$

$$F_f = (mg\cos\phi - L)f_{roll} \tag{18}$$

V is the vehicle speed (TAS), ρ is the air density (kg/m^3), S is the aircraft gross wing area, C_L is the lift coefficient (nondimensional), C_D is the drag coefficient (nondimensional), f_{roll} is the rolling friction coefficient (nondimensional), T is the engine thrust iin Newtons and



ϕ is the angle comprised between the runway plane and the horizontal



Notes on Various Parameters

1) C_L and C_D are specific to each airframe-flap configuration

2) f_{roll} is usually a function of runway surface conditions and aircraft speed

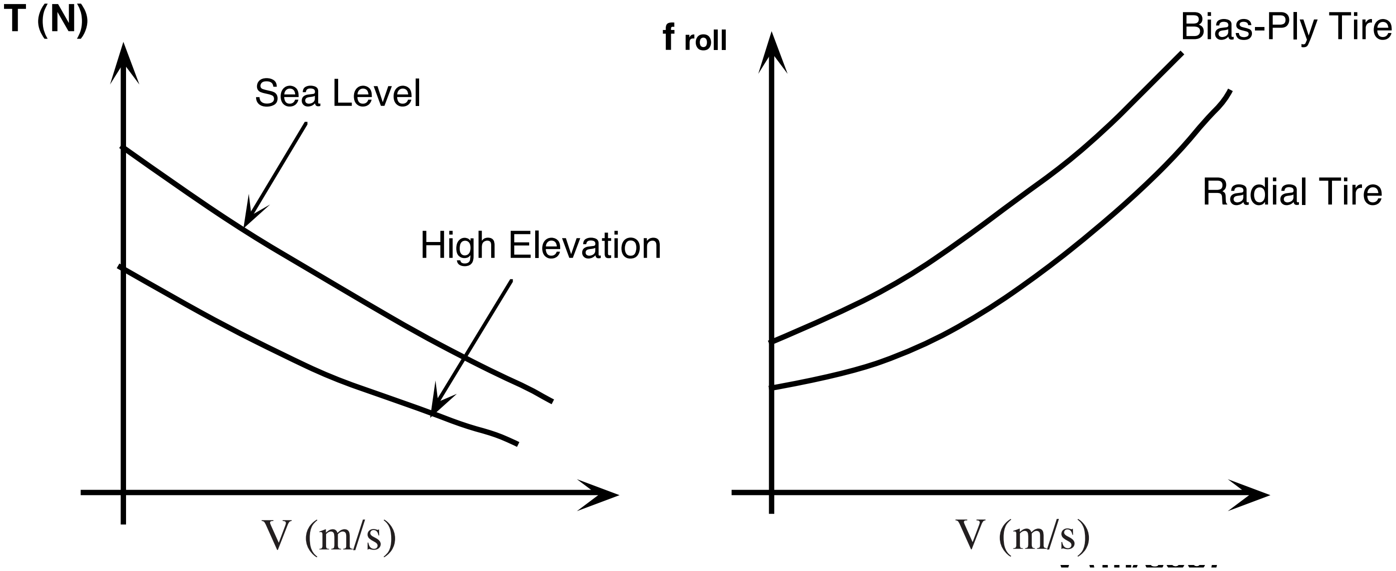
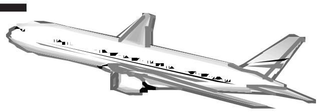


Figure 2. Typical Variations of T and f_{roll} with Aircraft Speed.



Estimating Runway Acceleration

Using Newton's second law and summing forces in the horizontal direction of motion (x),

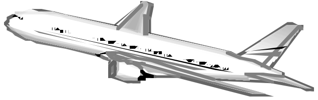
$$ma_x = T(V, \rho) - D - (mg\cos\phi - L)f_{roll} - mg\sin\phi \qquad (19)$$

linear variations of T (tractive effort or thrust) and f_{roll} can be assumed to be linear with respect to airspeed for the range of speed values encountered in practice. For small angles this equation can be expressed as,

$$ma_x = T(V, \rho) - D - (mg - L)f_{roll} \qquad (20)$$

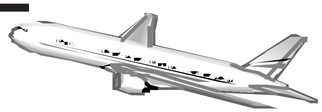
$$ma_x = T(V, \rho) - \frac{1}{2}\rho V^2 s c_D - \left(mg - \frac{1}{2}\rho V^2 S C_L\right)f_{roll} \qquad (21)$$

$$a_x = \frac{1}{m}(T(V, \rho) + \frac{1}{2}\rho V^2 S(C_L f_{roll} - C_D) - mgf_{roll} \qquad (22)$$



Remarks About the Aircraft Acceleration Equation

- The acceleration capability of the aircraft decreases as speed is gained during the takeoff roll due to a reduction in the thrust produced by the engines
- If Eq. 22 is **integrated twice** between an initial speed, V_0 and the lift-off speed, V_{lo} the distance traversed during the takeoff roll can be found
- Usually this requires a computer simulation since many parameters such as T and f_{roll} vary with speed (time varying) making the coefficient of the differential equation of motion time dependent.



Aerodynamic Coefficients

- The flap setting affects C_D and C_L and hence affects acceleration and runway length required for a takeoff. Typical variations of C_D with flap angle are shown below

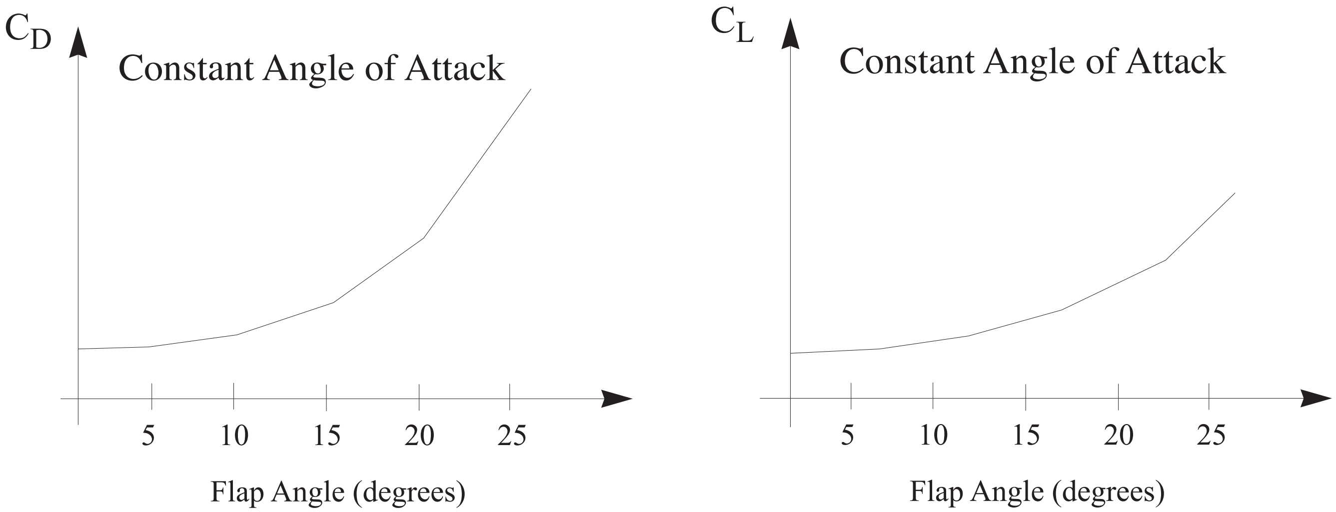
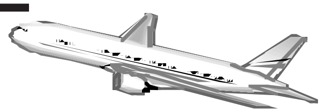
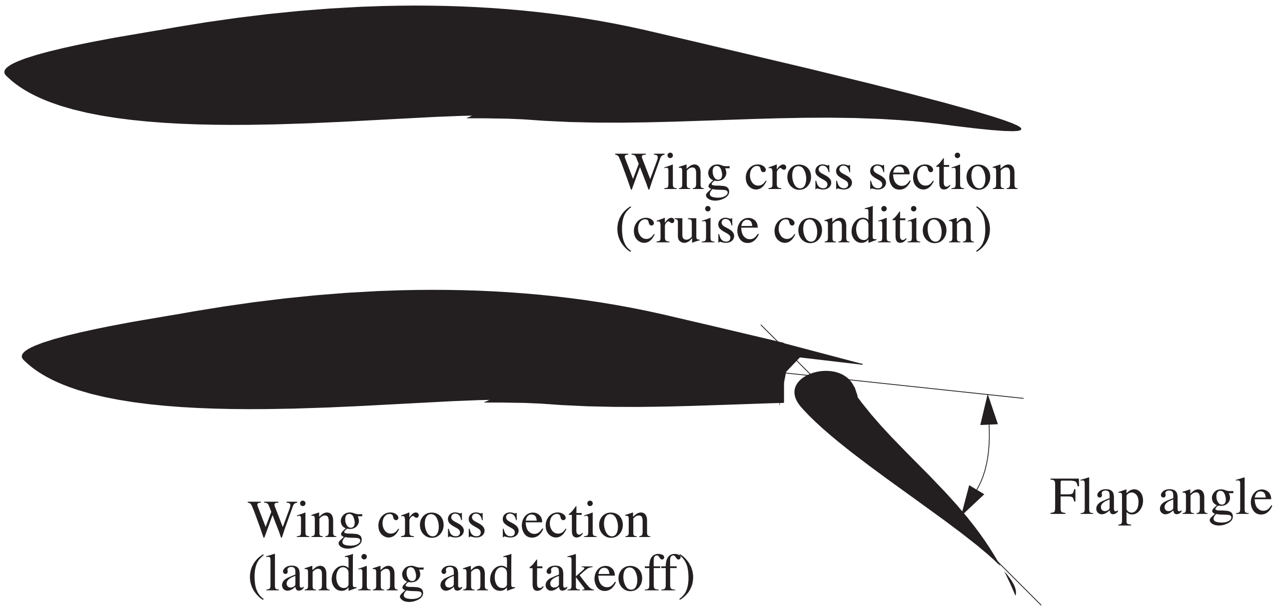


Figure 3. Typical Variations of C_D and C_L with Aircraft Wing Flap Angle.

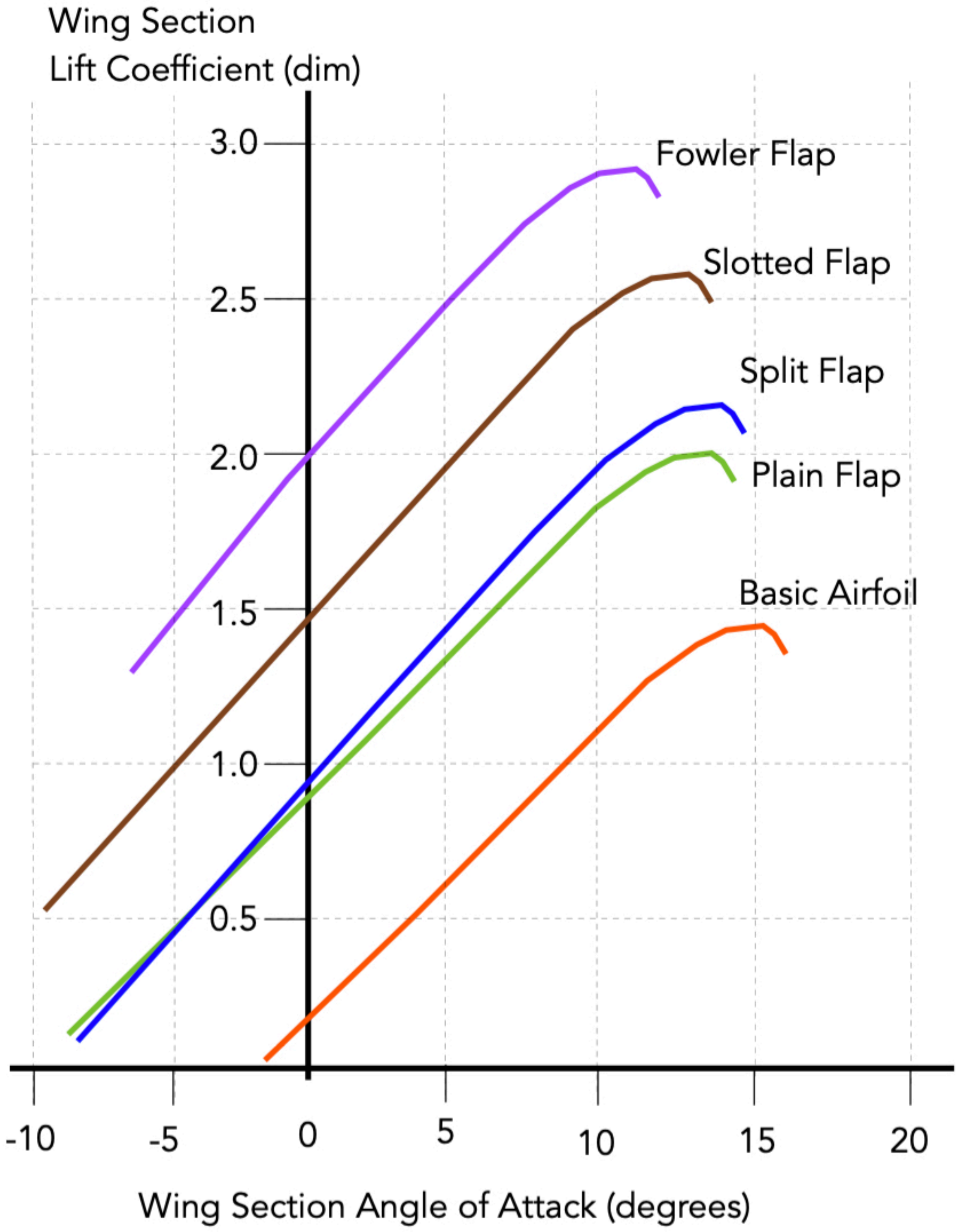


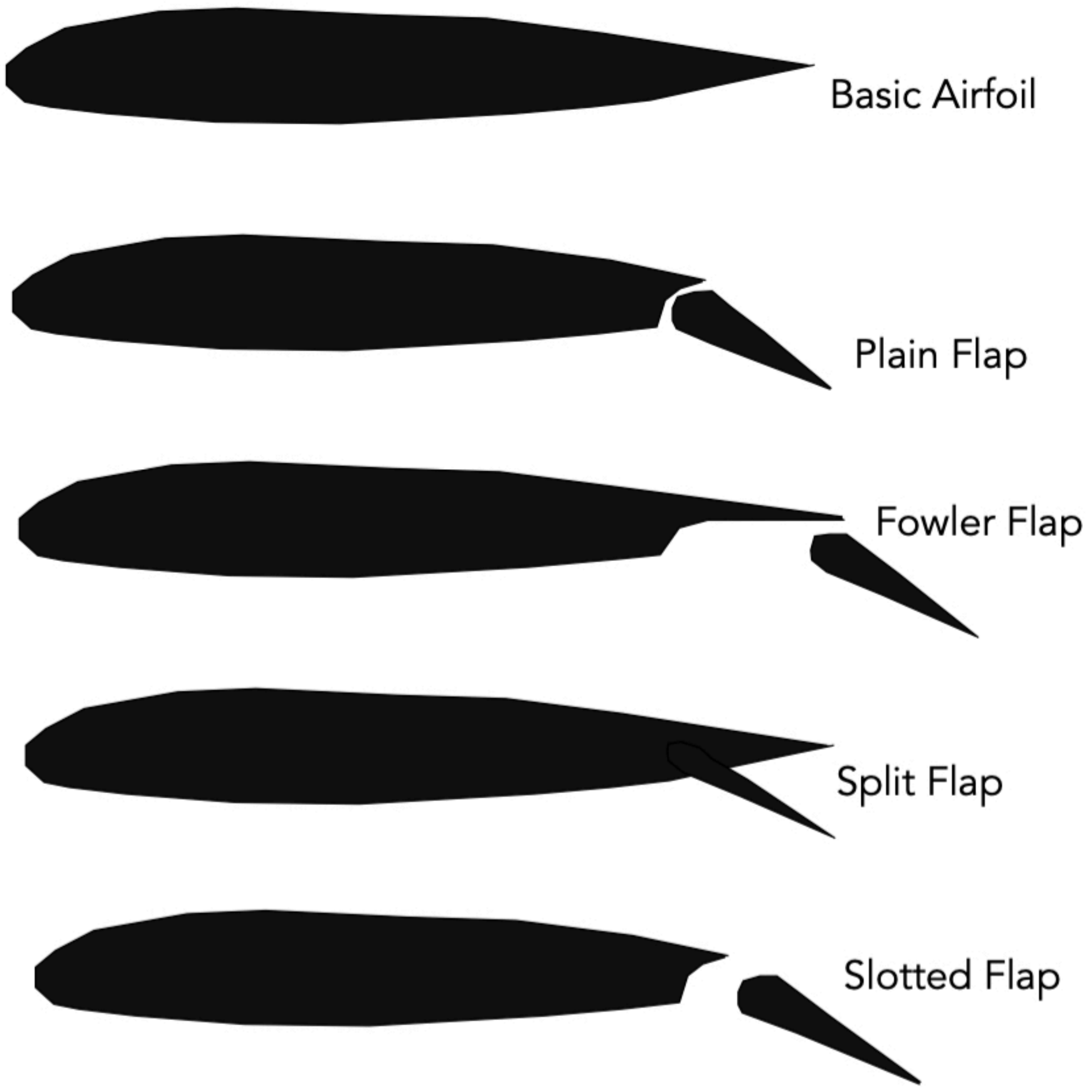
Flap Angle

- Angle formed between the flap chord and the wing chord
- Flaps are used to increase lift (but they increase drag too) during takeoff and landing maneuvers
- Flaps reduce the stalling speed of the aircraft



Different Types of Flaps and Their Performance





source: Adapted from Whitford
Evolution of the Airliner

Landing Flap Configuration (Boeing 787-8)

- Increases lift substantially and reduces landing speed (reduces landing runway length required)
- Increases drag

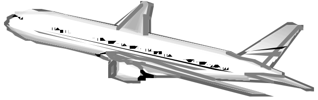
source: A. Trani

Takeoff Flap Configuration (Boeing 787-8)

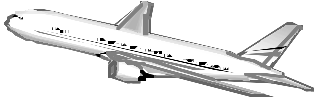
- Increases lift (lower takeoff speeds)
- Lower drag compared to landing configuration

source: A. Trani

Remarks About Aerodynamic Coefficients



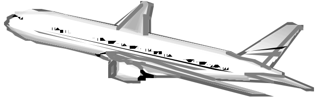
- An increase in flap angle increases both C_L and C_D. However, these increments are not linear and consequently are more difficult to interpret
- Increasing the flap angle (δ_f) increases C_L and thus reduces the lift-off speed required for takeoff due to an increase in the lifting force generated.
- Increments in flap angle increases the value of C_D more rapidly which tends to reduce more drastically the acceleration of the aircraft on the runway thus increasing the runway length necessary to reach the lift off speed



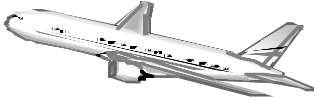
Remarks

- The mass of the aircraft affects its acceleration (according to Newton's second law).
  - Larger takeoff masses produce corresponding increments in the runway length requirement.
- The density of the air, ρ decreases with altitude
  - Lower thrust generation capability at high airfield elevations
  - The runway length increases as the field elevation increases
  - The density also affects the second and third terms in Equation 2.10 (less drag at higher altitude)

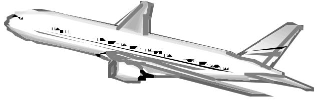
Aircraft Operational Practices (Takeoff)



- At **small flap settings** (i.e., 5 or 10 degrees) the takeoff runway length is increased due to small gains in C_L (little increase in the lifting force). Useful for high-hot takeoff conditions.
- At **medium flap angle settings** (15-25 degrees) the gains in lift usually override those of the drag force. These are the flap settings typically used for takeoff **except** under extremely abnormal airport environments such as high elevation, hot temperature airport conditions and high aircraft weights or a combination of both. Note that the **maximum allowable takeoff weight (MTOW)** increases as the takeoff flap setting is reduced.



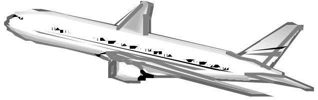
- At **large flap angles** (> 25 degrees) C_D **is excessive** and the airplane requires unreasonable large takeoff runway lengths. These flap settings are only used for landing since pilots want to land at the lowest speed possible thus reducing runway length.



Application of Equations of Motion to Takeoff Runway Length Requirements

- Equation 22 describes the motion of an air vehicle as it accelerates on a runway from an initial speed V_o to a final liftoff speed V_{lof}
- This equation can be integrated twice with respect to time to obtain the distance traveled from a starting point to the point of liftoff
- With a little more effort we could also predict the distance required to clear a 35 ft. obstacle as required by Federal Aviation Regulations Part 25 or 23 that sets airworthiness criteria for aircraft in the U.S.
- Airport engineers use tabular or graphical data derived from this integration procedure

A Word on Stalling and Lift-off Speeds



The stalling speed can be estimated from the basic lift equation

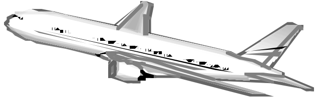
$$L = \frac{1}{2}\rho V^2 S C_L$$

Under steady flight conditions $L \cong mg$ so,

$$V = \sqrt{\frac{2mg}{\rho S C_L}}$$

define C_{Lmax} as the maximum attainable lift coefficient, then

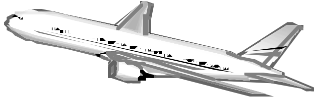
$$V_{stall} = \sqrt{\frac{2mg}{\rho S C_{Lmax}}}$$



FAR Regulation Principles

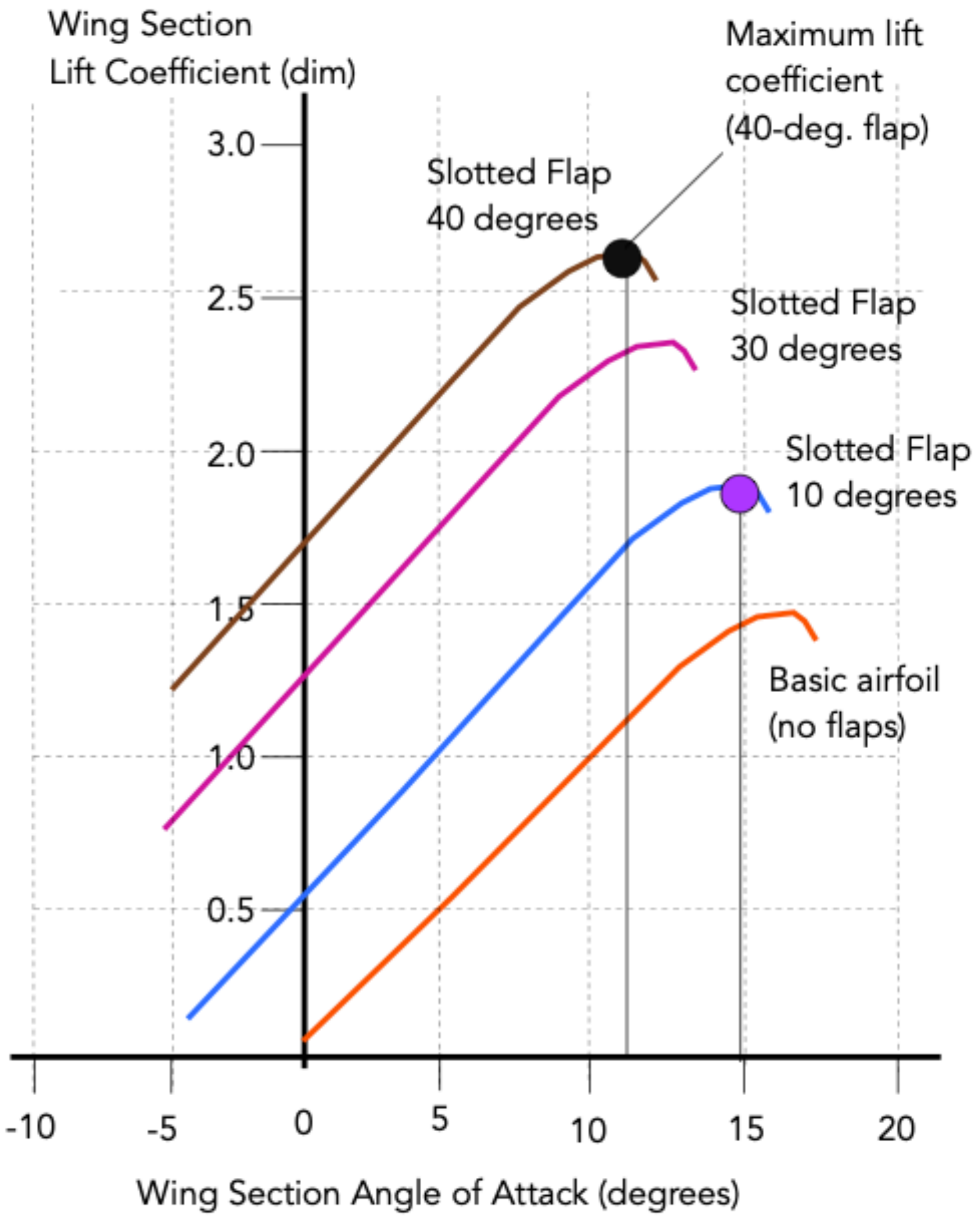
Regulations (FAR 25) specify that:

- Aircraft should lift off at 10% above the stalling speed (V_{lof})
- Aircraft climb initially at 20% above the stalling speed (V_2)
- Aircraft speed during a regular approach be 30% above the stalling speed (V_{app})
- During takeoff aircraft should clear an imaginary 11 m (35 ft.) obstacle
- During landing aircraft should cross the runway threshold 15 m (50 ft.) above ground)

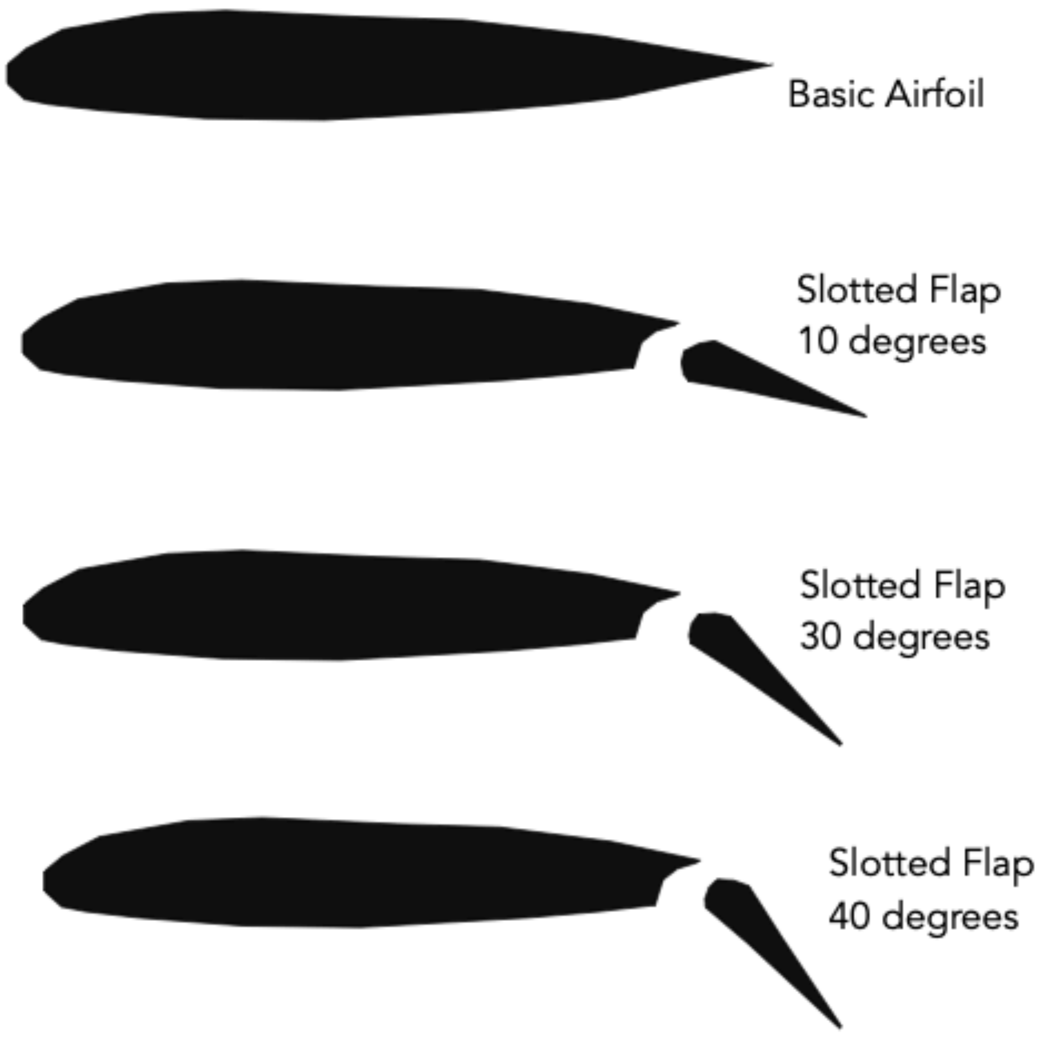


These considerations are necessary to estimate takeoff and landing distances (and thus size runway length)

Different Flap Settings Yield Different Lift Coefficient Performance



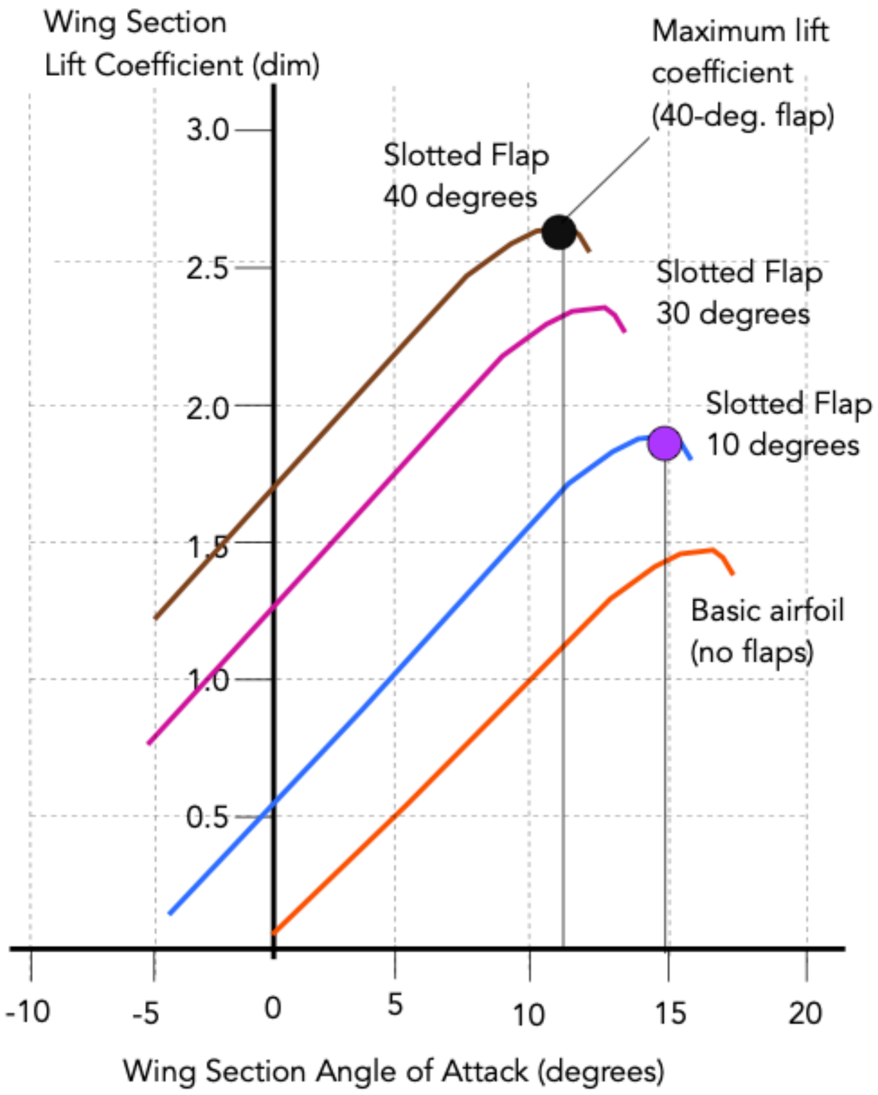
Typical for Narrow-Body Aircraft



Every aircraft configuration and performance is unique

Example Problem

A narrow-body aircraft has the following characteristics:



S = 127 square meters
Airport elevation = sea level
Takeoff Cl_{max} = 1.75 (10-deg flaps)
Takeoff mass = 75,000 kilograms

Landing Cl_{max} =2.63 (40-deg. flaps)
Landing mass = 65,000 kilograms

1. Estimate the takeoff safe speed (knots)
2. Estimate the landing or approach speed (knots)

Takeoff Performance

- Find the takeoff stall speed ($V_{stall\text{-}TO}$)

Basic Lift Equation

$$V_{stall-TO} = \sqrt{2 * mg / (\rho * S * Cl_{max})}$$

$$V_{stall-TO} = \sqrt{2 * (75000)(9.81) / (1.225 * 127 * 1.75)} = 73.5 \text{ m/s}$$

The safe takeoff speed (V_2) is 88.2 m/s or 171.2 knots

Landing Performance

- Find the stall speed ($V_{stall\text{-}Landing}$) in the landing configuration

$$V_{stall-Landing} = \sqrt{2 * mg/\rho] * S * Cl_{max}}$$

$$V_{stall-Landing} = \sqrt{2 * (65000)(9.81)/(1.225 * 127 * 2.63)} = 55.8 \text{ m/s}$$

The landing speed (V_{ref}) is 72.6 m/s or 141knots

Observations

- Takeoff speeds are, in general, faster because:
    - Aircraft are loaded with fuel and passengers (higher aircraft mass)
    - Flap settings are lower compared to the landing configuration (i.e., lower lift coefficients)
- Landing speeds are, in general, lower because:
    - Aircraft fuel has been consumed in the flight (i.e., lighter aircraft mass)
    - Maximum flap setting is normally used providing higher lift coefficients

Typical Flap Settings for Common Commercial Aircraft

Aircraft	Takeoff Flap Settings (degrees) or Label	Landing Flap Settings (degrees) or Label
Boeing 737-900	0,1, 5, 10,15, 20	25, 30, 40
Airbus A320	18/10 (1+F)	22/15 (2), 22/20 (3), 27/35 (Full)
Boeing 787-8	0,1,5,15, 20	25, 30
Boeing 757-200	0, 1, 5, 15	25, 30
Airbus A330-300	1+F	2, Full
Airbus A350-900	1+F, 2	2, Full
Boeing 777-300ER	0,1, 5, 15, 20	25, 30

Airbus uses labels for slats (leading edge) /flaps (training edge) settings independently

Leading Edge (Slats) versus Training Edge Flaps

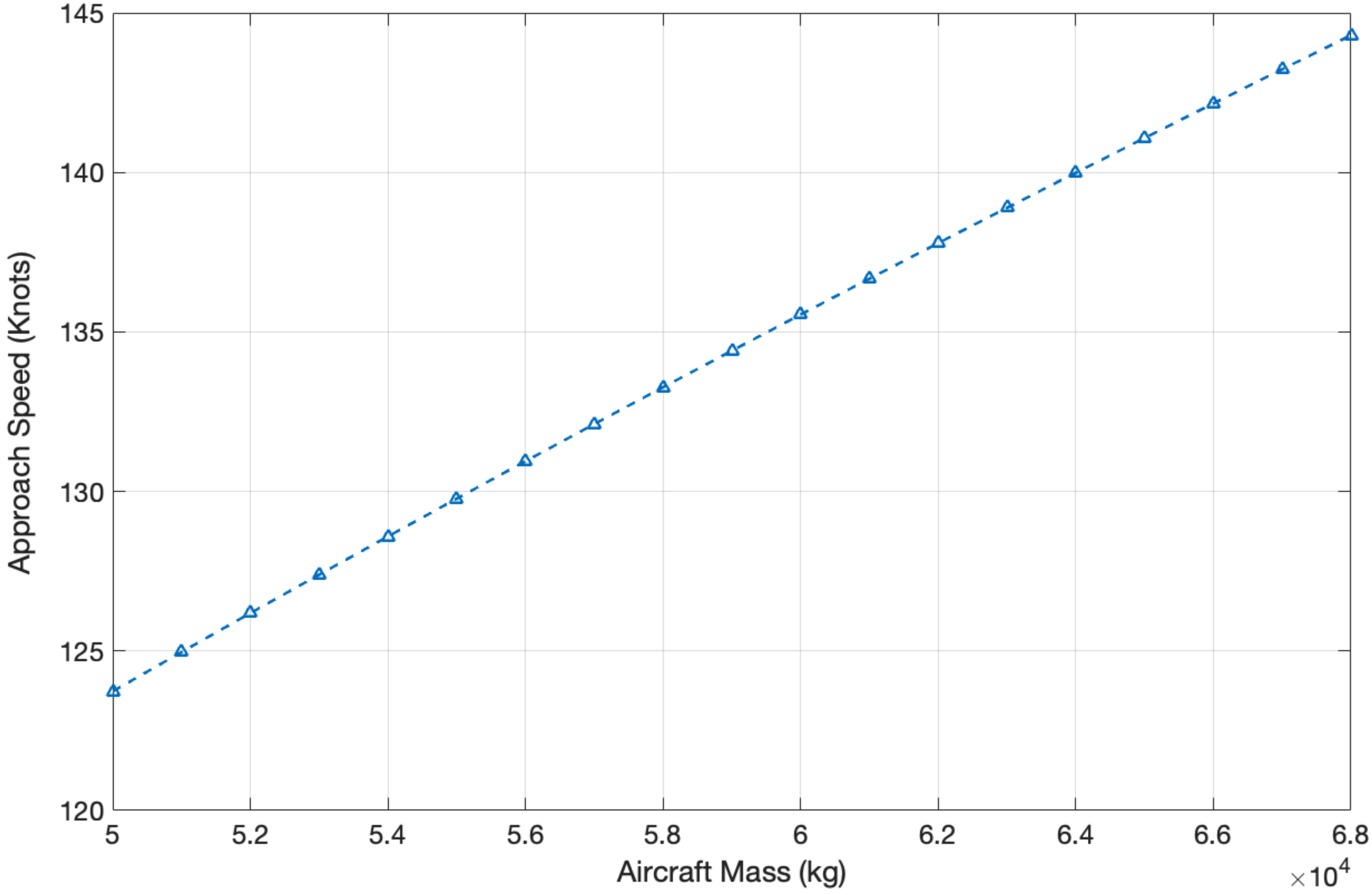
Airbus A350-1000

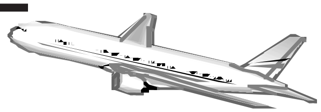
Most commercial aircraft have both leading edge and trailing edge flaps (few exceptions like the Bombardier CRJ-200 and the Embraer 145 regional jets)

Leading Edge (Slats) versus Training Edge Flaps

Some small aircraft may have both leading edge and trailing edge flaps (the JA35 Super Stop aircraft shown)

Variation of Landing Speeds with Aircraft Mass





Integration of Acceleration Equation

First obtain the aircraft speed at time t,

$$V_t = \int_{V_o}^{V_{lof}} \frac{1}{m}(T(V,\rho) + \frac{1}{2}\rho V^2 S(C_L f_{roll} - C_D) - mg f_{roll})dt \qquad (23)$$

Now get the distance traveled, S_t

$$S_t = \int_{o}^{D_{lof}} V_t dt \qquad (24)$$

Runway Simulation Case Study

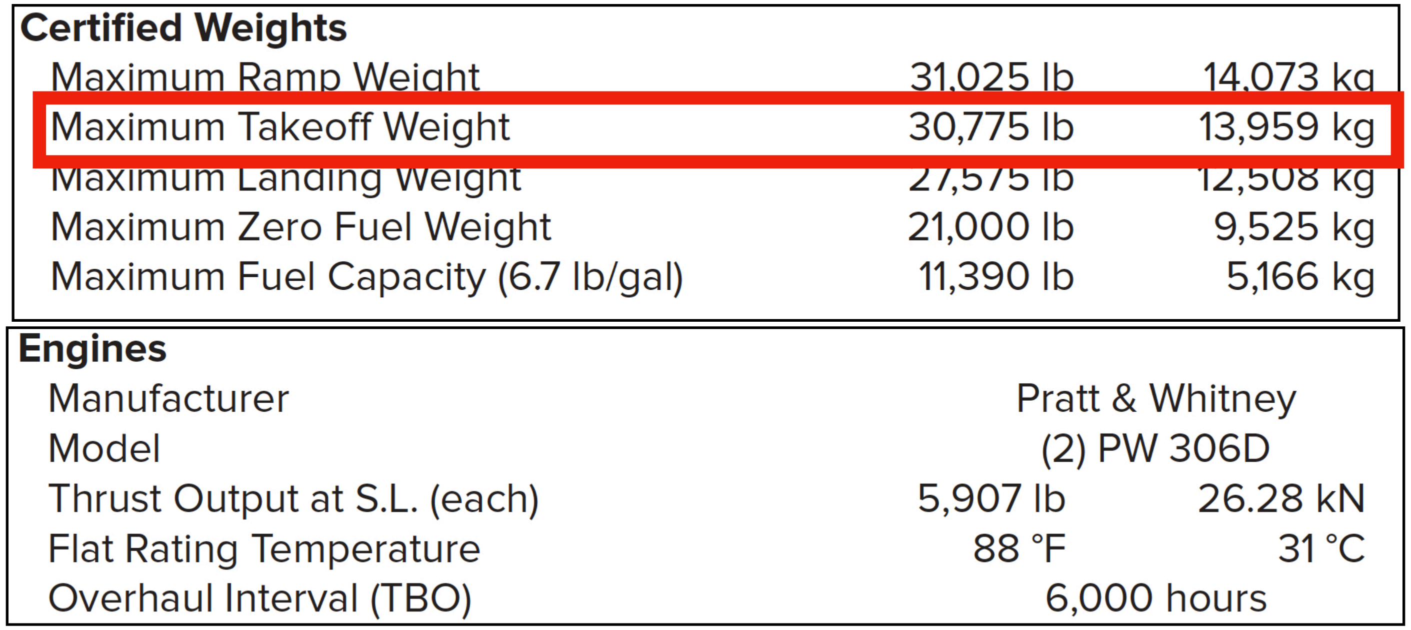
High-performance Business Jet Simulation

Objectives

- Demonstrate the use of the fundamental equations of motion to predict the takeoff field length of a corporate jet
- Aircraft modeled has similar characteristics to the Cessna Citation Latitude (Cessna C680)
- Model developed and implemented in Matlab Simulink

Cessna Latitude (Cessna C680)

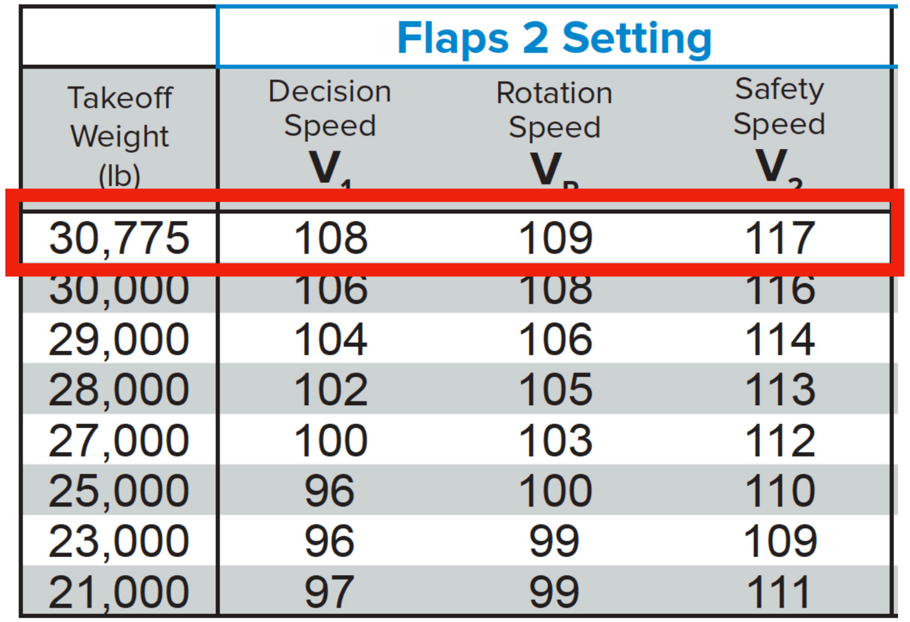
- A high-performance corporate jet
- High thrust-to-weight ratio (~2.7 lb weight per lb of thrust)



Certified Weights		
Maximum Ramp Weight	31,025 lb	14,073 kg
Maximum Takeoff Weight	30,775 lb	13,959 kg
Maximum Landing Weight	27,575 lb	12,508 kg
Maximum Zero Fuel Weight	21,000 lb	9,525 kg
Maximum Fuel Capacity (6.7 lb/gal)	11,390 lb	5,166 kg

Engines		
Manufacturer	Pratt & Whitney	
Model	(2) PW 306D	
Thrust Output at S.L. (each)	5,907 lb	26.28 kN
Flat Rating Temperature	88 °F	31 °C
Overhaul Interval (TBO)	6,000 hours	

Source: Cessna Latitude Planning Guide



	Flaps 2 Setting		
Takeoff Weight (lb)	Decision Speed V_1	Rotation Speed V_R	Safety Speed V_2
30,775	108	109	117
30,000	106	108	116
29,000	104	106	114
28,000	102	105	113
27,000	100	103	112
25,000	96	100	110
23,000	96	99	109
21,000	97	99	111

Operational Takeoff Speeds

Other parameters:

S (wing area) = 50.4 sq. meters
Cd = 0.12 includes gear + flaps
Cl = 0.6 for flaps 2 setting
Takeoff weight ~ 13,900 kg
Installation trust loss = 10%

Simulink Model

- Integrates the second-order (DEQ) acceleration equation of motion to obtain:
  - Speed profile
  - Distance traveled profile
- Engine model uses Matlab/Simulink Aerospace Block turbofan system block
- Atmospheric model uses the Matlab/Simulink Aerospace Block ISA model block
- Assumes 4-5 seconds between V_r (rotation speed) and point to clear the 35-foot obstacle height (typical for business jets)

Takeoff Distance Equation of Motion

$$ma = \frac{dV}{dt} = \sum F_{external}$$

$$\frac{dV}{dt} = \left(\frac{1}{m}\right) \quad (T - D - F_f - (mg\sin\phi))$$

$$L = \frac{1}{2}\rho V^2 S C_l$$

$$D = \frac{1}{2}\rho V^2 S C_D$$

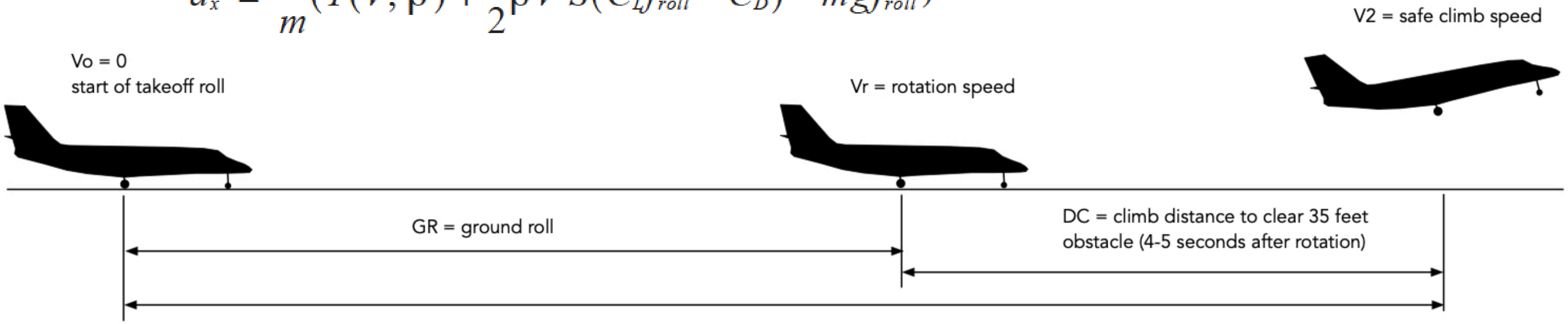
$$F_f = (mg\cos\phi - L) f_{roll}$$

$$T = f(V, \rho)$$

Second-order differential equation

Initial conditions:
Initial speed = 0
Initial distance = 0
Initial mass = 13,998 kg

$$a_x = \frac{1}{m}\left(T(V,\rho) + \frac{1}{2}\rho V^2 S (C_L f_{roll} - C_D) - m g f_{roll}\right)$$



Numerical Example: Model Parameters

$$ma = \frac{dV}{dt} = \sum F_{external}$$

$$\frac{dV}{dt} = \left(\frac{1}{m}\right)(T - D - F_f - (mg\sin\phi))$$

$$L = \frac{1}{2}\rho V^2 S C_l$$

$$D = \frac{1}{2}\rho V^2 S C_D$$

$$F_f = (mg\cos\phi - L) f_{roll}$$

$$T = f(V, \rho)$$

$m = 13900$ kilograms

$g = 9.81$ m/s^2

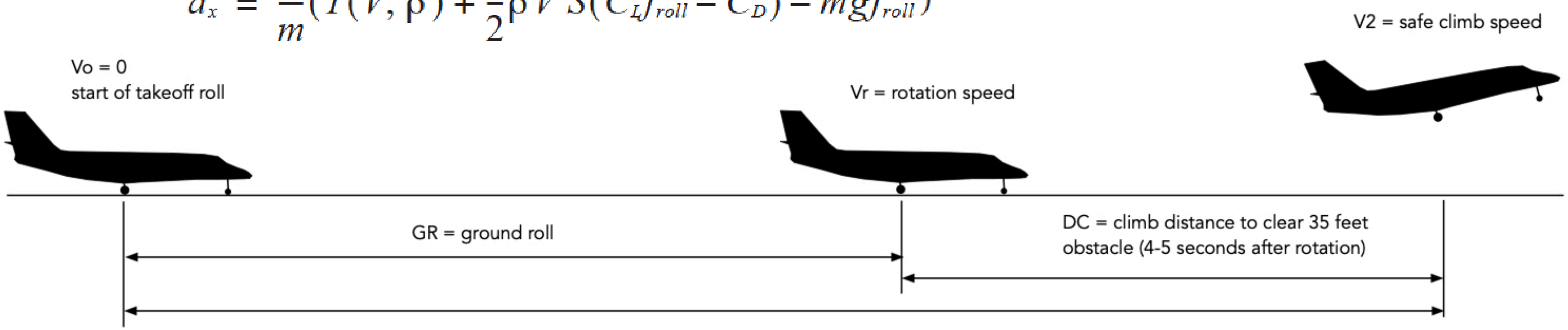
$S = 50.4$ square meters

$C_D = 0.12$ (0.02 base, 0.04 flaps and 0.06 landing gear)

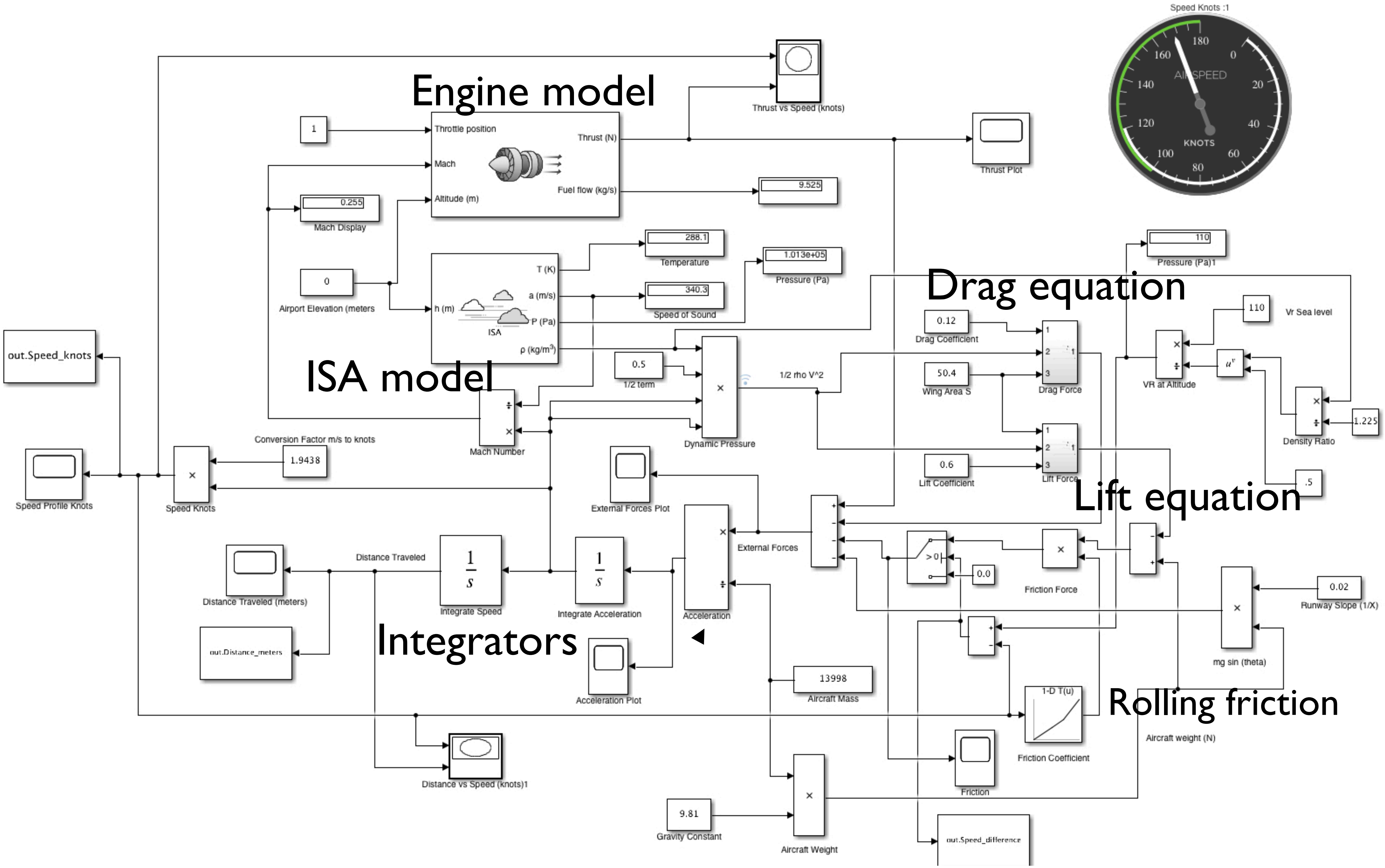
$C_l = 0.6$ (~zero angle of attack on takeoff roll)

$f_{roll} =$ [0.025 0.028 0.030 0.035] for speed values [0 60 100 150] knots

$$a_x = \frac{1}{m}(T(V,\rho) + \frac{1}{2}\rho V^2 S(C_L f_{roll} - C_D) - mgf_{roll})$$

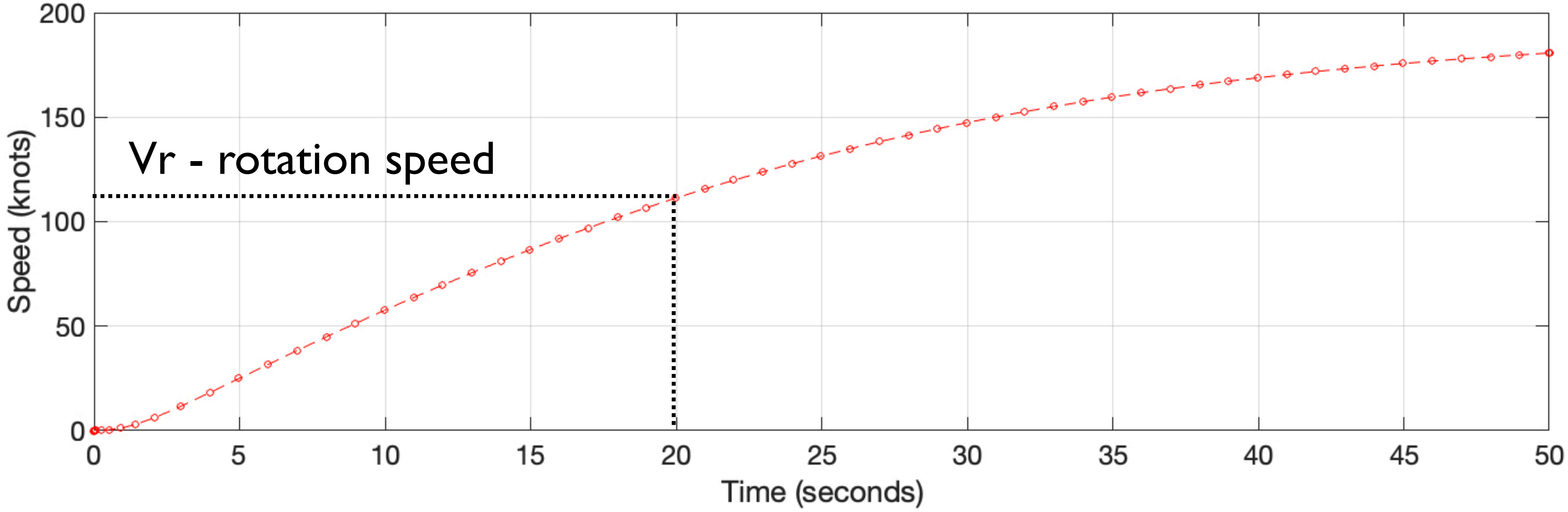


Simulink Model



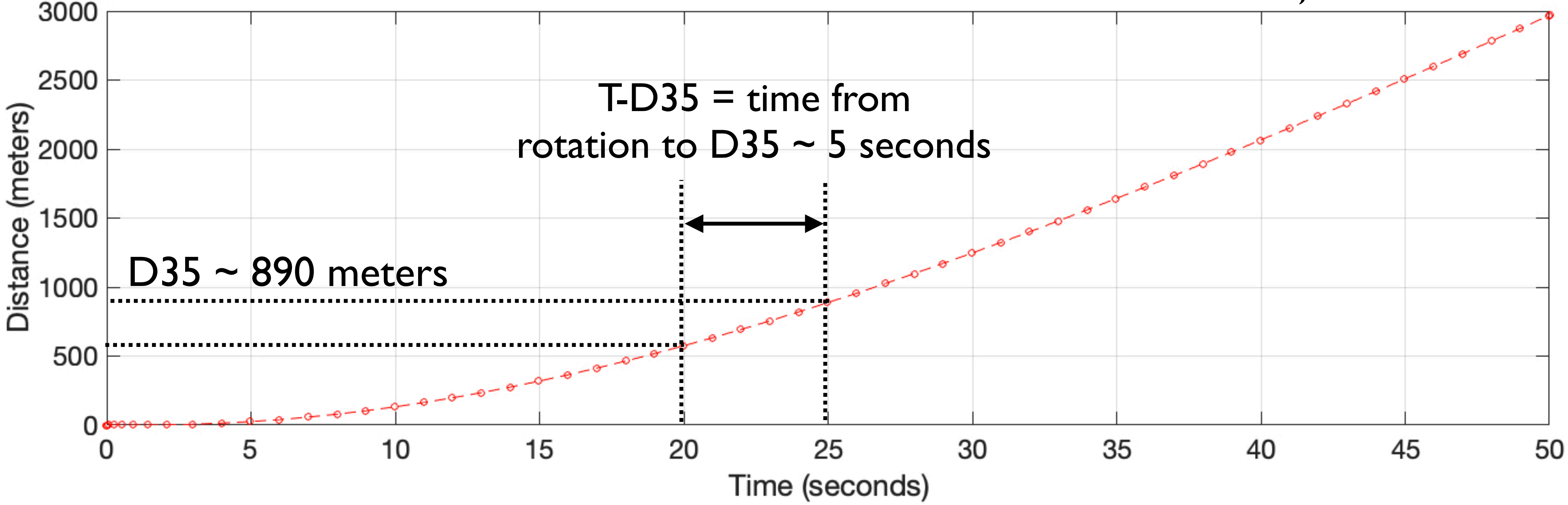
$$\frac{1}{m}\left(T(V,\rho)+\frac{1}{2}\rho V^2 S(C_L f_{roll}-C_D)-mgf_{roll}\right)$$

High-performance Business Jet Simulink Model (Sea Level ISA, zero slope conditions)



Vr - rotation speed

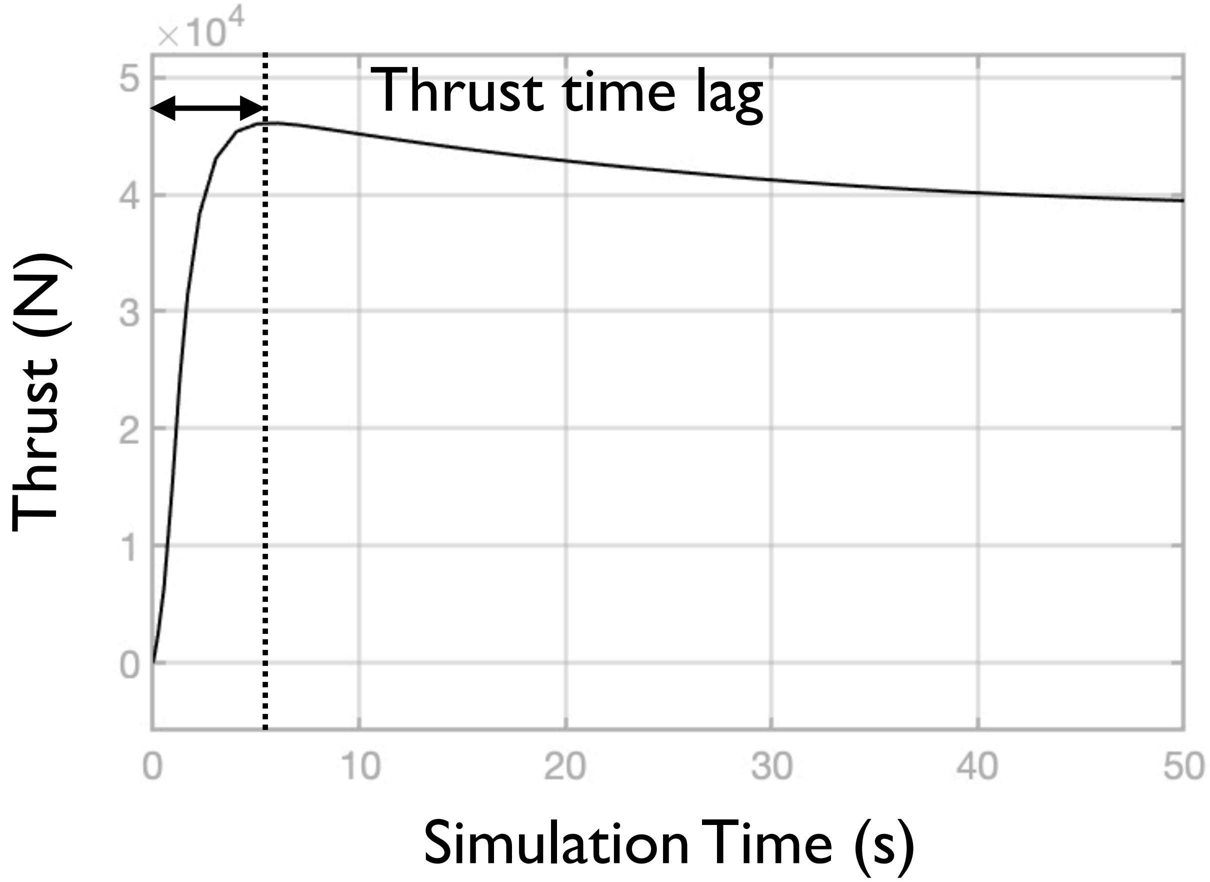
Takeoff distance = 1.15 * D35 = 1,019 meters

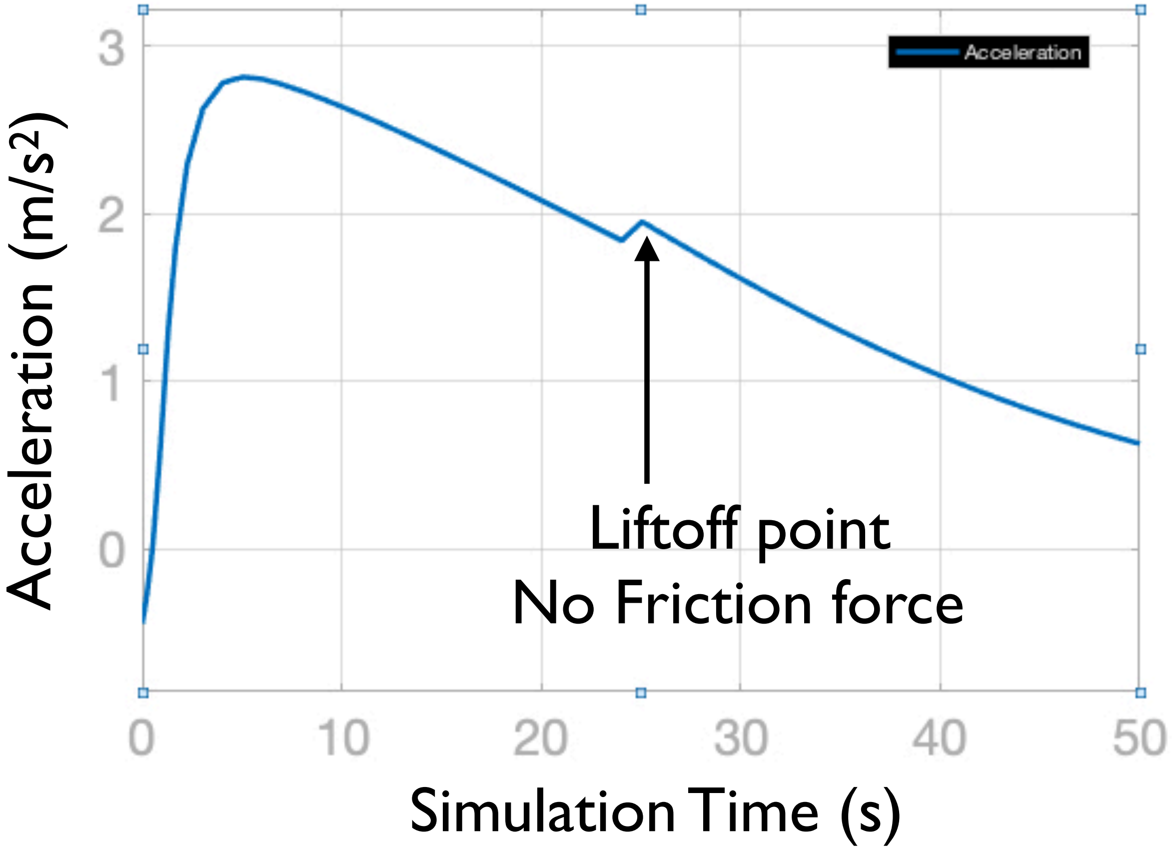


T-D35 = time from rotation to D35 ~ 5 seconds

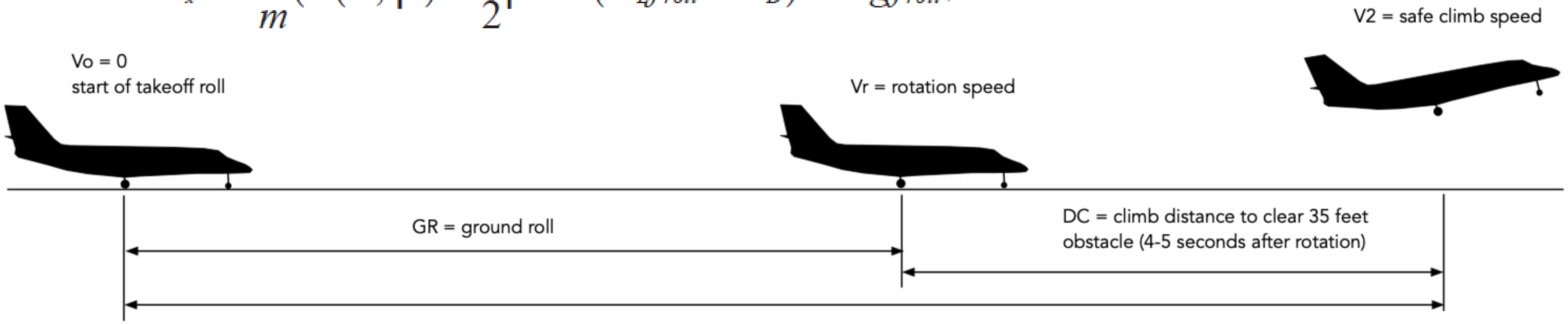
D35 ~ 890 meters

High-performance Business Jet Simulink Model (Sea Level ISA, zero slope conditions)





$$a_x = \frac{1}{m}\left(T(V, \rho) + \frac{1}{2}\rho V^2 S(C_L f_{roll} - C_D) - mg f_{roll}\right)$$



Vo = 0
start of takeoff roll

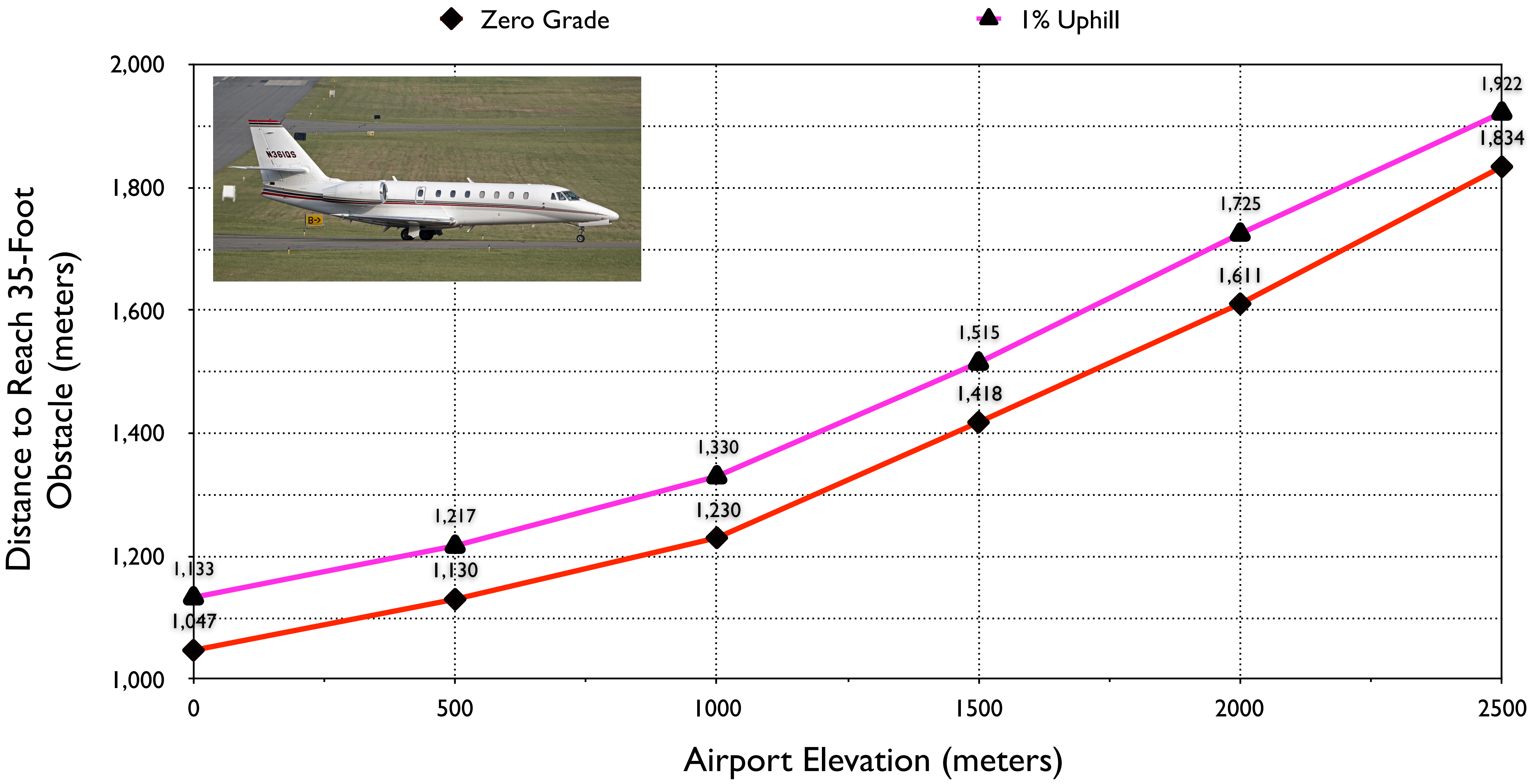
Vr = rotation speed

V2 = safe climb speed

GR = ground roll

DC = climb distance to clear 35 feet
obstacle (4-5 seconds after rotation)

High-performance Business Jet Simulink Model A 1% Grade Increases the Takeoff Distance by 8.2% at Sea Level ISA Conditions

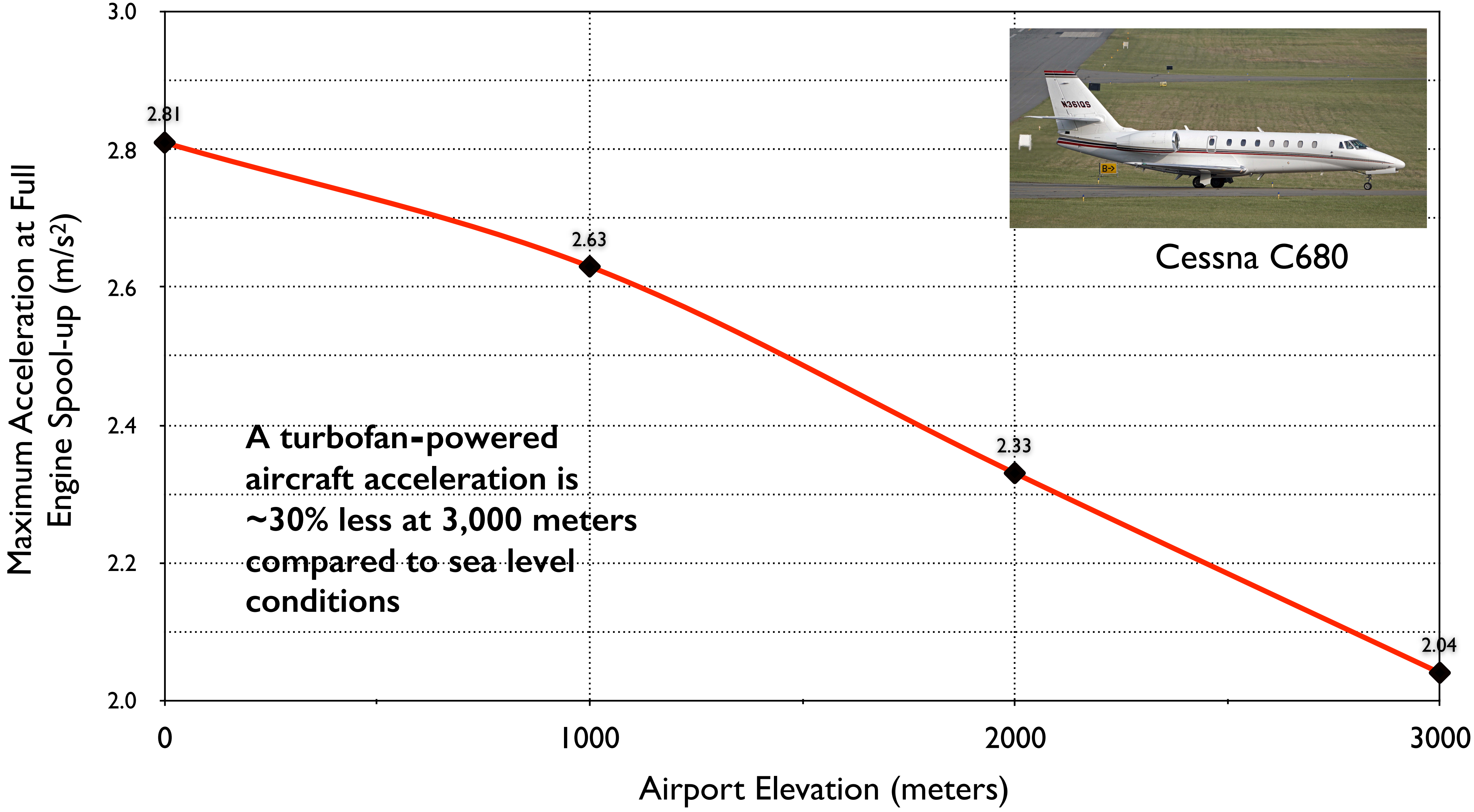


Validation:

Cessna takeoff field length data at Sea Level ISA conditions is 1,076 meters

Cessna takeoff field length data at 1500 meters is 1,310 meters

High-performance Business Jet Simulink Model
Peak Acceleration versus Airport Altitude
ISA Conditions for Every Airport Elevation

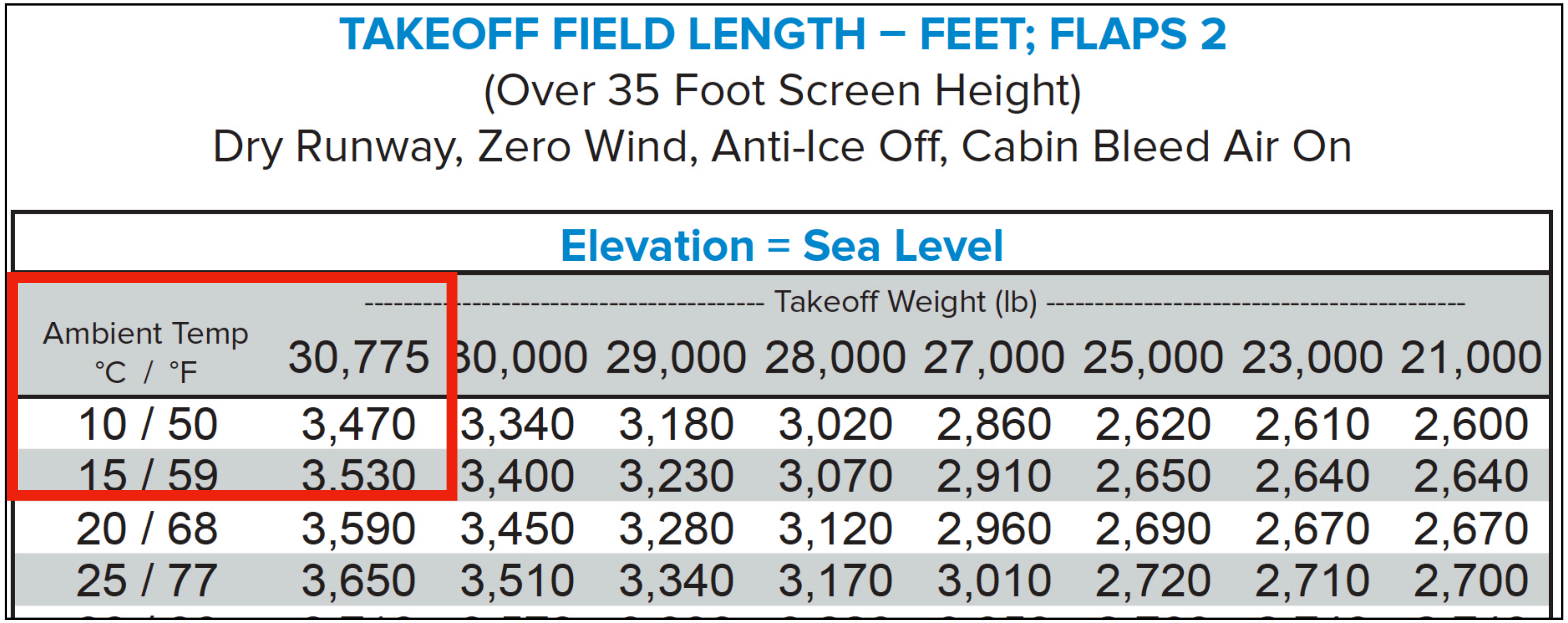


Cessna C680

A turbofan-powered aircraft acceleration is ~30% less at 3,000 meters compared to sea level conditions

The loss of acceleration capability is roughly the same magnitude as the density ratio

Cessna Latitude Performance



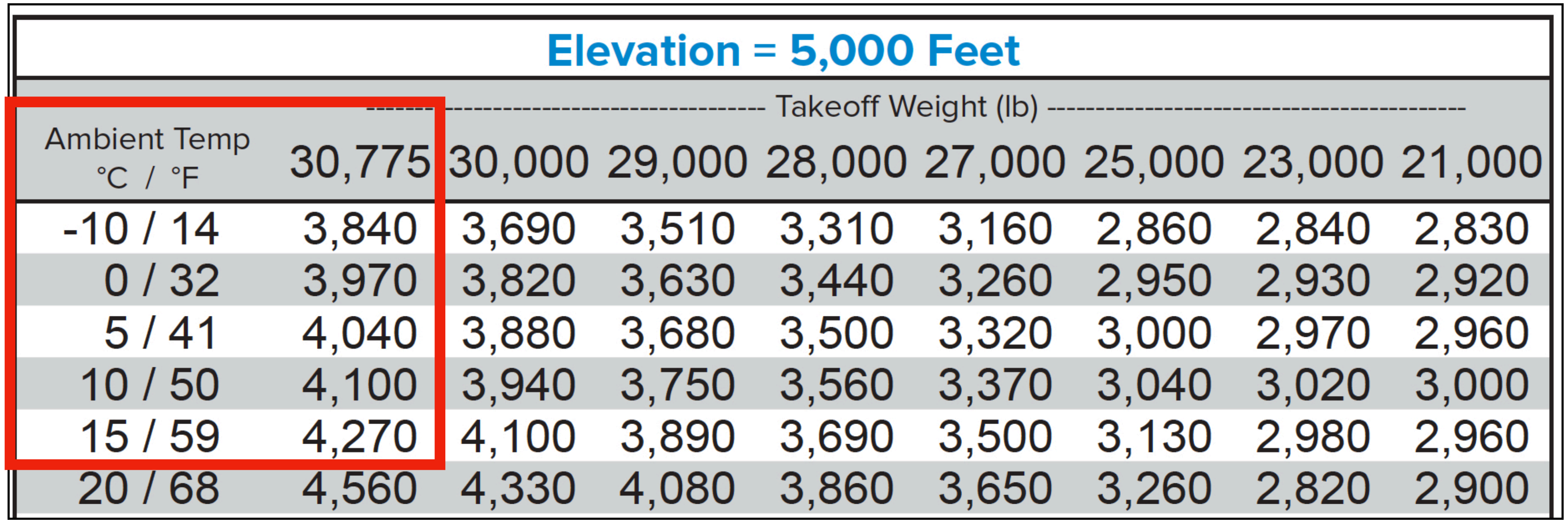
TAKEOFF FIELD LENGTH – FEET; FLAPS 2

(Over 35 Foot Screen Height)

Dry Runway, Zero Wind, Anti-Ice Off, Cabin Bleed Air On

Elevation = Sea Level

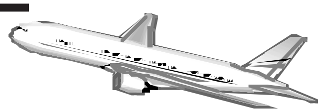
Ambient Temp °C / °F	Takeoff Weight (lb)							
	30,775	30,000	29,000	28,000	27,000	25,000	23,000	21,000
10 / 50	3,470	3,340	3,180	3,020	2,860	2,620	2,610	2,600
15 / 59	3,530	3,400	3,230	3,070	2,910	2,650	2,640	2,640
20 / 68	3,590	3,450	3,280	3,120	2,960	2,690	2,670	2,670
25 / 77	3,650	3,510	3,340	3,170	3,010	2,720	2,710	2,700



Elevation = 5,000 Feet

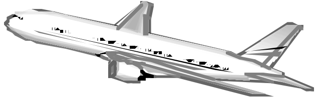
Ambient Temp °C / °F	Takeoff Weight (lb)							
	30,775	30,000	29,000	28,000	27,000	25,000	23,000	21,000
-10 / 14	3,840	3,690	3,510	3,310	3,160	2,860	2,840	2,830
0 / 32	3,970	3,820	3,630	3,440	3,260	2,950	2,930	2,920
5 / 41	4,040	3,880	3,680	3,500	3,320	3,000	2,970	2,960
10 / 50	4,100	3,940	3,750	3,560	3,370	3,040	3,020	3,000
15 / 59	4,270	4,100	3,890	3,690	3,500	3,130	2,980	2,960
20 / 68	4,560	4,330	4,080	3,860	3,650	3,260	2,820	2,900

Source: Cessna Latitude Planning Guide



Regulatory Method to Estimate Runway Length at Airports

General Procedure for Runway Length Estimation (Runway Length Components)



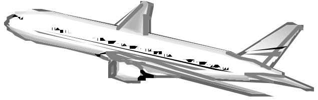
Runways can have three basic components:

- Full strength pavement (FS)
- Clearways (CL)
- Stopways (SW)

Full strength pavement should support the full weight of the aircraft

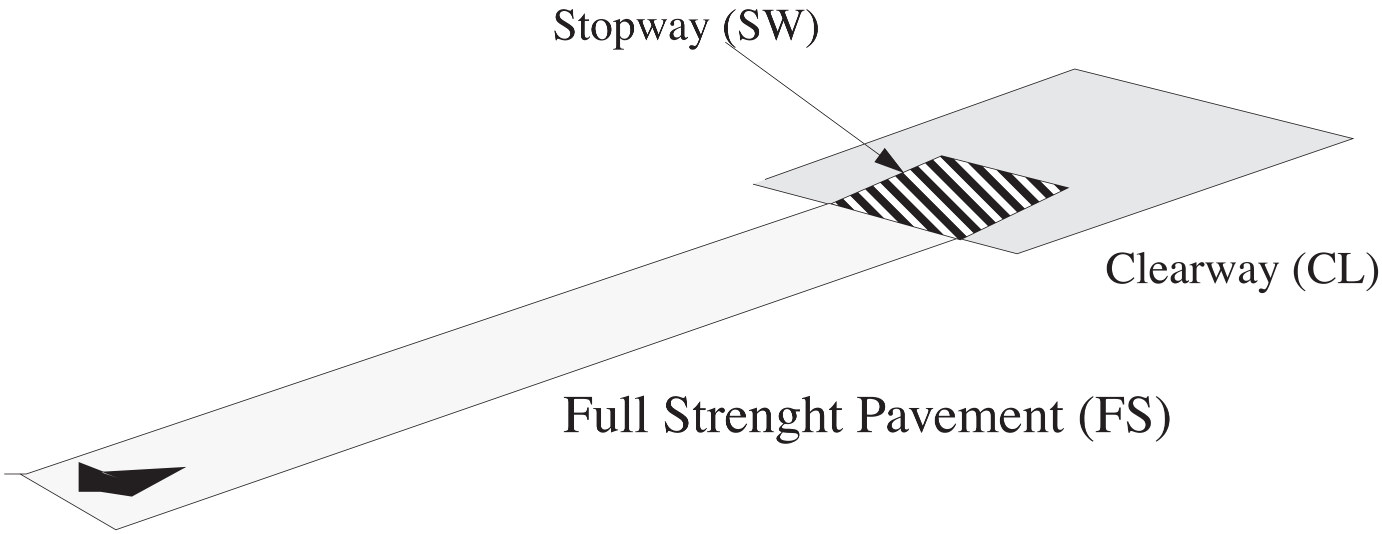
Clearway is a prepared area are beyond FS clear of obstacles (max slope is 1.5%) allowing the aircraft to climb safely to clear an imaginary 11 m (35' obstacle)

Stopway is a paved surface that allows and aircraft overrun to take place without harming the vehicle structurally (cannot be used for takeoff)



Runway Components

Each runway end will have to be considered individually for runway length analysis

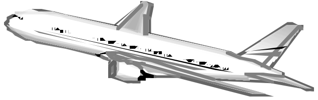


Stopway (SW)

Clearway (CL)

Full Strenght Pavement (FS)

FAR Certification Procedures

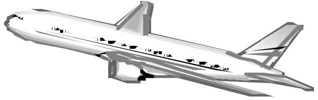


FAR 25 (for turbojet and turbofan powered aircraft) consider three cases in the estimation of runway length performance

- Normal takeoff (all engines working fine)
- Engine-out takeoff condition
  - Continued takeoff
  - Aborted takeoff
- Landing

All these cases consider stochastic variations in piloting technique (usually very large for landings and smaller for takeoffs)

Regulations for piston aircraft do not include the normal takeoff case (an engine-out condition is more critical in piston-powered aircraft)



Nomenclature

FL = field length (total amount of runway needed)

FS = full strength pavement distance

CL = clearway distance

SW = stopway distance

LOD = lift off distance

TOR = takeoff run

TOD = takeoff distance

LD = landing distance

SD = stopping distance

D35 = distance to clear an 11 m (35 ft.) obstacle

DAS = Distance to accelerate and stop

Landing Distance Case

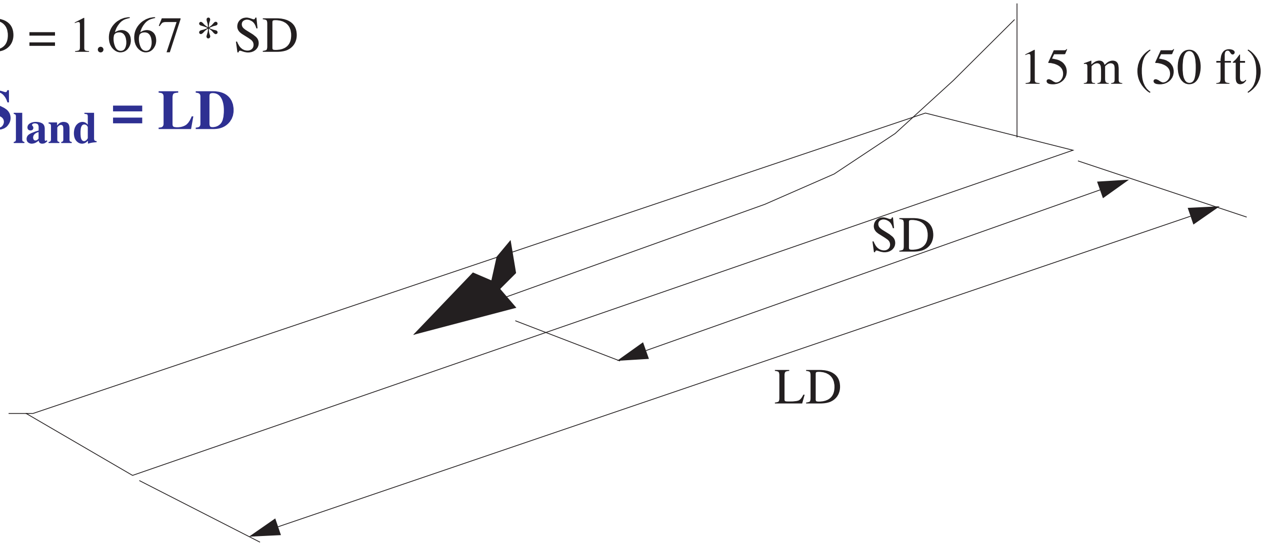
The landing distance should be 67% longer than the demonstrated distance to stop an aircraft

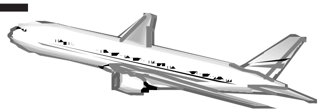
Large landing roll variations exist among pilots

Example touchdown point variations (μ=400 m, σ=125 m for Boeing 727-200 landing in Atlanta)

$LD = 1.667 * SD$

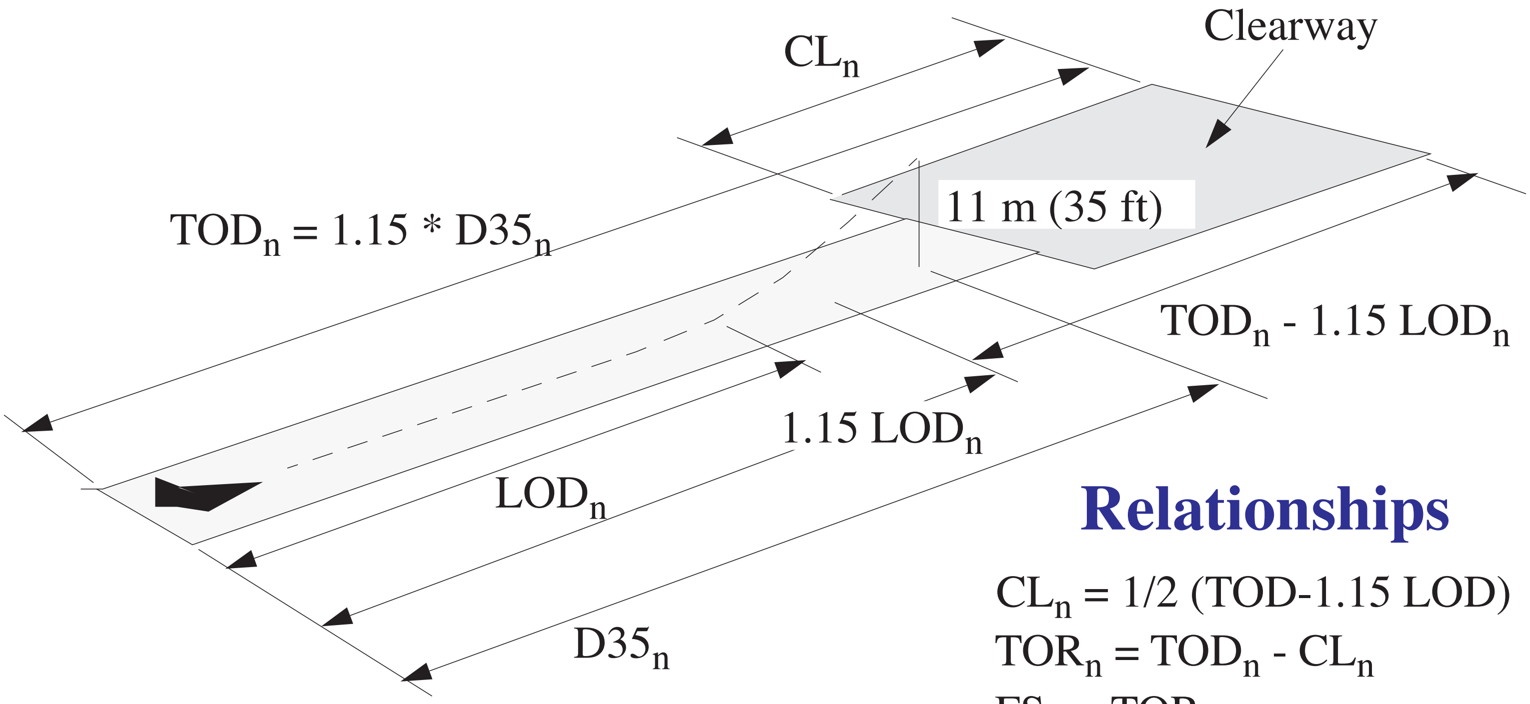
$\mathbf{FS_{land} = LD}$





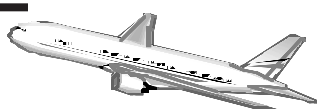
Normal Takeoff Case

The takeoff distance (TOD) is 15% longer than the demonstrated distance to clear the 35-foot obstacle (D35) in flight tests.



Relationships

$CL_n = 1/2\ (TOD - 1.15\ LOD)$
$TOR_n = TOD_n - CL_n$
$FS_n = TOR_n$
$FL_n = FS_n + CL_n$



Engine-Out Takeoff Case

Dictated by two scenarios:

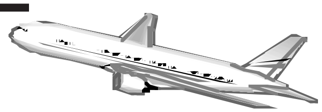
Continued takeoff subcase

- Actual distance to clear an imaginary 11 m (35 ft.) obstacle D35 (with an engine-out)

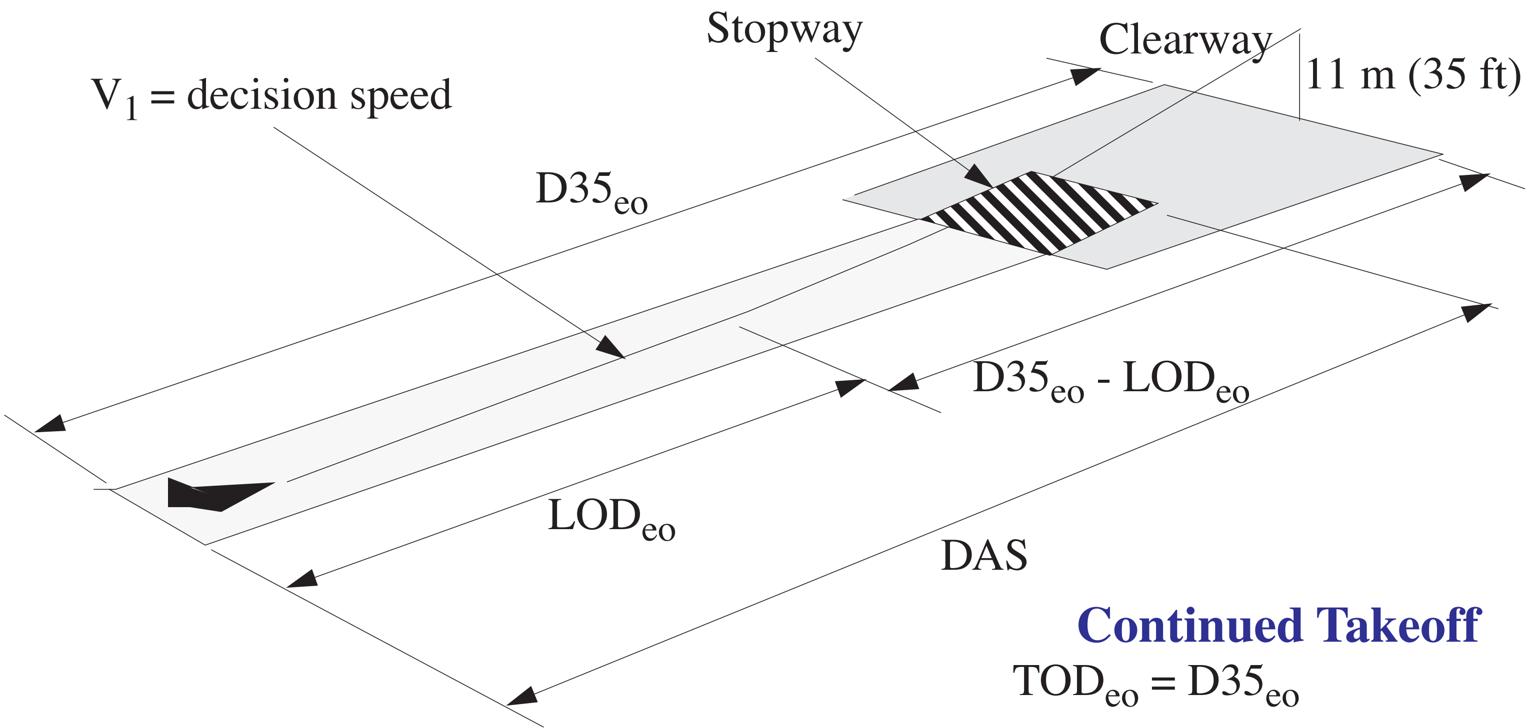
Aborted or rejected takeoff subcase

- Distance to accelerate and stop (DAS)

Note: no correction is applied due to the rare nature of engine-out conditions in practice for turbofan/turbojet powered aircraft



Engine-Out Analysis



Continued Takeoff

$TOD_{eo} = D35_{eo}$

$CL_{eo} = 1/2\ (D35_{eo} - LOD_{eo})$

$TOR_{eo} = D35_{eo} - CL_{eo}$

$FS_{eo\text{-}c} = TOR_{eo}$

$FL_{eo\text{-}c} = FS_{eo\text{-}c} + CL_{eo}$

Aborted Takeoff

$FS_{eo\text{-}a} = DAS - SW$

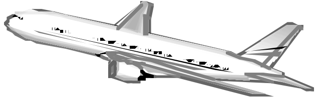
$FL_{eo\text{-}a} = FS_{eo\text{-}a} + SW$

Runway Length Procedures (AC 150/5325-4)

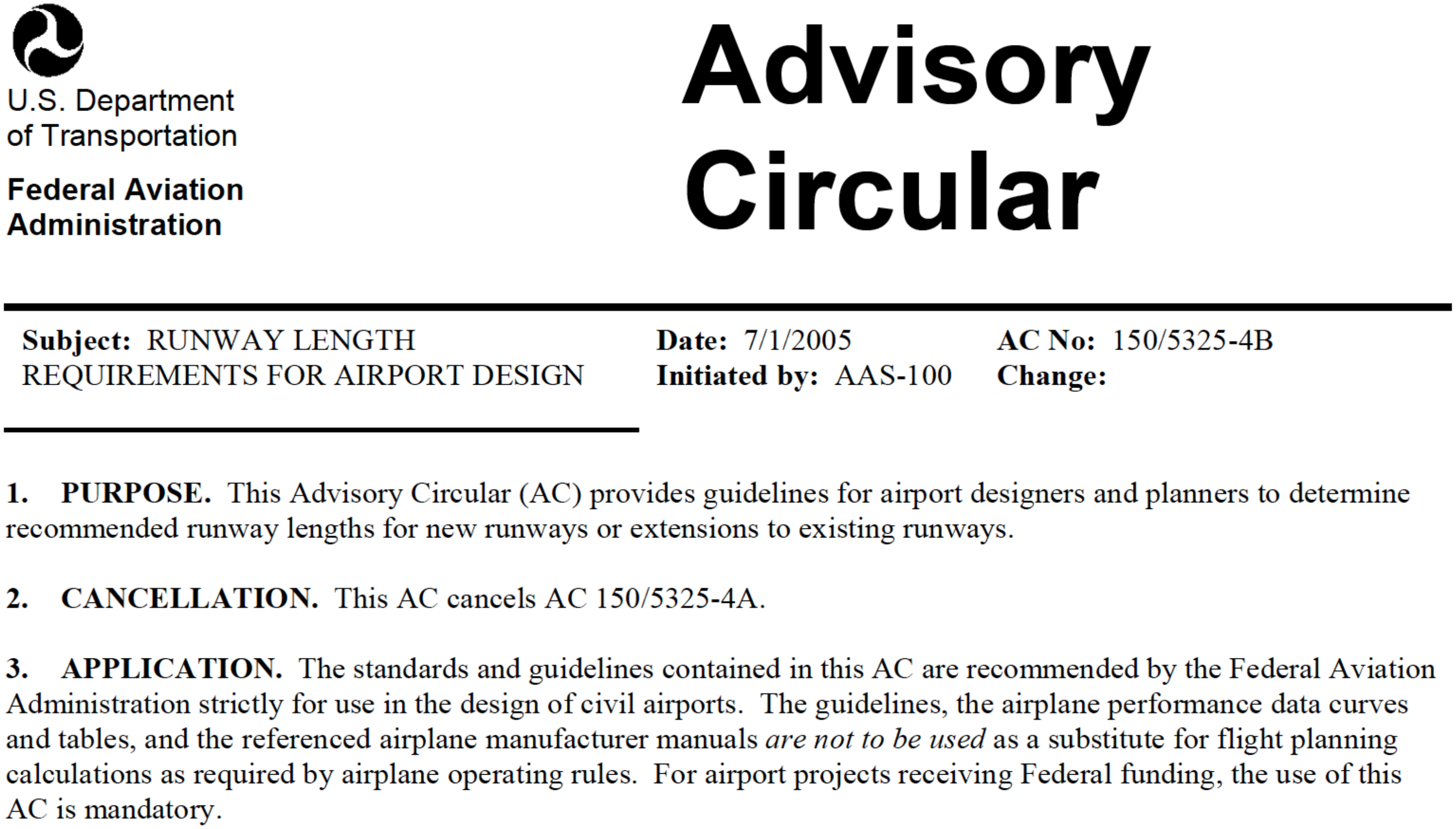
Two different views of the problem:

- For aircraft with MTOW up to 27,200 kg (60,000 lb.) use the aircraft grouping procedure
  - If MTOW is less than 5,670 kg use Figures 2-1 and 2-2 in FAA AC 150/5325-4
  - If MTOW is > 5,670 kg but less than 27,200 kg use Figures 2-3 and 2-4 provided in Chapter 2 of the AC 150/5325-4
- For aircraft whose MTOW is more than 27,200 kg (60,000 lb.) use the critical aircraft concept
  - The critical aircraft is that one with the longest runway performance characteristics
  - This aircraft needs to be operated 250 times in the year from that airport

Review some examples



Advisory Circular 150/5325-4



U.S. Department
of Transportation

**Federal Aviation
Administration**

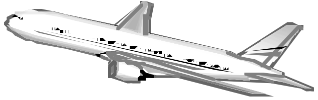
**Advisory
Circular**

Subject: RUNWAY LENGTH REQUIREMENTS FOR AIRPORT DESIGN	**Date:** 7/1/2005 **Initiated by:** AAS-100	**AC No:** 150/5325-4B **Change:**

1. **PURPOSE.** This Advisory Circular (AC) provides guidelines for airport designers and planners to determine recommended runway lengths for new runways or extensions to existing runways.

2. **CANCELLATION.** This AC cancels AC 150/5325-4A.

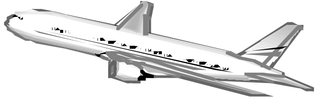
3. **APPLICATION.** The standards and guidelines contained in this AC are recommended by the Federal Aviation Administration strictly for use in the design of civil airports. The guidelines, the airplane performance data curves and tables, and the referenced airplane manufacturer manuals *are not to be used* as a substitute for flight planning calculations as required by airplane operating rules. For airport projects receiving Federal funding, the use of this AC is mandatory.



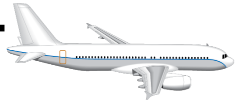
Contents of Advisory Circular 150/5325-4

Be familiar with all items contained in FAA AC 150/5325-4

- Chapter 1 - Introduction (background)
- Chapter 2 - Runway length design based on aircraft groupings
- Chapter 3 - Runway length design for specific aircraft
  - Aircraft performance curves
  - Aircraft performance tables
- Chapter 4 - Use of aircraft manufacturer data
  - Airport temperature and elevation
  - Wind and runway surface
  - Difference in runway centerline elevations
- NOTE: The runway length procedure using **declared the distance concept** is outlined in FAA AC 150/5300-13

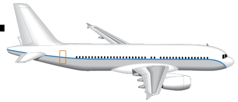


Runway Length Analysis using Aircraft Manufacturer Data for Airport Design



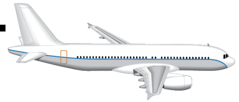
Runway Length for Regional Jets and Aircraft with MTOW > 60,000 lb (27,200 kg)

- Inputs to the procedure:
  - Critical aircraft
  - Maximum certificated takeoff weight (MTOW)
  - Maximum landing weight (MALW)
  - Airport elevation (above mean sea level)
  - Mean daily maximum temperature of the hottest month of the year
  - Runway gradient
  - Airport Planning Manual (APM)
  - Payload-range diagram (optional)



Runway Length for Regional Jets and Aircraft with MTOW > 60,000 lb (27,200 kg)

- Determine takeoff runway length
- Determine landing runway length
- Apply adjustments to obtained runway length
- The longest runway length becomes the recommended runway length for airport design



Temperature Effects in Runway Length Charts

- All design charts have a temperature parameter (be careful)
- While determining runway length for airport design, we need to use the temperature that closely matches the mean daily maximum temperature of the hottest month of the year
- When a temperature values in the chart is "no more than 3° F (1.7° C) lower than the recorded value for the mean daily maximum temperature of the hottest month at the airport" the chart is set to apply
- If the design temperature is too high consult with the aircraft manufacturer

Landing Procedure (FAA)

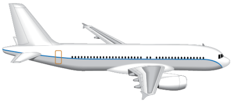
a) Use the landing chart with the highest landing flap setting (if more than one flap setting is offer), zero wind, and zero effective runway gradient.

b) Enter the horizontal weight axis with the operating landing weight equal to the maximum certificated landing weight. Linear interpolation along the weight axis is allowed. Do not exceed any indicated limitations on the chart.

c) Proceed vertically to the airport elevation curve, sometimes labeled “pressure altitude.” Interpolation between curves is allowed. Use the wet pavement charts. Otherwise use 15% above the dry condition

d) Read the runway length. Linear interpolation along the length axis is allowed.

e) Increase the obtained landing length for “dry runway” condition by 15 percent for those cases noted in paragraph 508. No landing length adjustment is necessary by regulation for non-zero effective runway gradients for any airplane type.

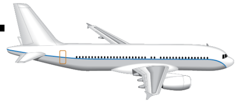


Takeoff Runway Length Procedure (FAA)

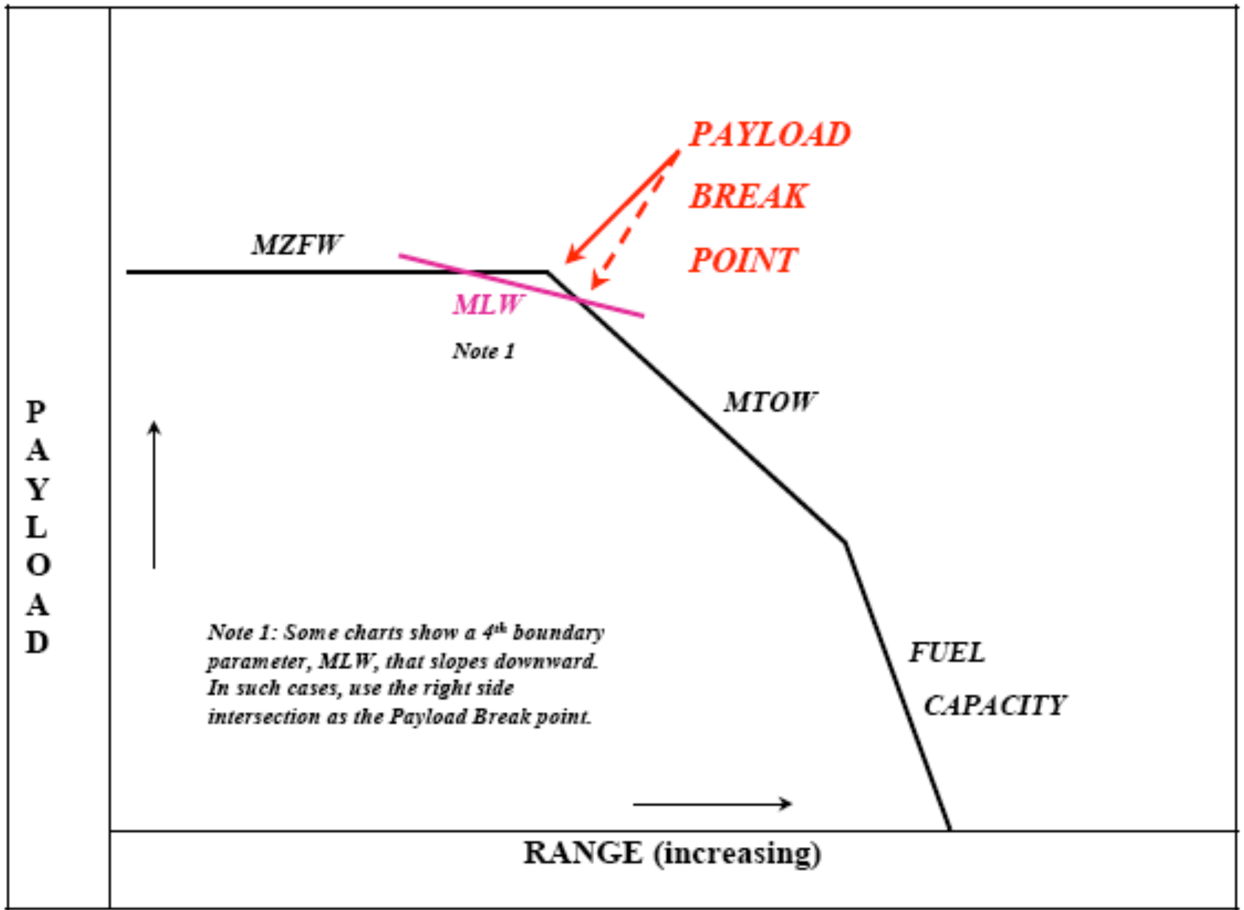
Select the correct **aircraft-engine combination** of runway length design charts

Two possible paths to calculate runway length:

- **No stage length provided**: use the MTOW value from the payload-range diagram (near payload-break point – see diagram in next page)
- **For actual routes expected to be flown** (and used as design point) use the actual takeoff (or Desired Takeoff Weight – DTW)
- For design operating takeoff weight equal to the actual operating takeoff weight.
- *"Consult with AC 120-27D, Aircraft Weight and Balance Control, provides average weight values for passengers and baggage for payload calculations for short-haul routes"*

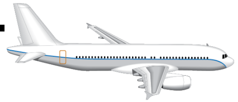


Hypothetical Payload-Range Diagram



Note 1: Some charts show a 4th boundary parameter, MLW, that slopes downward. In such cases, use the right side intersection as the Payload Break point.

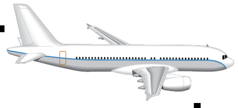
MLW maximum design landing weight
MTOW maximum design takeoff weight (some APMs label it Brake Release)
MZFW maximum design zero fuel weight (some APMs label it Maximum Design Payload)



Weights Authorized by FAA (source: *AC 120-27E)*

Standard Average Passenger Weight	Weight Per Passenger
Summer Weights	
Average adult passenger weight	190 lb
Average adult male passenger weight	200 lb
Average adult female passenger weight	179 lb
Child weight (2 years to less than 13 years of age)	82 lb
Winter Weights	
Average adult passenger weight	195 lb
Average adult male passenger weight	205 lb
Average adult female passenger weight	184 lb
Child weight (2 years to less than 13 years of age)	87 lb

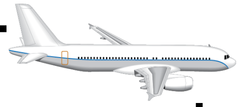
- Summer weights apply from May 1 to October 31
- Allowance of 16 lb per person for carry-out items in table above
- Average weight of a bag is 30 lb
- Heavy bags are 60 lbs
- Use 220 lb/passenger (190 + 30) for airport design



Weights Authorized by FAA (source: *AC 120-27E)*

- Some operators do surveys of passenger and luggage item weights
- If an operator conducts a survey and finds that the 16 lb allowance is small, it will be necessary to increase the weight allowance
- A recommended random sample is necessary:

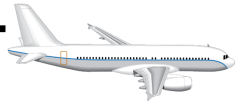
Survey Subject	**Minimum Sample Size**	**Tolerable Error**
Adult (standard adult/male/female)	2,700	1%
Child	2,700	2%
Checked bags	1,400	2%
Heavy bag	1,400	2%
Plane-side loaded bags	1,400	2%
Personal items and carry-on bags	1,400	2%
Personal items only (for operators with a no carry-on bag program)	1,400	2%



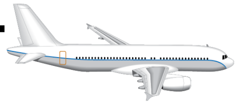
Final Notes on Runway Length Calculations

- Read the runway length requirement by entering the desired takeoff weight and airport elevation
- Linear interpolation along the runway length axis is allowed
- Adjust the takeoff runway length for non-zero effective runway gradients
- Increase the runway length by 10 feet (3 m) per foot (0.3m) of difference in runway centerline elevations between the high and low points of the runway centerline

- Final runway length is the most demanding of the landing and the takeoff

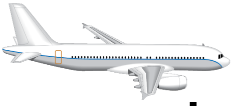


Example Calculation
No Stage Length Defined



Boeing 737-900 per FAA AC
Example 1 in FAA AC Appendix 3

- Airplane Boeing 737-900 (CFM56-7B27 Engines)
- Mean daily maximum temperature of hottest month at the airport 84° Fahrenheit (28.9° C)
- Airport elevation 1,000 feet
- Maximum design landing weight (see table A3-1-1) 146,300 pounds
- Maximum design takeoff weight 174,200 pounds
- Maximum difference in runway centerline elevations 20 feet



Boeing 737-900 Example (per FAA AC) Landing Analysis

Step 1 – the Boeing 737-900 APM provides three landing charts for flap settings of 40-degrees, 30-degrees, and 15-degrees. **The 40-degree flap setting landing chart**, figure A3-1-1, is chosen since, it results in the shortest landing runway length requirement.

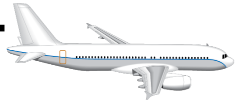
Steps 2 and 3 – Enter the horizontal weight axis at 146,300 pounds and proceed vertically and interpolate between the airport elevations “wet” curves of sea level and 2,000 feet for the 1,000-foot wet value. Wet curves are selected because the airplane is a turbo-jet powered airplane (see paragraph 508). Interpolation is allowed for both design parameters.

Step 4 – Proceed horizontally to the length axis to read 6,600 feet. Interpolation is allowed for this design parameter.

Step 5 – Do not adjust the obtained length since the “Wet Runway” curve was used. See paragraph 508 if only “dry” curves are provided.

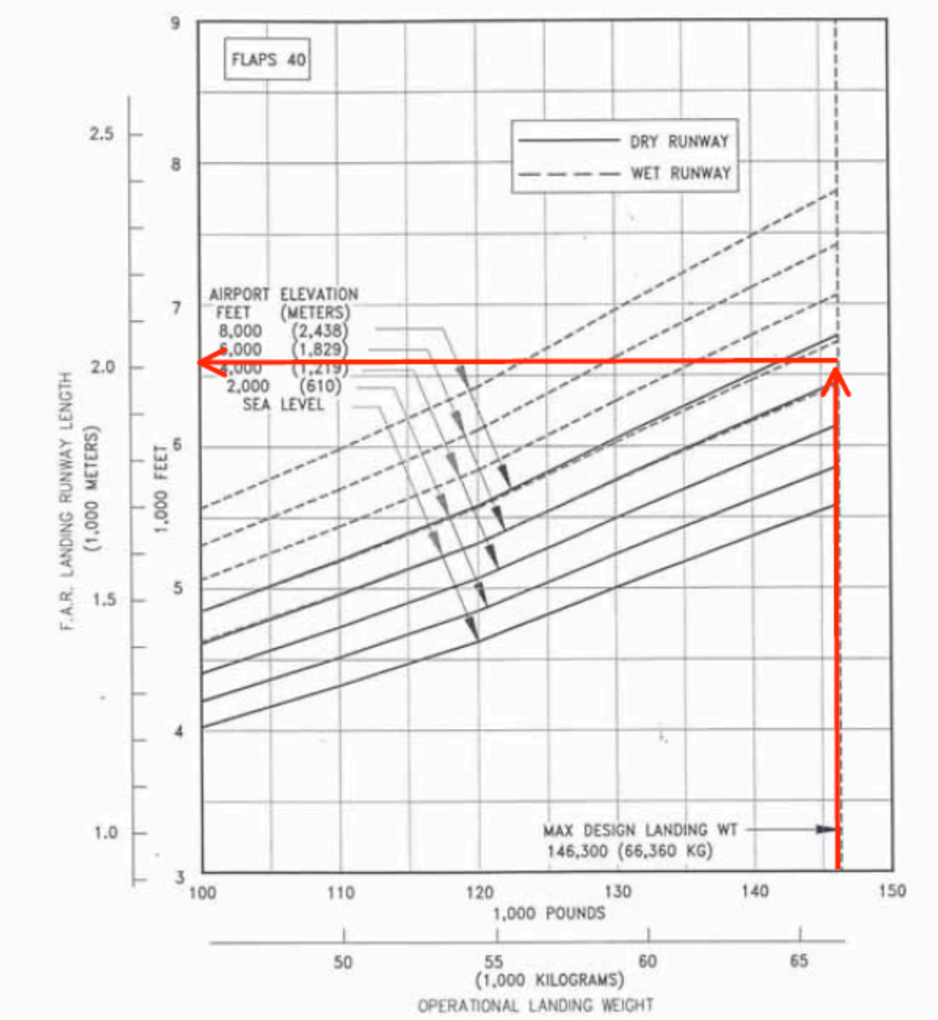
The length requirement is 6,600 feet. Note: Round lengths of 30 feet and over to the next 100-foot interval. Thus, the landing length for design is **6,600 feet.**

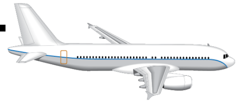
Boeing 737-900 Example (per FAA AC)
Landing Analysis (Chart)



Note:

Highest flap
Setting selected
According to
FAA procedure



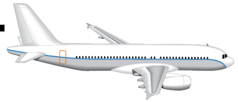


Boeing 737-900 Example (per FAA AC) Takeoff Analysis

Step 1 – The Boeing 737-900 APM provides a takeoff chart at the standard day + 27°F (SDT + 15° C) temperature applicable to the various flap settings. Notice that this chart can be used for airports whose mean daily maximum temperature of the hottest month at the airport is equal to or less than 85.4° F (29.7° C). Since the given temperature for this example is 84° F (28.9° C) falls within this range, select this chart.

Steps 2 and 3 – Enter the horizontal weight axis at 174,200 pounds and proceed vertically and interpolate between the airport elevation curves of sea level and 2,000 feet for the 1,000-foot value. Interpolation is allowed for both design parameters.

Note: As observed in this example, a takeoff chart may contain under the “Notes” section the condition that linear interpolation between elevations is invalid. Because the application of the takeoff chart is for airport design and not for flight operations, interpolation is allowed.



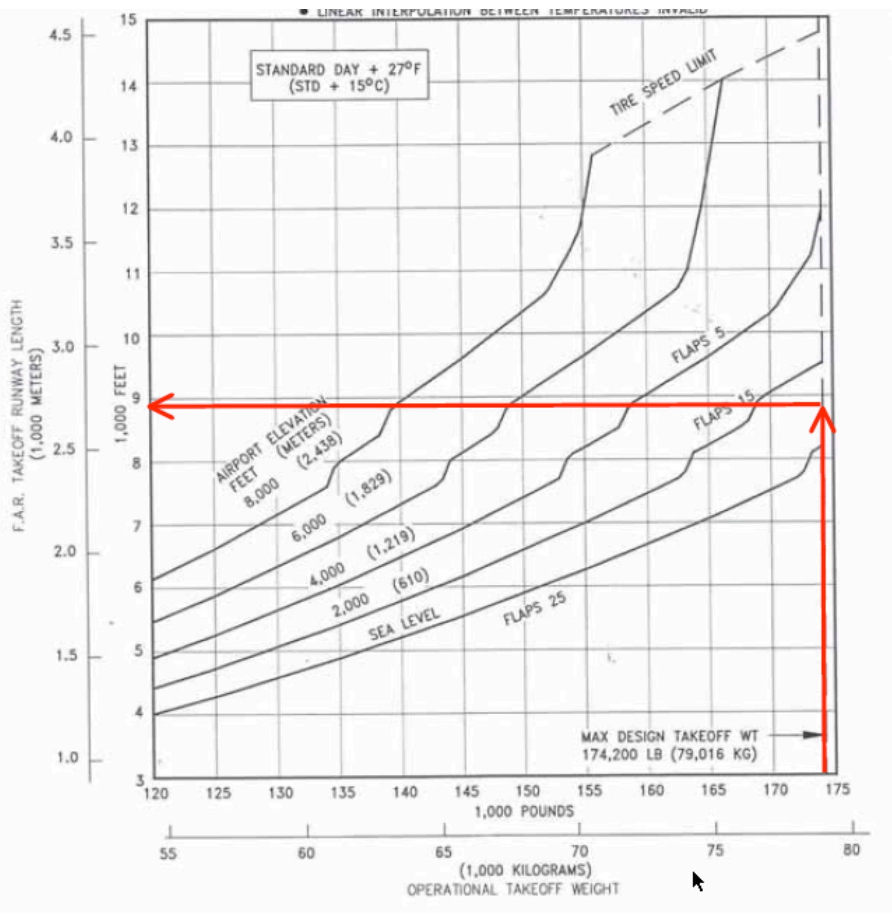
Boeing 737-900 Example (per FAA AC) Takeoff Analysis (Chart)

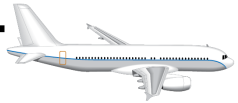
Step 4 – Proceed horizontally to the length axis to read 8,800 feet. Interpolation is allowed for this design parameter.

Step 5 – Adjust for non-zero effective runway gradient (see paragraph 509).

8,800 + (20 x 10) = 8,800 + 200 = 9,000 feet

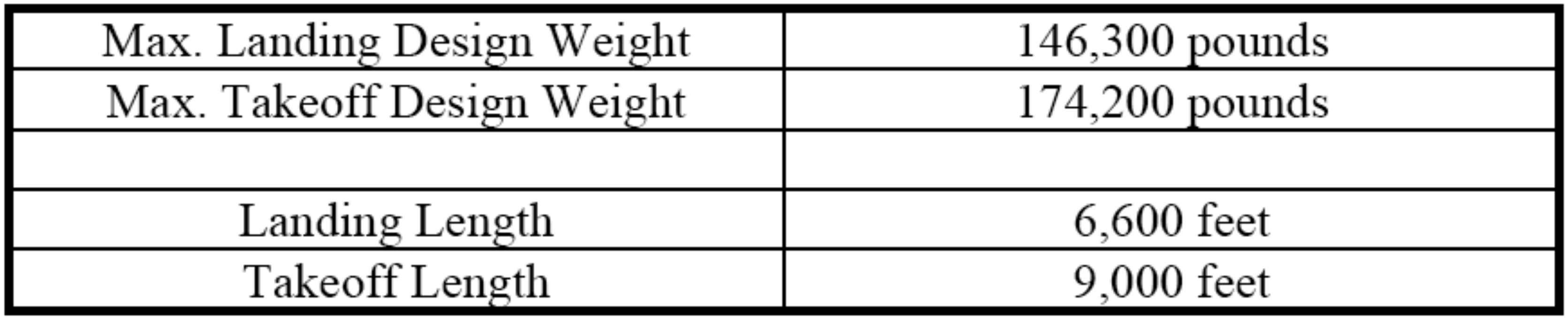
The takeoff length requirement is 9,000 feet. Note: Round lengths of 30 feet and over to the next 100-foot interval. Thus, the takeoff length for design is 9,000 feet.



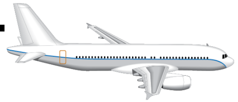


Boeing 737-900 Example (per FAA AC) Recommended Runway Length

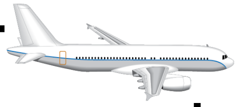
- The recommended runway length is 9,000 feet
- The takeoff runway length is dominant



Max. Landing Design Weight	146,300 pounds
Max. Takeoff Design Weight	174,200 pounds
Landing Length	6,600 feet
Takeoff Length	9,000 feet



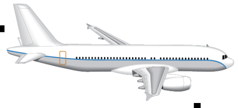
Example Calculation With Stage Length Defined



Boeing 777-200 HGW Example

- Boeing 777-200 High Gross Weight Estimate the runway length to operate a Boeing 777-200 High Gross Weight (HGW) from Washington Dulles to Sao Paulo Guarulhos airport in Brazil (a stage length of 4,200 nm) at Mach .84. After consultation with the airline you learned that their B777s have a gross weight of 592,000 lb. (HGW option) and have a standard three-class seating arrangement
- The airline has B 777-200 HGW with General Electric engines
- Assume hot day conditions.

Aircraft Basic Information

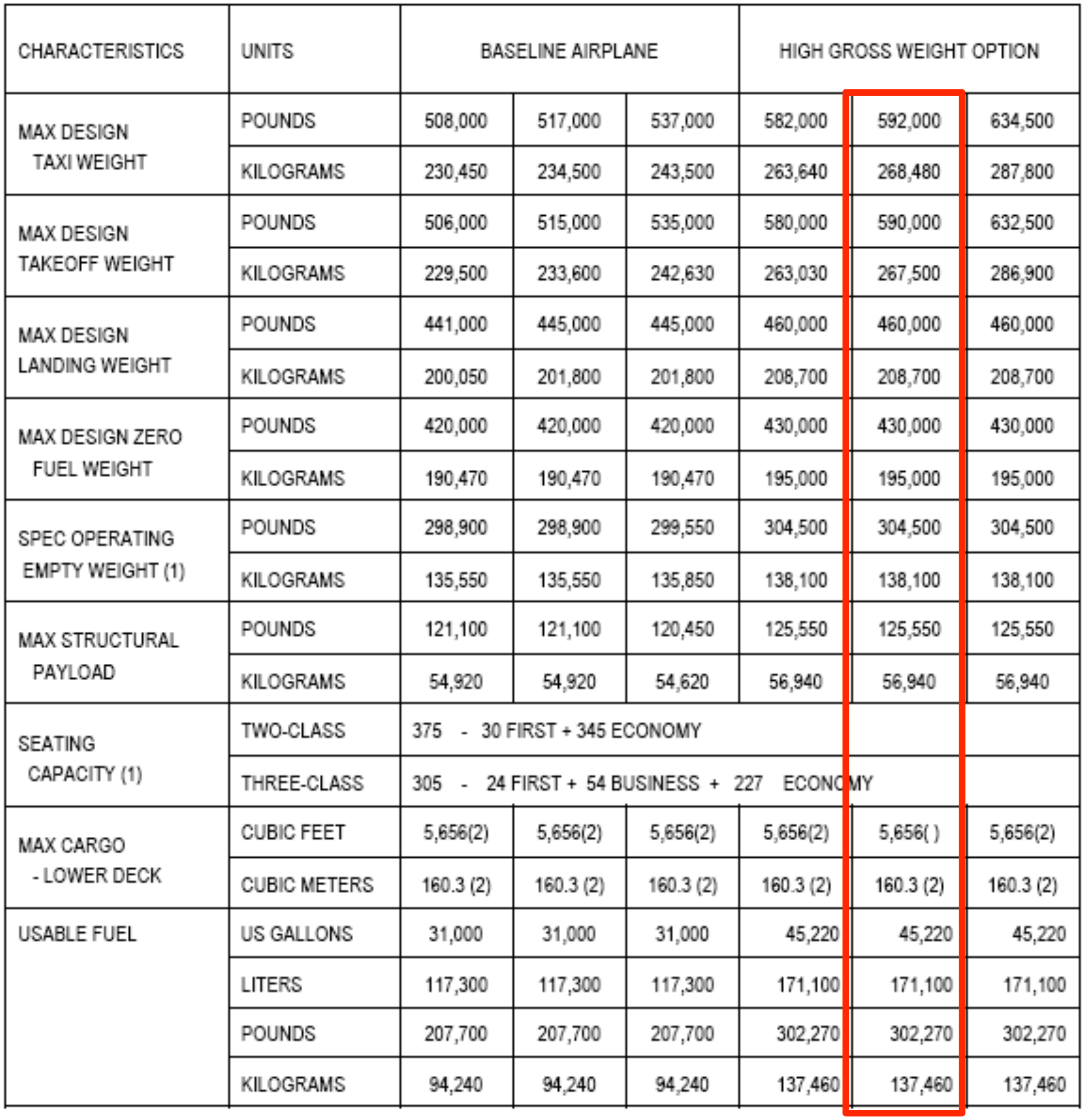


777-200/300

Airplane Characteristics for

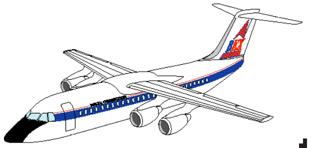
Airport Planning

Boeing Document D6-58329



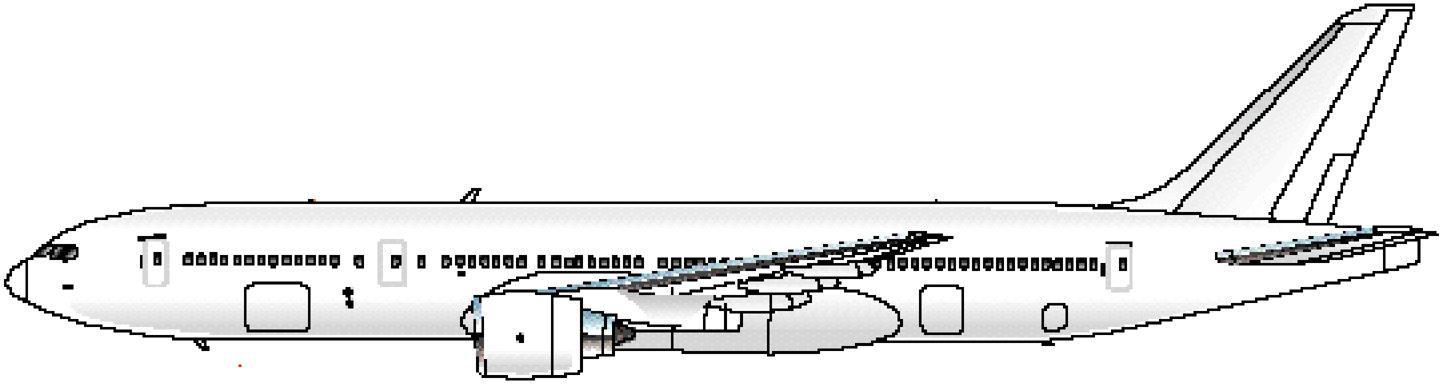
CHARACTERISTICS	UNITS	BASELINE AIRPLANE			HIGH GROSS WEIGHT OPTION		
MAX DESIGN TAXI WEIGHT	POUNDS	508,000	517,000	537,000	582,000	592,000	634,500
	KILOGRAMS	230,450	234,500	243,500	263,640	268,480	287,800
MAX DESIGN TAKEOFF WEIGHT	POUNDS	506,000	515,000	535,000	580,000	590,000	632,500
	KILOGRAMS	229,500	233,600	242,630	263,030	267,500	286,900
MAX DESIGN LANDING WEIGHT	POUNDS	441,000	445,000	445,000	460,000	460,000	460,000
	KILOGRAMS	200,050	201,800	201,800	208,700	208,700	208,700
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	420,000	420,000	420,000	430,000	430,000	430,000
	KILOGRAMS	190,470	190,470	190,470	195,000	195,000	195,000
SPEC OPERATING EMPTY WEIGHT (1)	POUNDS	298,900	298,900	299,550	304,500	304,500	304,500
	KILOGRAMS	135,550	135,550	135,850	138,100	138,100	138,100
MAX STRUCTURAL PAYLOAD	POUNDS	121,100	121,100	120,450	125,550	125,550	125,550
	KILOGRAMS	54,920	54,920	54,620	56,940	56,940	56,940
SEATING CAPACITY (1)	TWO-CLASS	375 - 30 FIRST + 345 ECONOMY					
	THREE-CLASS	305 - 24 FIRST + 54 BUSINESS + 227 ECONOMY					
MAX CARGO - LOWER DECK	CUBIC FEET	5,656(2)	5,656(2)	5,656(2)	5,656(2)	5,656( )	5,656(2)
	CUBIC METERS	160.3 (2)	160.3 (2)	160.3 (2)	160.3 (2)	160.3 (2)	160.3 (2)
USABLE FUEL	US GALLONS	31,000	31,000	31,000	45,220	45,220	45,220
	LITERS	117,300	117,300	117,300	171,100	171,100	171,100
	POUNDS	207,700	207,700	207,700	302,270	302,270	302,270
	KILOGRAMS	94,240	94,240	94,240	137,460	137,460	137,460

Boeing 777-200 High Gross Weight

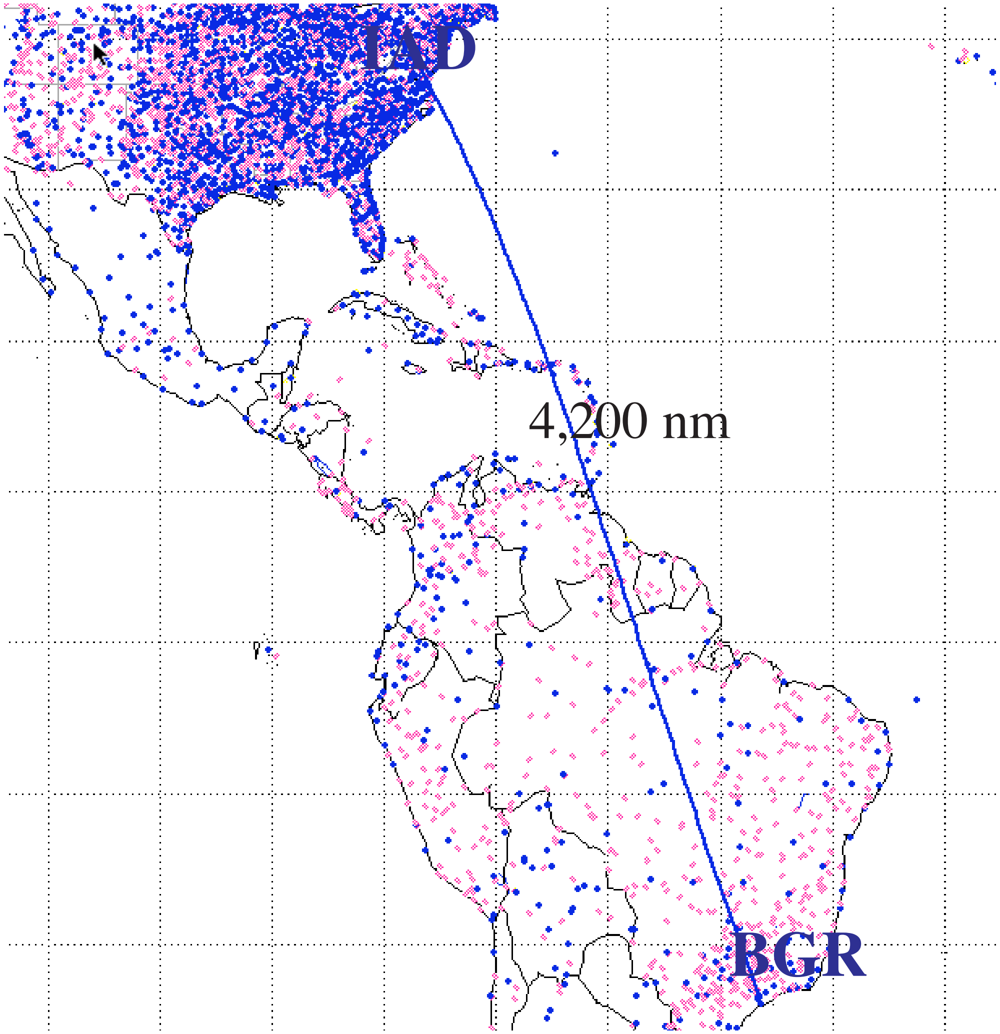


Estimate the runway length to operate a Boeing 777-200 High Gross Weight (HGW) from Washington Dulles to Sao Paulo Guarulhos airport in Brasil (a stage length of 4,200 nm) at Mach .84.

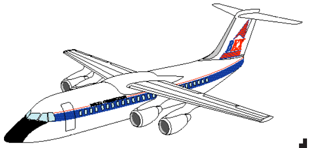
After consultation with the airline you learned that their B777s have a gross weight of 592,000 lb. (HGW option) and have a standard three-class seating arrangement.The airline has B 777-200 HGW with General Electric engines. Assume hot day conditions.



IAD-BGR Trip



Discussion of Computations



1) Estimation of Desired Takeoff Weight (DTW)

$$DTW = PYL + OEW + FW$$

where:

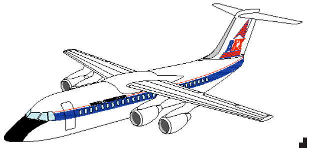
PYL is the payload carried (passengers and cargo)

OEW is the operating empty weight

FW is the fuel weight to be carried (usually includes reserve fuel)

Note: PYL and OEW can be easily computed

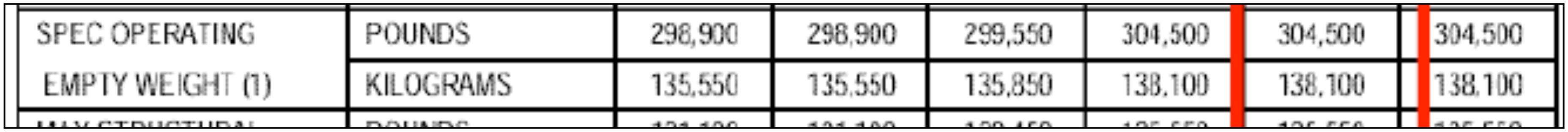
Boeing 777-200 (GE Engines)



CHARACTERISTICS	UNITS	BASELINE AIRPLANE			HIGH GROSS WEIGHT OPTION		
MAX DESIGN TAXI WEIGHT	POUNDS	508,000	517,000	537,000	582,000	592,000	634,500
	KILOGRAMS	230,450	234,500	243,500	263,640	268,480	287,800
MAX DESIGN TAKEOFF WEIGHT	POUNDS	506,000	515,000	535,000	580,000	590,000	632,500
	KILOGRAMS	229,500	233,600	242,630	263,030	267,500	286,900
MAX DESIGN LANDING WEIGHT	POUNDS	441,000	445,000	445,000	460,000	460,000	460,000
	KILOGRAMS	200,050	201,800	201,800	208,700	208,700	208,700
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	420,000	420,000	420,000	430,000	430,000	430,000
	KILOGRAMS	190,470	190,470	190,470	195,000	195,000	195,000
SPEC OPERATING EMPTY WEIGHT (1)	POUNDS	298,900	298,900	299,550	304,500	304,500	304,500
	KILOGRAMS	135,550	135,550	135,850	138,100	138,100	138,100
MAX STRUCTURAL PAYLOAD	POUNDS	121,100	121,100	120,450	125,550	125,550	125,550
	KILOGRAMS	54,920	54,920	54,620	56,940	56,940	56,940
SEATING CAPACITY (1)	TWO-CLASS	375 - 30 FIRST + 345 ECONOMY					
	THREE-CLASS	305 - 24 FIRST + 54 BUSINESS + 227 ECON MY					
MAX CARGO - LOWER DECK	CUBIC FEET	5,656(2)	5,656(2)	5,656(2)	5,656(2)	5,656( )	5,656(2)
	CUBIC METERS	160.3 (2)	160.3 (2)	160.3 (2)	160.3 (2)	160.3 (2)	160.3 (2)
USABLE FUEL	US GALLONS	31,000	31,000	31,000	45,220	45,220	45,220
	LITERS	117,300	117,300	117,300	171,100	171,100	171,100
	POUNDS	207,700	207,700	207,700	302,270	302,270	302,270
	KILOGRAMS	94,240	94,240	94,240	137,460	137,460	137,460

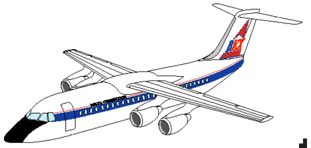
Computation of Payload and OEW

- OEW = 304,500 lb (138,100 kg)
- PYL = (305 passengers) (100 kg/passenger)
  - PYL = 30,500 kg (67,100 lb)
  - OEW + PYL = 168,600 kg (370,920 lb)
- NOTE: I used the more accepted standard of 100 kg per passengers in this solution



SPEC OPERATING EMPTY WEIGHT (1)	POUNDS	298,900	298,900	299,550	304,500	304,500	304,500
	KILOGRAMS	135,550	135,550	135,850	138,100	138,100	138,100

Computation of Fuel Weight

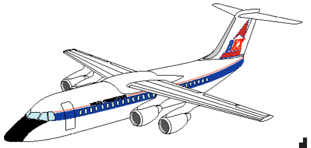


This analysis requires information on fuel consumption for this aircraft flying at a specific cruising condition. Use the payload range diagram of the aircraft to estimate the average fuel consumption in the trip.

The Payload-Range Diagram is a composite plot that shows the operational tradeoffs to carry fuel and payload.

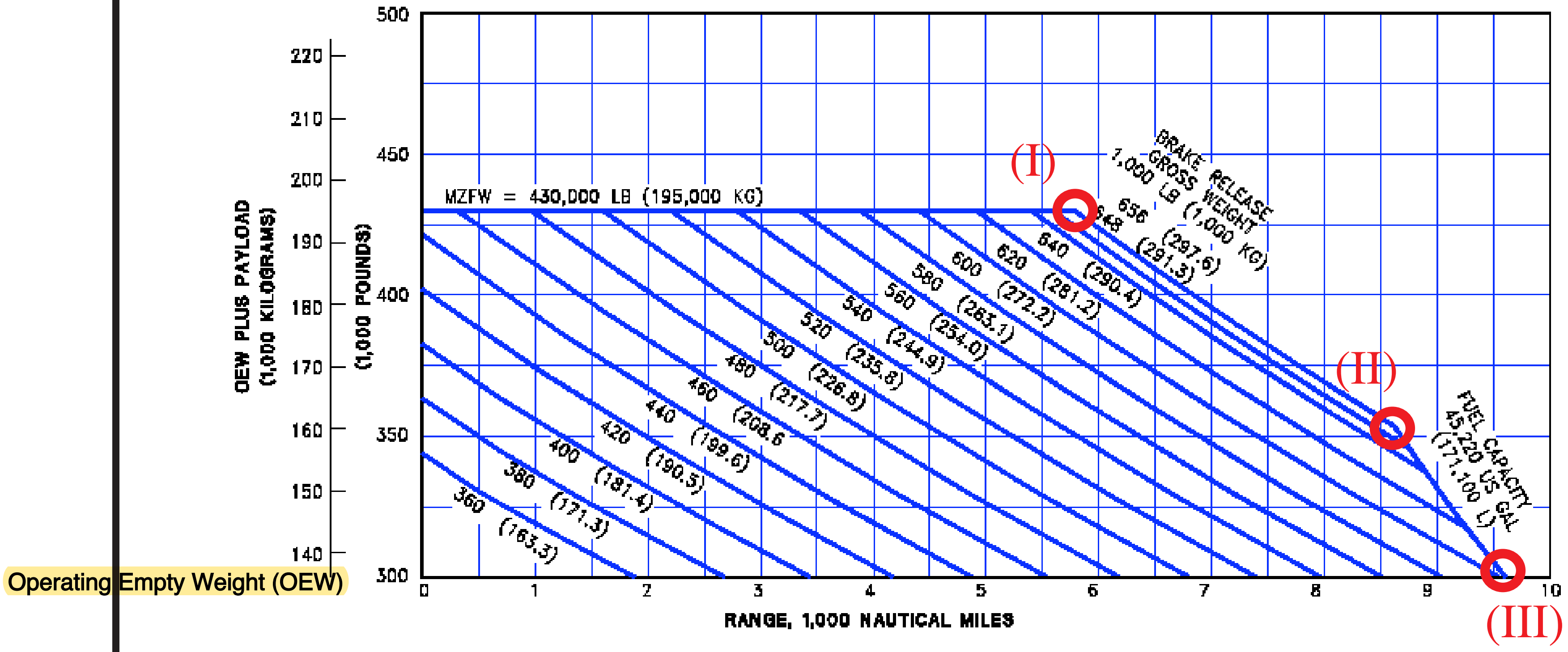
- As the payload carried increases the amount of fuel to conduct a flight might be decreased thus reducing the actual range (distance) of the mission
- P-R diagrams consider operational weight limits such as MZFW, MTOW and MSPL

Range-Payload Diagram for Boeing 777-200

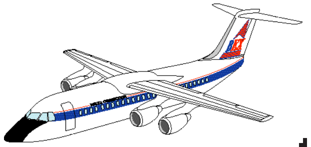


NOTES:

- STANDARD DAY, ZERO WIND
- 0.84 MACH STEP CRUISE
- TYPICAL MISSION RULES
- NORMAL POWER EXTRACTION AND AIR CONDITIONING BLEED
- CONSULT USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE AND OEW PRIOR TO FACILITY DESIGN



Expalantion of P-R Diagram Boundaries

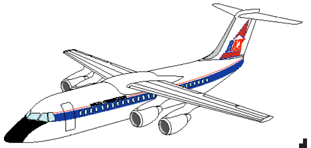


From this diagram three corner points representing combinations of range and payload are labeled with roman numerals (I-III). An explanation of these points follows.

Operating point (I) represents an operational point where the aircraft carries its maximum payload at departs the origin airport at maximum takeoff gross weight (note the brake release gross weight boundary) of 297.6 metric tons.

The corresponding range for condition (I) is a little less than 5,900 nautical miles. Note that under this conditions the aircraft can carry its maximum useful payload limit of 56,900 kg (subtract 195,000 kg. from 138,100 kg. which is the OEW for this aircraft).

Payload-Range Diagrams Explanations

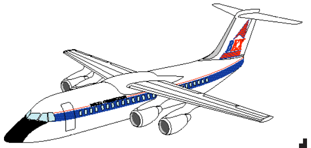


Operating Point (II) illustrates a range-payload compromise when the fuel tanks of the aircraft are full (note the fuel capacity limit boundary).

Under this condition the aircraft travels 8,600 nm but can only carry 20,900 kg of payload (includes cargo and passengers), and a fuel complement of fuel (171,100 liters or 137,460 kg.).

The total brake release gross weight is still 297.6 metric tons for condition (II).

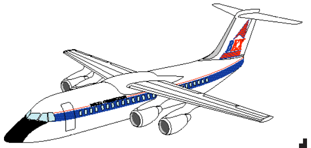
Payload-Range Diagrams Explanations



Operating Point (III) represents the ferry range condition where the aircraft departs with maximum fuel on board and zero payload. This condition is typically used when the aircraft is delivered to its customer (i.e., the airline) or when a non-critical malfunction precludes the carrying of passengers.

This operating point would allow this aircraft to cover 9,600 nautical miles with 137,460 kg.of fuel on board and zero payload for a brake release gross weight of 275,560 kg. (137,460 + 138,100 kg.) or below MTOW.

Limitations of P-R Diagram Information



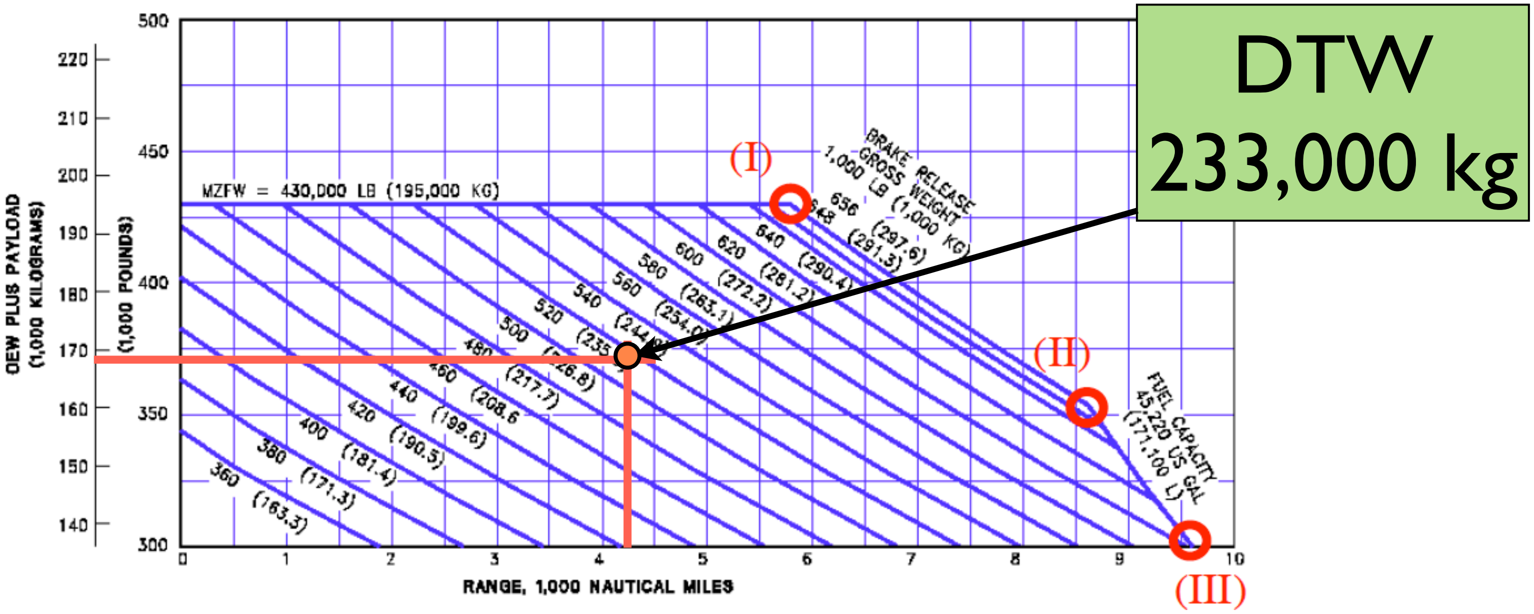
A note of caution about payload range diagrams is that they only apply to a given set of flight conditions.

For example, in Figure Boeing claims that this diagram only applies to zero wind conditions, 0.84 Mach, standard day conditions (e.g., standard atmosphere) and Air Transport Association (ATA) domestic fuel reserves (this implies enough fuel to fly 1.25 hours at economy speed at the destination point).

If any of these conditions changes so does the payload-range diagram.

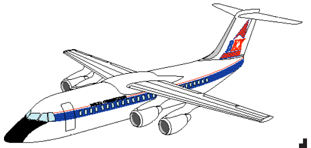
Back to the Problem

- Our critical aircraft (B777-200 HGW option) is expected to fly 4,200 nm with full passengers
- From the Payload-Range diagram read off the Desired Takeoff Weight (DTW) as ~233,000 kg
- Recall: OEW + PYL = 168,600 kg
- The amount of fuel carried for the trip would be:
    - FW = DTW - OEW - PYL = 64,400 kg.



DTW
233,000 kg

Presentation of Runway Length Information



For the aircaft in question we have two sets of curves available to compute runway length:

- Takeoff
- Landing

These curves apply to specific airfield consitions so you should always use good judgement in the analysis. Typically two sets of curves are presented by Boeing:

- Standard day conditions
- Standard day + ΔT conditions

where ΔT represents some increment from standard day conditions (typically 15^{o}).

Conversion of Standard Temperatures (Table 4.1 in FAA AC 150/5325-4b)

- Use the table to understand what constitutes standard temperature (ISA) for various airfield elevations

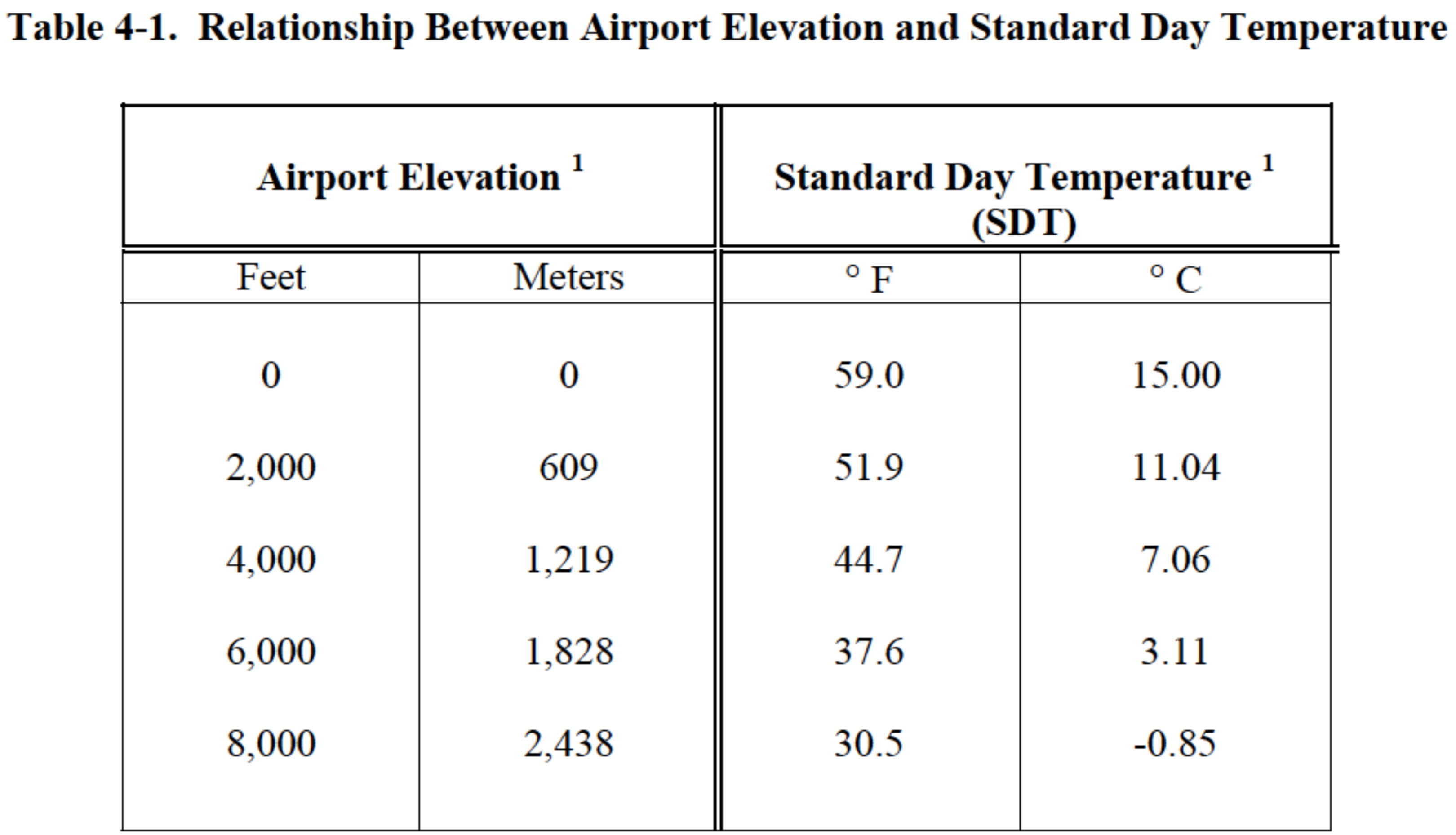
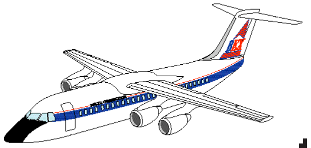
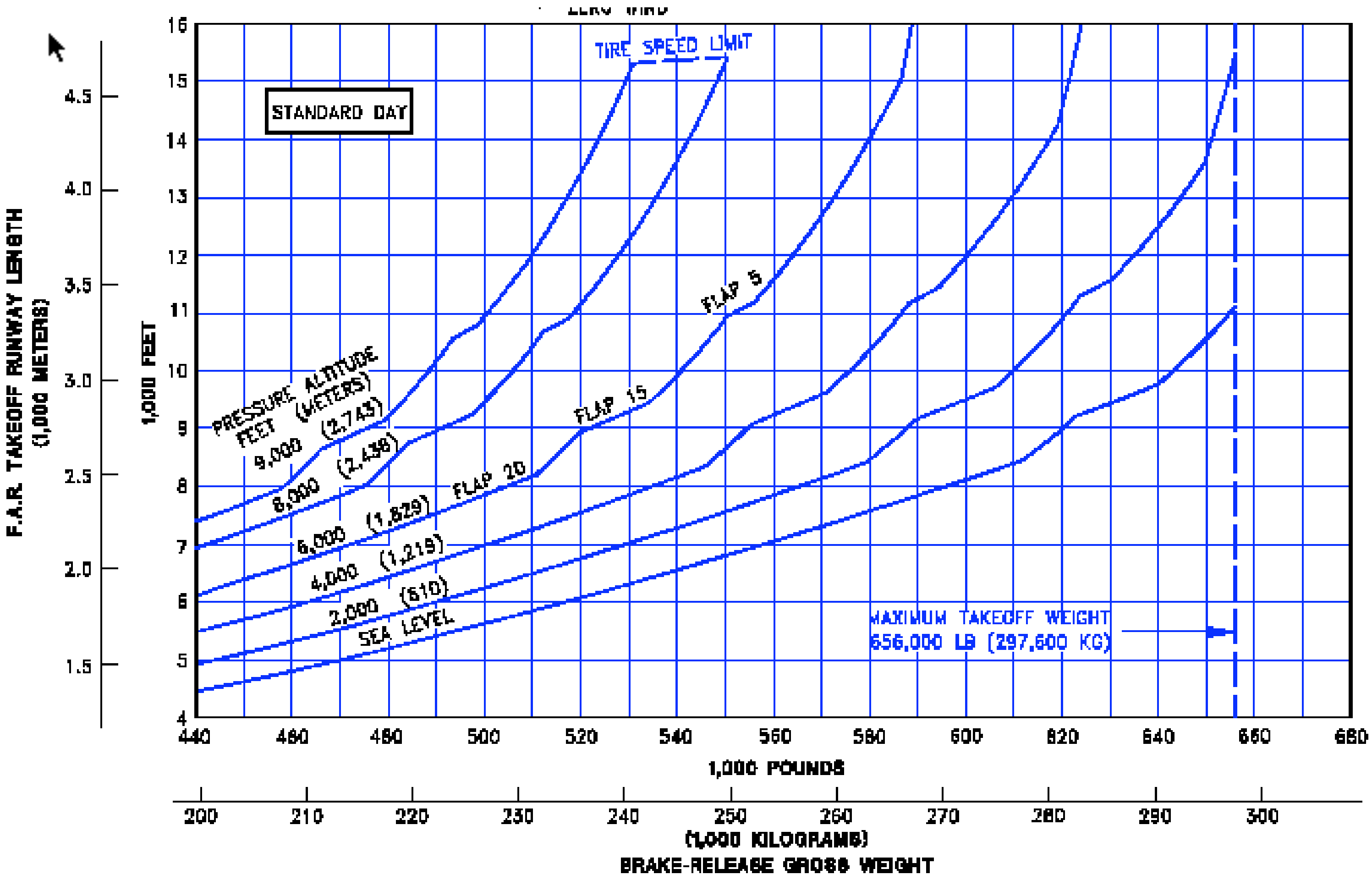


Table 4-1. Relationship Between Airport Elevation and Standard Day Temperature

Airport Elevation [1]		**Standard Day Temperature** [1] **(SDT)**	
Feet	Meters	° F	° C
0	0	59.0	15.00
2,000	609	51.9	11.04
4,000	1,219	44.7	7.06
6,000	1,828	37.6	3.11
8,000	2,438	30.5	-0.85

Boeing 777-200 HGW Takeoff Performance

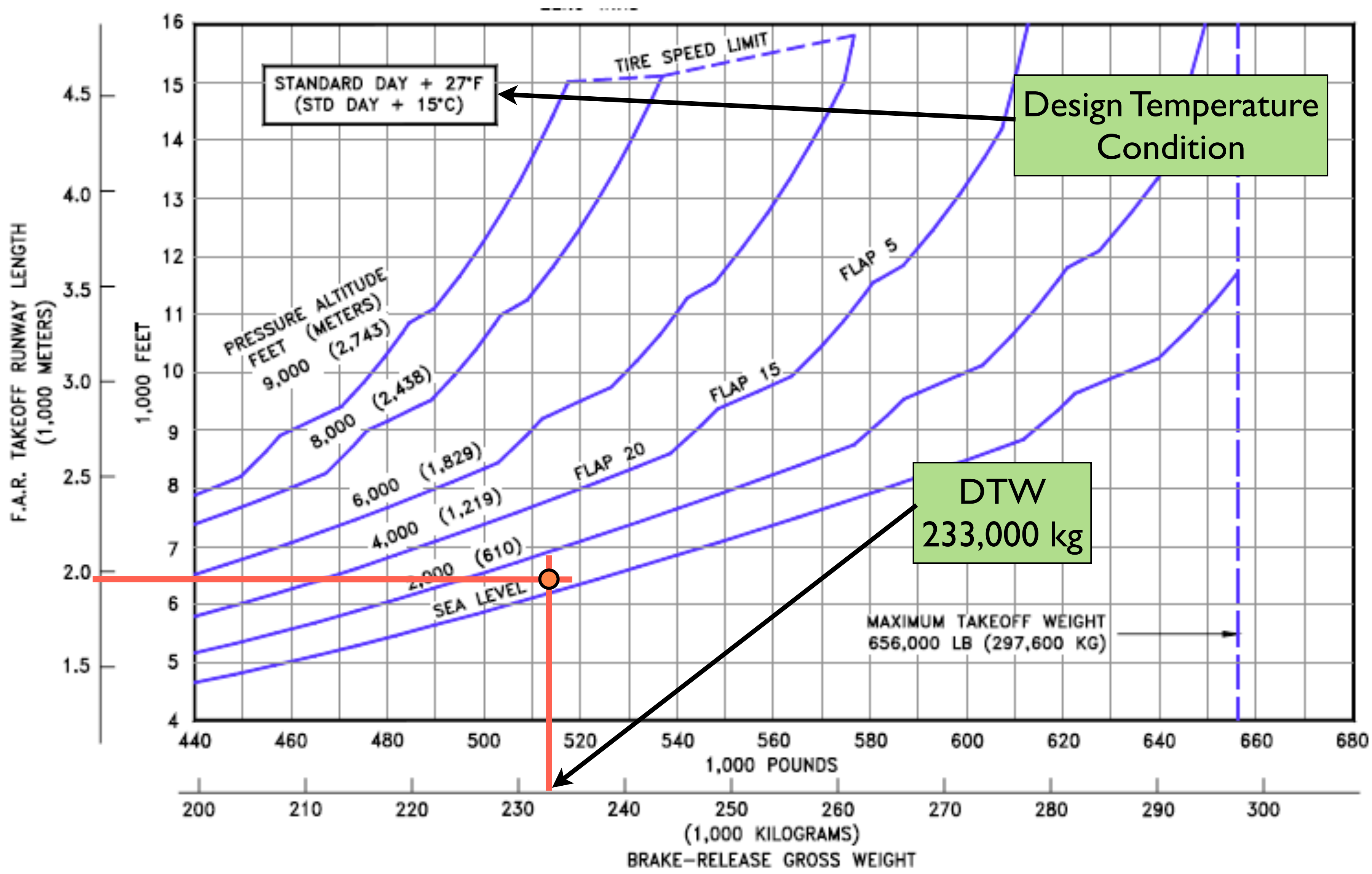




3.3.3 FAA TAKEOFF RUNWAY LENGTH REQUIREMENTS - STANDARD DAY

MODEL 777-200 (HIGH GROSS WEIGHT AIRPLANE)

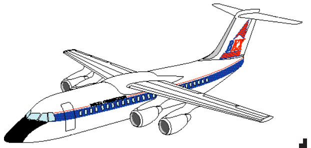
Takeoff Curves for Boeing 777-200 HGW



Design Temperature Condition

DTW
233,000 kg

Takeoff Runway Length Analysis



From the performance chart we conclude:

- **$RL_{takeoff}$ = 1,950 m.**
- Optimum flap setting = 20 degress for takeoff (see flap setting lines in the diagram)
- DTW is way below the maximum capability for this aircraft.

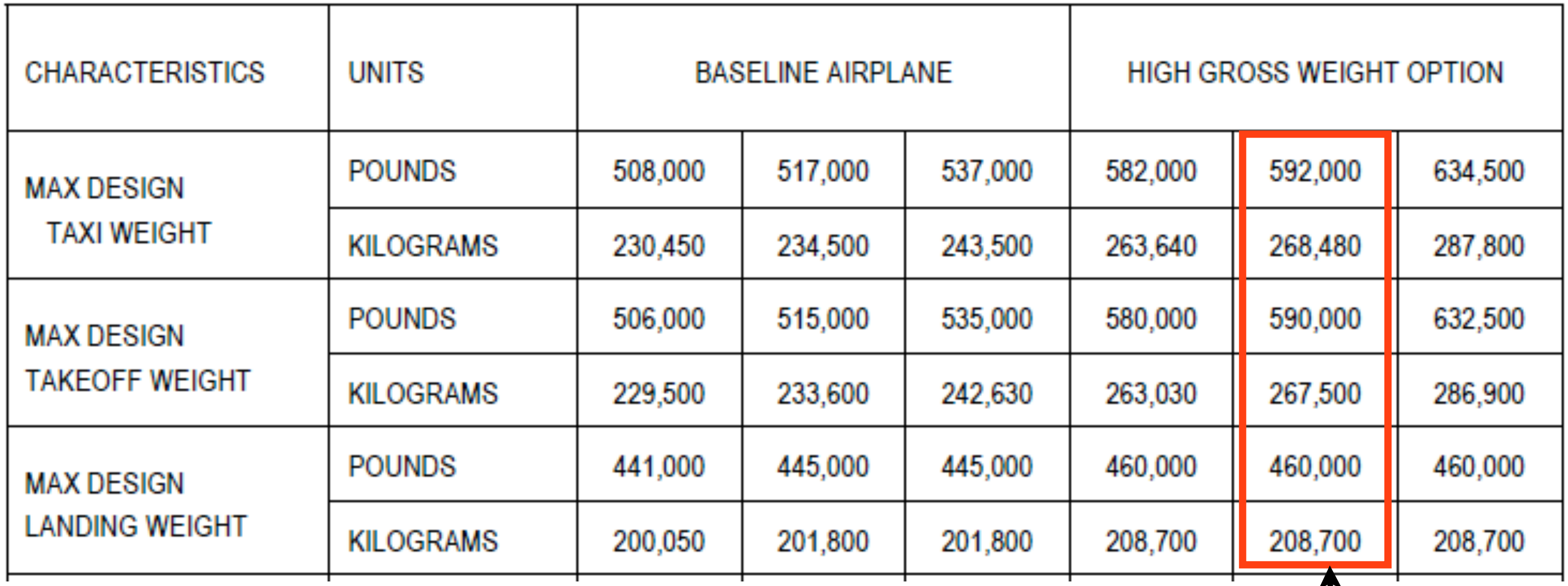
Repeat the takeoff problem solution if the aircraft departs from **Bogota** in Colombia (airport elevation is 8,360 feet).

Verify the takeoff field length to be: 12,300 feet
Bogota has runways 12,467 feet long.

Landing Analysis (Boeing 777-200 HGW)

- The analysis is similar to that performed under FAA AC 150/5325-4b
- Consider an emergency situation and compute the landing weight at the departing airport
  - DTW = 233,000 kg
- The maximum allowable landing weight for the aircraft is:
  - MALW = 208,700 kg.
- Since DTW > MALW use the Maximum allowable landing weight
  - RL_{land} = **1,850 meters** (using wet pavement conditions)

Landing Analysis (Boeing 777-200 HGW)



CHARACTERISTICS	UNITS	BASELINE AIRPLANE			HIGH GROSS WEIGHT OPTION		
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	KILOGRAMS	230,450	234,500	243,500	263,640	268,480	287,800
MAX DESIGN TAKEOFF WEIGHT	POUNDS	506,000	515,000	535,000	580,000	590,000	632,500
	KILOGRAMS	229,500	233,600	242,630	263,030	267,500	286,900
MAX DESIGN LANDING WEIGHT	POUNDS	441,000	445,000	445,000	460,000	460,000	460,000
	KILOGRAMS	200,050	201,800	201,800	208,700	208,700	208,700

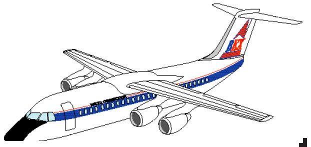
In most emergencies after takeoff, pilots would like to land "legally" at or below the MALW limit (landing gear is designed to withstand landings up to MALW)

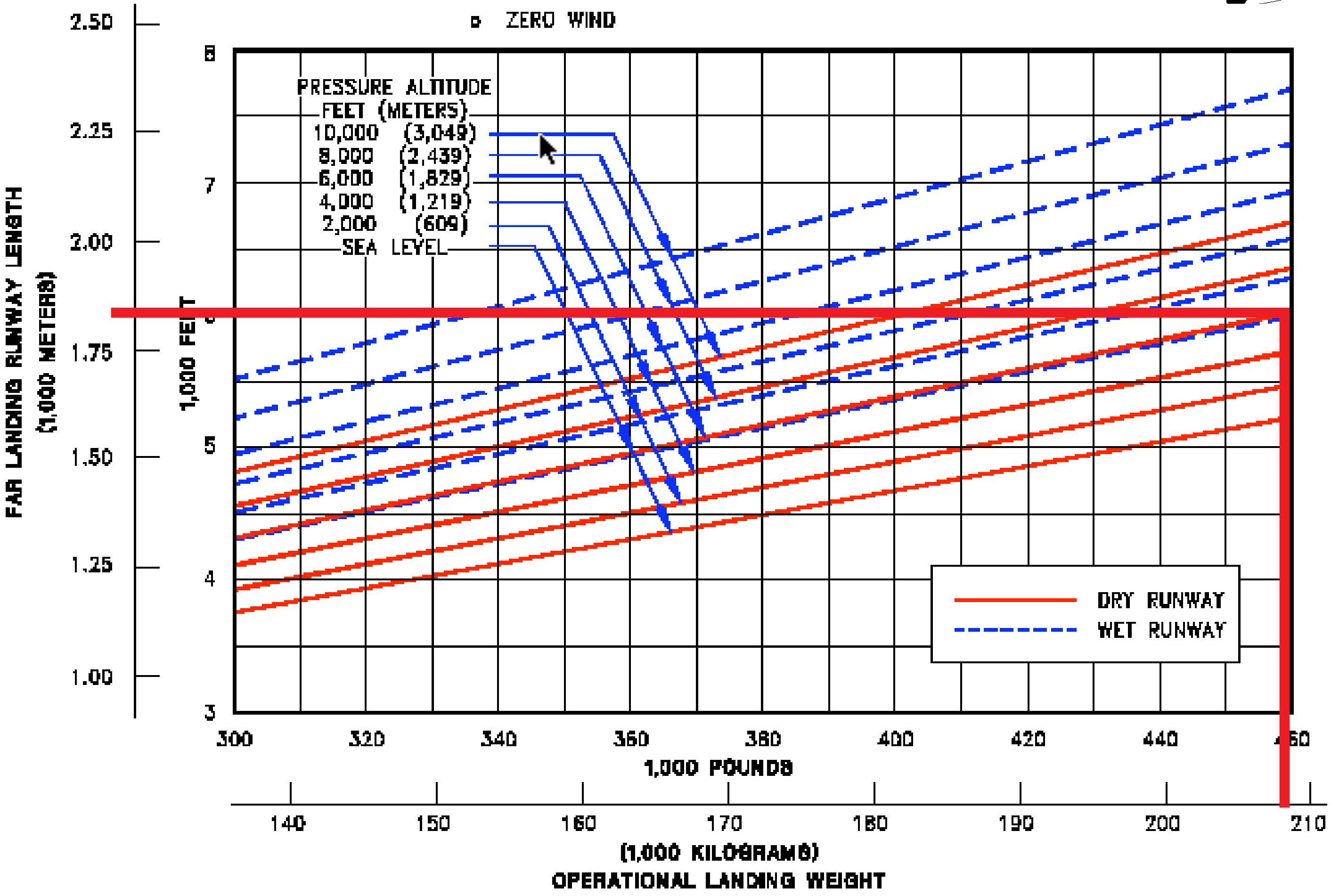
Maximum Allowable Landing Weight

Example Incident (Source: Aviation Herald)

- United Airlines B772 near Tokyo on July 28th 2010 suffered an engine failure after departure
- Article at: http://avherald.com/h?article=42f0df24/0000&opt=0
- Pilots shut down the bad engine and **dumped fuel**
  - “*The NTSB reported that the crew heard a loud bang from the #2 engine followed by a high pitch grinding noise for about 3-4 seconds”.*
  - *Within a few more seconds all instruments of the #2 engine had decreased to 0”.*
  - *“90,000 lbs of fuel were dumped before the airplane landed with about 12,000 lbs overweight. The engine failure was contained but metal debris was observed in the tailpipe*”.

Boeing 777-200 HGW Landing Performance

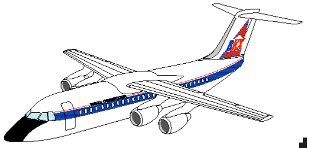




3.4.1 FAA LANDING RUNWAY LENGTH REQUIREMENTS

MODEL 777-200

Reconcile Takeoff and Landing Cases



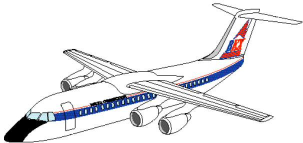
Select worst case scenario and use that as runway length requirement.

$RL_{takeoff}$ = 1,950 m.

RL_{land} = 1,850 m.

Takeoff dominates so use the $RL_{takeoff}$ as the design number.

Observe Some Trends from Takeoff Curves



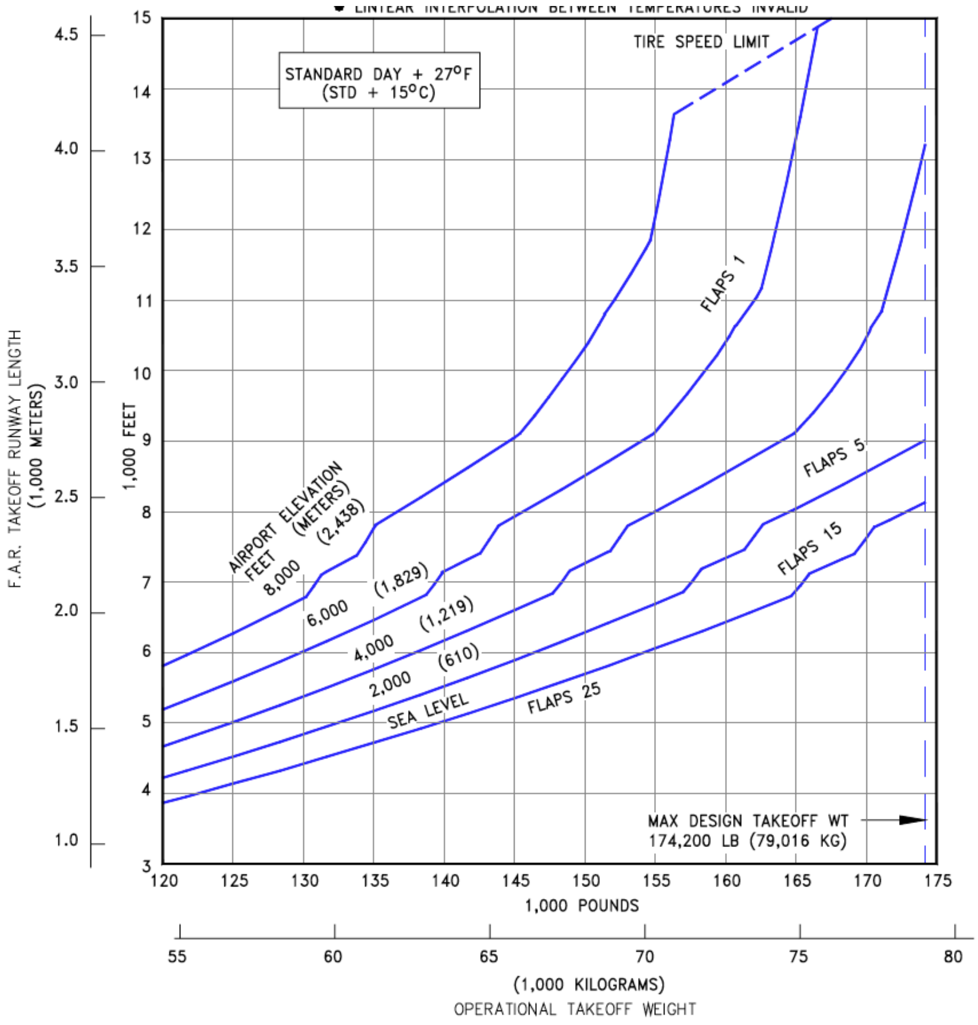
- If DTW increases the RL values increase non-linearly (explain using the fundamental aircraft acceleration equation)
- As field elevation increases (pressure altitude) the RL values increase as well (temperature effect on air density)
- As DTW and field elevation increase the optimum flap setting for takeoff decreases
  - This is consistent with our knowledge of C_d and C_L. Hot and high airfield elevations require very low flap settings during takeoff to reduce the drag of the aircraft.
- High airfield elevations (and large to moderate DTWs) could hit a tire speed limit boundary. Aircraft tires are cretified to this limit and thus an airline would never dare to depart beyond this physical boundary.

Runway Surface Conditions in APM (Aircraft Manual for Airport Design and Planning)

- Until recently, most aircraft manufacturers provided takeoff runway length data for both dry and wet pavement conditions
- In recent publications, some aircraft airport design information only provides dry takeoff performance
- Paragraph 508 in AC 150/5325-4b states:
  - *Many airplane manufacturers' APMs for turbojet-powered airplanes provide both dry runway and wet runway landing curves.* ***If an APM provides only the dry runway condition, then increase the obtained dry runway length by 15 percent for landing operations.***

Example: Boeing 737-800 with CFM56-7B26 Engines

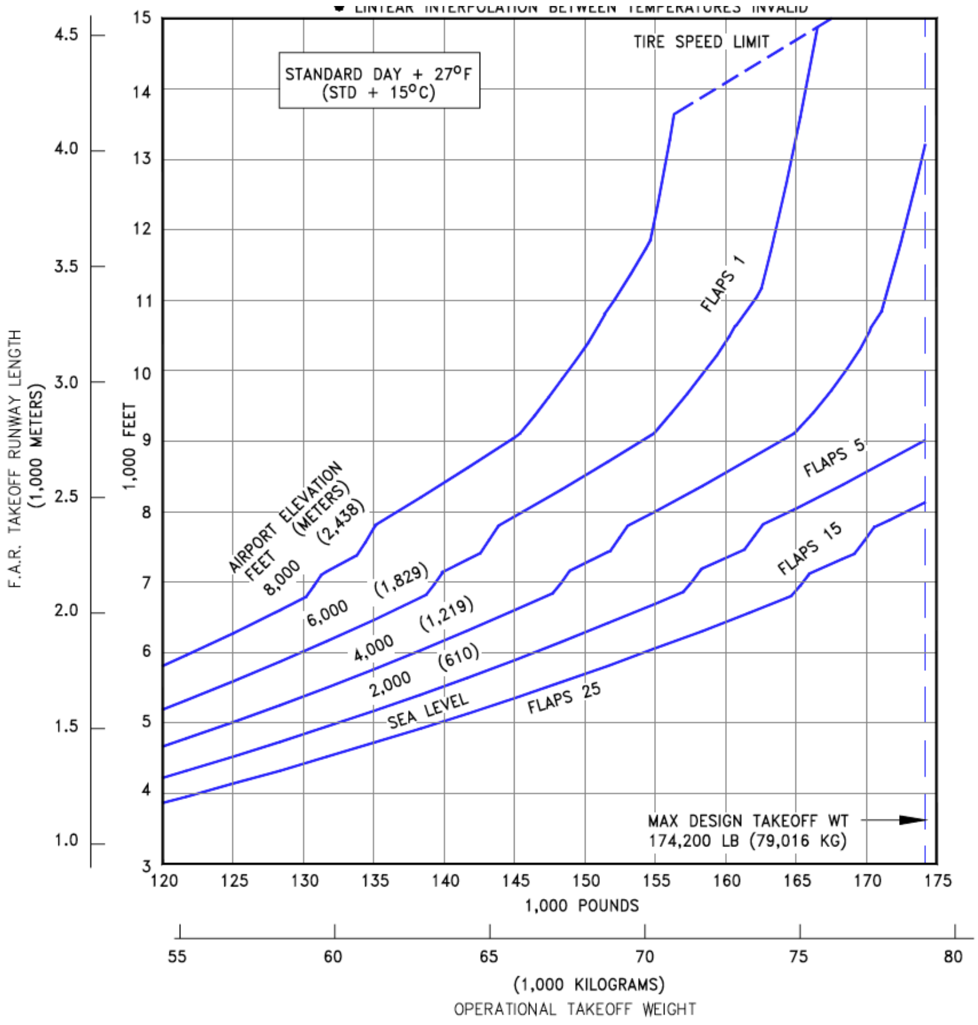
- Old Boeing 737-800 takeoff performance chart (December 2001)
- Engines CFM56-7B26
- Rated at 26,300 lb of thrust at sea level
- ISA + 15 deg. C



3.3.30 F.A.R. TAKEOFF RUNWAY LENGTH REQUIREMENTS
STANDARD DAY +27°F (STD + 15°C), DRY RUNWAY
MODEL 737-800 (CFM56-7B26 ENGINES AT 26,300 LB SLST)

Example: Boeing 737-800 with CFM56-7B26 Engines (APM circa 2001)

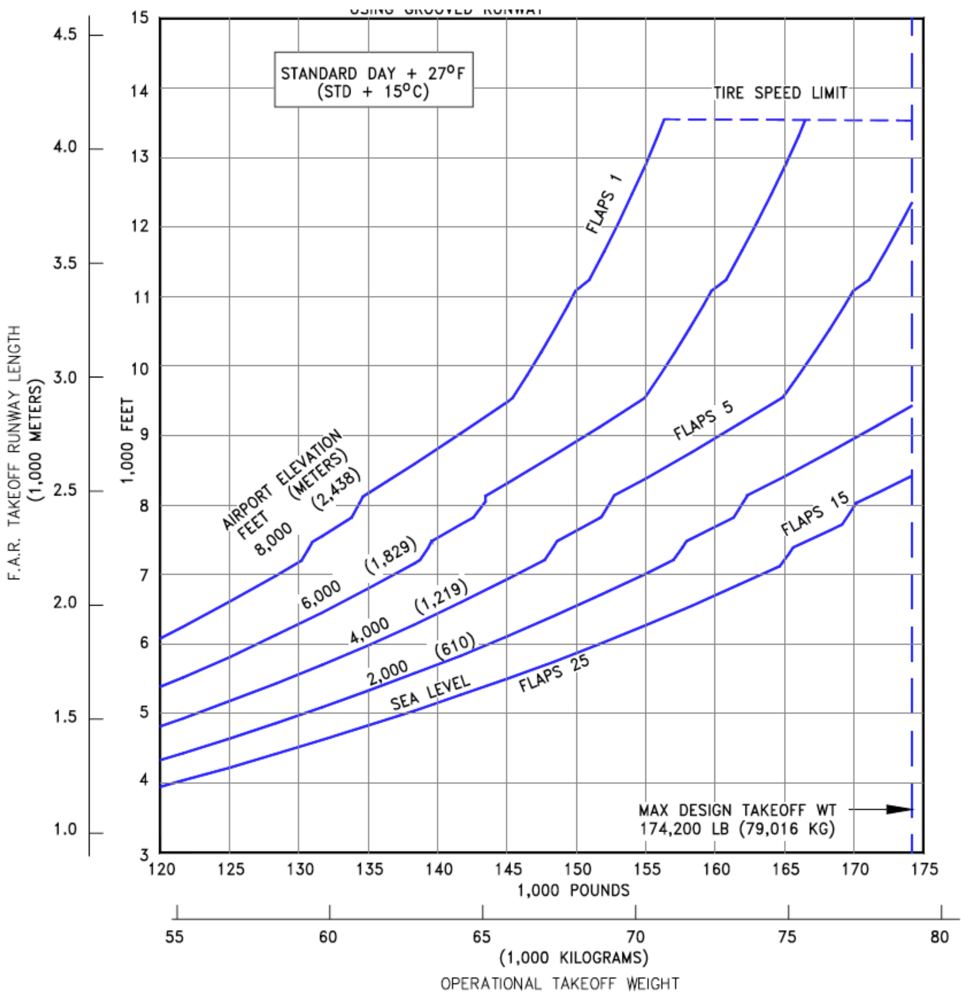
- Takeoff mass = 75,000 kg
- 4000 feet airport elevation
- ISA + 15 deg. C
- Dry Runway
- FAR Takeoff length is **9,100 feet**



3.3.30 F.A.R. TAKEOFF RUNWAY LENGTH REQUIREMENTS
STANDARD DAY +27°F (STD + 15°C), DRY RUNWAY
MODEL 737-800 (CFM56-7B26 ENGINES AT 26,300 LB SLST)

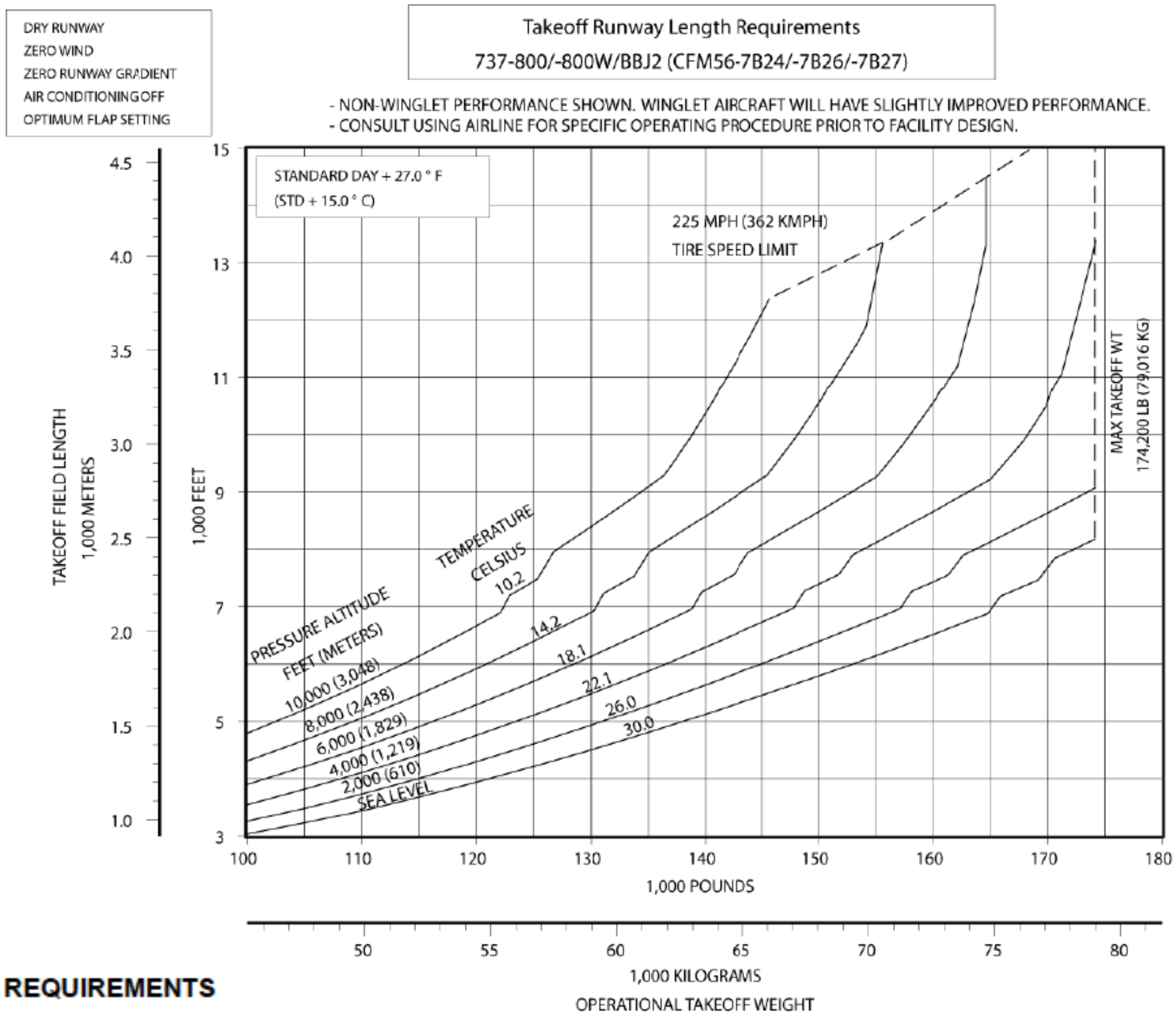
Example: Boeing 737-800 with CFM56-7B26 Engines (APM circa 2001)

- Takeoff mass = 75,000 kg
- 4000 feet airport elevation
- ISA + 15 deg. C
- **Wet Runway**
- FAR Takeoff length is 9,600 feet



3.3.32 J.A.A. TAKEOFF RUNWAY LENGTH REQUIREMENTS
STANDARD DAY +27°F (STD + 15°C), WET RUNWAY
MODEL 737-800 (CFM56-7B26 ENGINES AT 26,300 LB SLST)

Example: Boeing 737-800 with CFM56-7B26 Engines (APM circa 2010)



F.A.R. TAKEOFF RUNWAY LENGTH REQUIREMENTS

STANDARD DAY +27°F (STD + 15°C), DRY RUNWAY

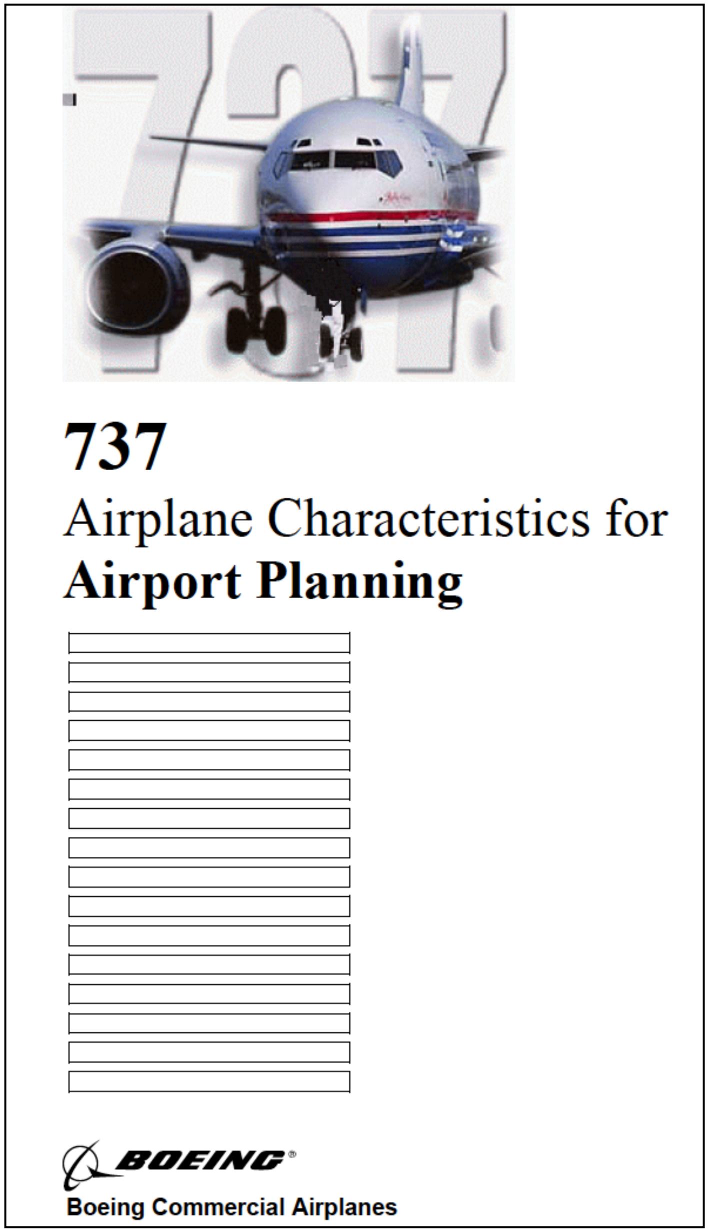
MODEL 737-800/-800W/BBJ2 (CFM56-7B24/-7B26/-7B27 ENGINES AT 26,000 LB SLST)

Example: Boeing 737-800 with CFM56-7B26 Engines (APM circa 2010)

- Takeoff mass = 75,000 kg
- 4000 feet airport elevation
- ISA + 15 deg. C
- **Dry Runway** (only chart provided in the new document)
- FAR Takeoff length is **9,100** feet
- **For takeoff operations use dry runway charts**
- During certification (FAA and EASA), dry pavement conditions do not consider the use of thrust reversers (i.e., conservative approach)

Temperature and Field Effects

- Consider the effects of airport elevation in the runway performance of a Boeing 737-800 aircraft
- Engines are GE/Snecma CFM56-7B24/-7B26/-7B27 producing 26,000 lb of thrust
- See Boeing document D6-58325-6: at
- http://www.boeing.com/commercial/airports/737.htm



737

Airplane Characteristics for

Airport Planning

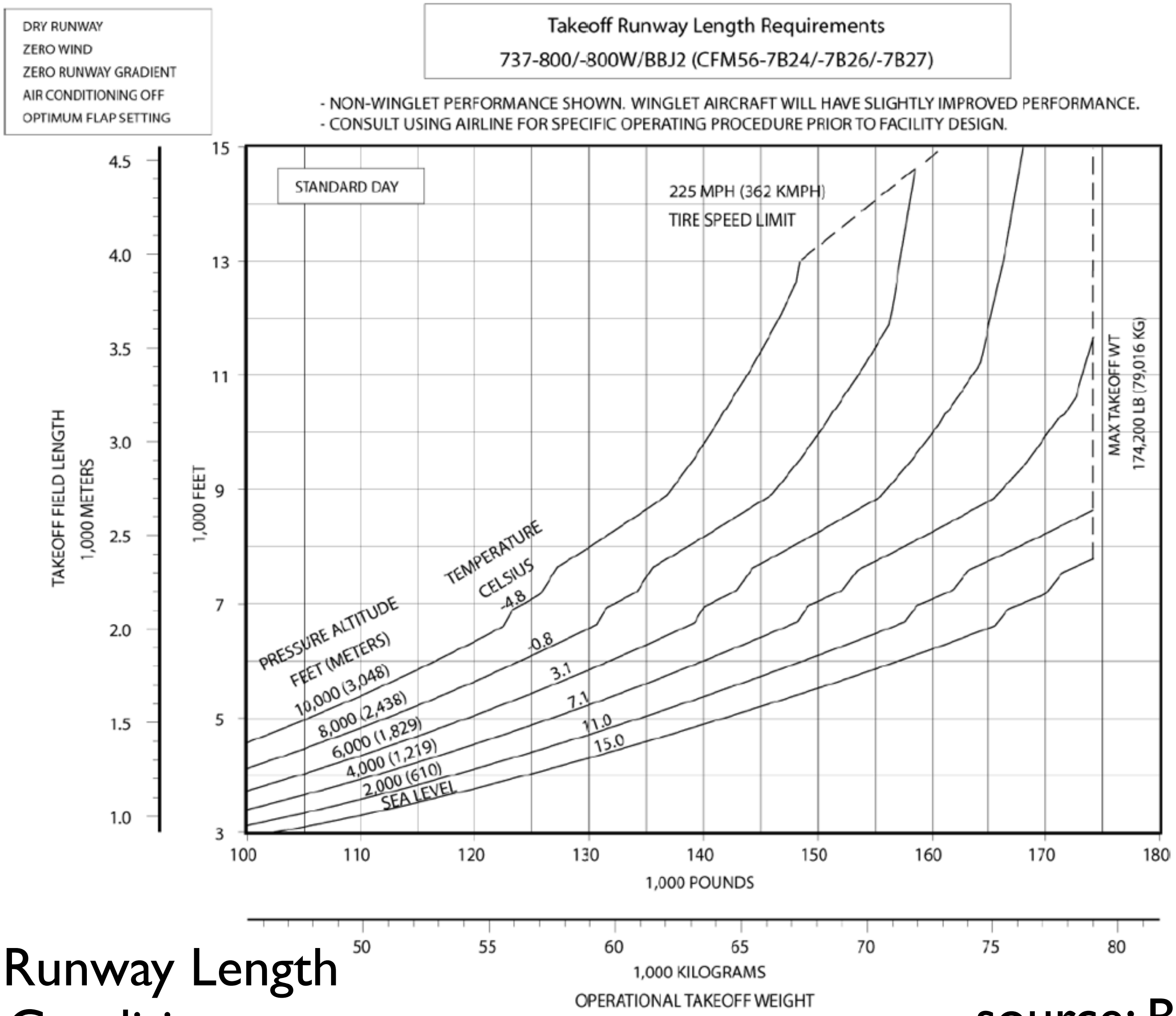
BOEING

Boeing Commercial Airplanes

Identify the Aircraft

- Twin engine commercial airliner
- Boeing 738 has two emergency exits over the wing
- Some versions have winglets

Sample Performance Chart - Boeing 737-800

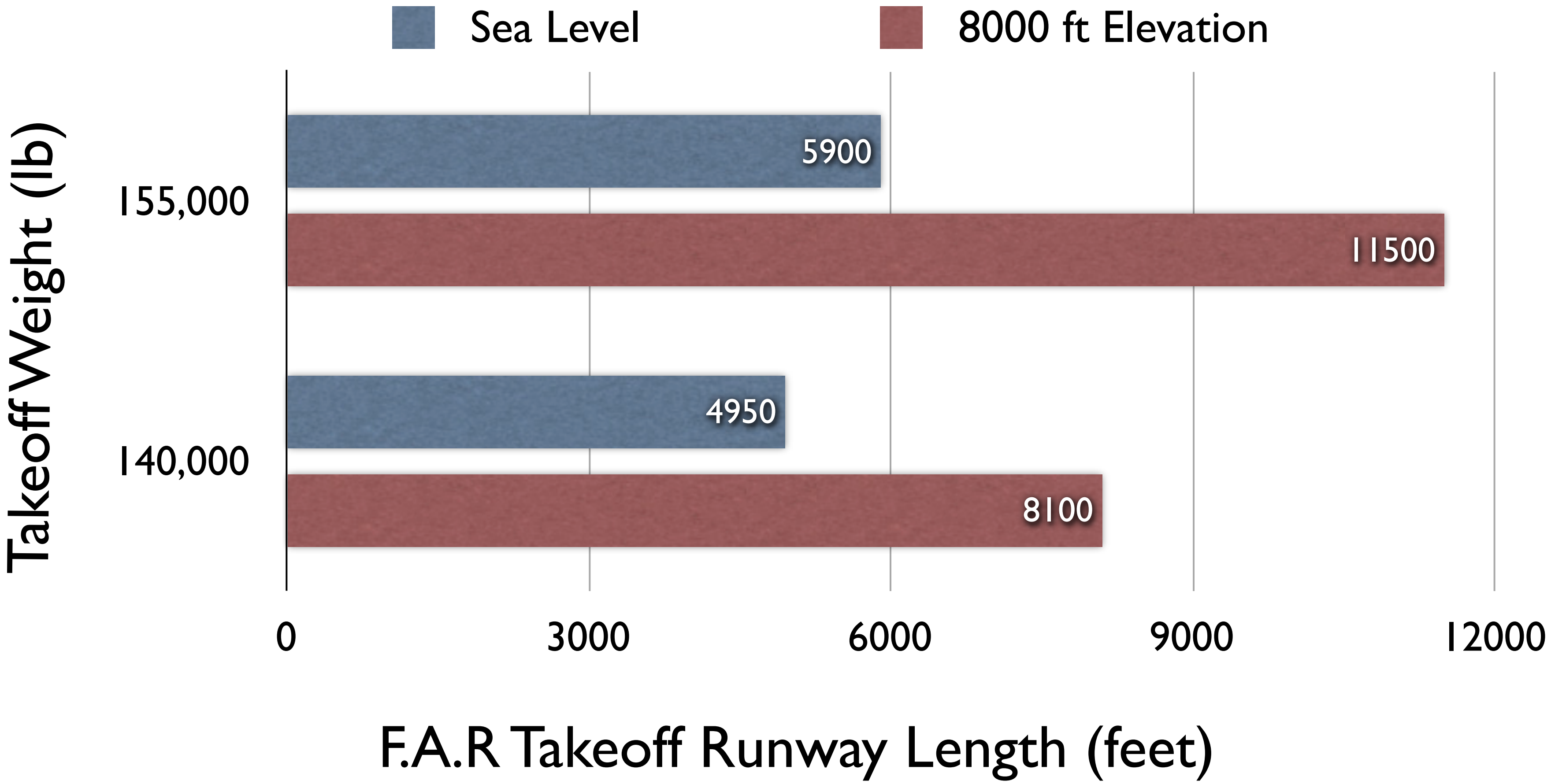


Takeoff Runway Length
ISA Conditions

source: Boeing (2011)

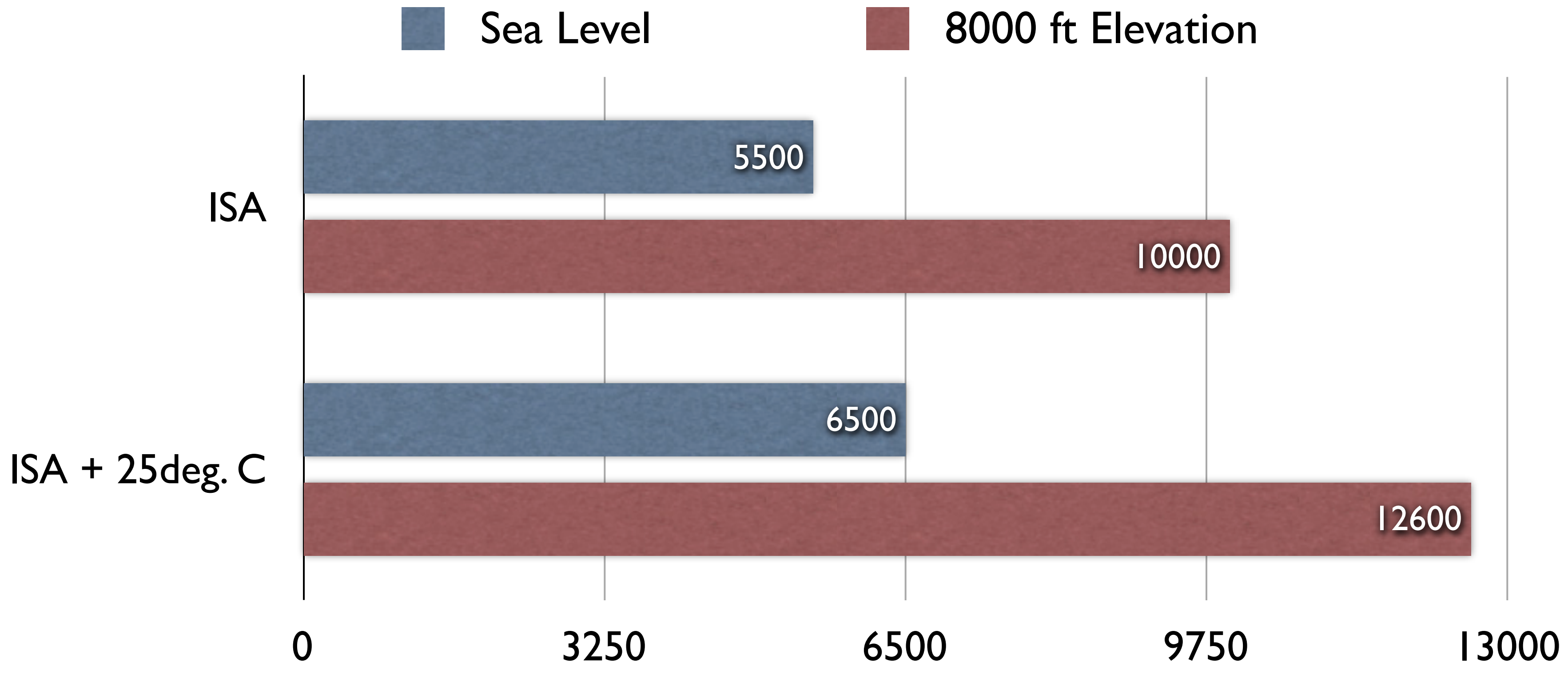
Practical Example - Boeing 737-800

- International Standard Atmosphere (ISA) conditions (see ISA table)



Practical Example - Boeing 737-800

- Variations with airfield temperature
- 150,000 lb. takeoff weight



F.A.R Takeoff Runway Length (feet)

Observed Trends

- Airfield Elevation Effect
  - A Boeing 737-800 requires 94% more runway departing from an airport located 8000 feet above sea level than an airport at sea level with a typical weight of 155,000 lb. (MTOW is 172,500 lb.)
- Temperature Effects
  - The Boeing 737-800 requires 26% more runway departing from a high elevation airfield (i.e., 8,000 ft) when the temperature increases by 25 deg. C.
  - The increase in F.A.R. runway length is 18% when departing an airport at sea level conditions

Runway Lengths for Small Aircraft

- Airport elevation and temperature affect the performance of small aircraft
- Performance varies according to engine technology, aerodynamic design, and factors such as power loading and thrust/weight ratio

Takeoff field length data presented in various formats:

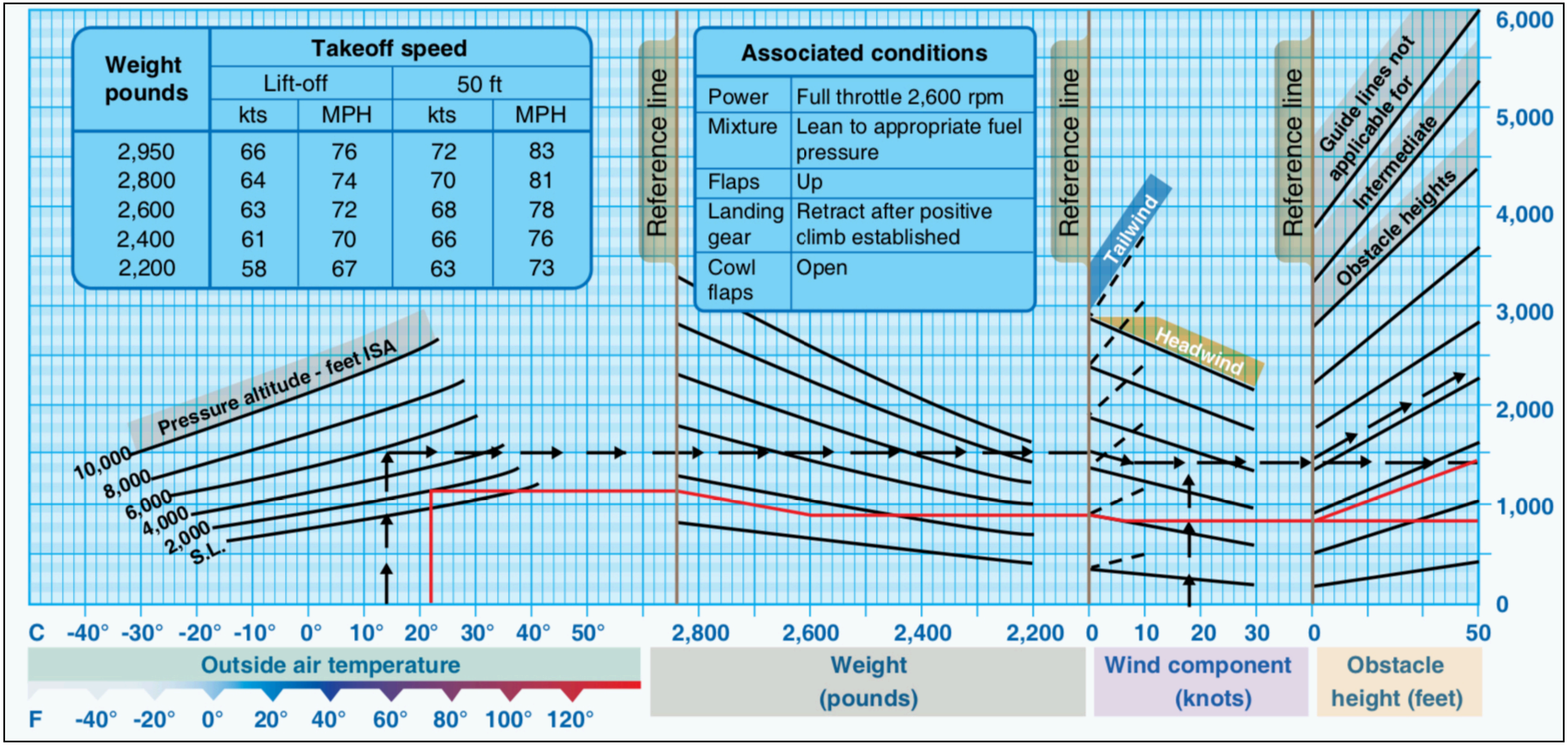
- Tables
- Nomographs


Cessna CitationJet I (Turbofan aircraft)


Columbia 400 (Piston-powered aircraft)


Beechcraft King Air B200 (Turboprop aircraft)

Nomograph Presentation



Weight pounds	Takeoff speed			
	Lift-off		50 ft	
	kts	MPH	kts	MPH
2,950	66	76	72	83
2,800	64	74	70	81
2,600	63	72	68	78
2,400	61	70	66	76
2,200	58	67	63	73

Associated conditions	
Power	Full throttle 2,600 rpm
Mixture	Lean to appropriate fuel pressure
Flaps	Up
Landing gear	Retract after positive climb established
Cowl flaps	Open

Source: FAA Handbook of Aeronautical Knowledge

Characteristics of data:
Pressure altitude
Outside air temperature
Aircraft weight
Wind correction
Obstacle height (0 or 50 feet)
Runway material type

Runway Length and Elevation for General Aviation Aircraft: Lancair Columbia 400

Runway grade and unprepared runway operation corrections for takeoff distance are normally included in the data

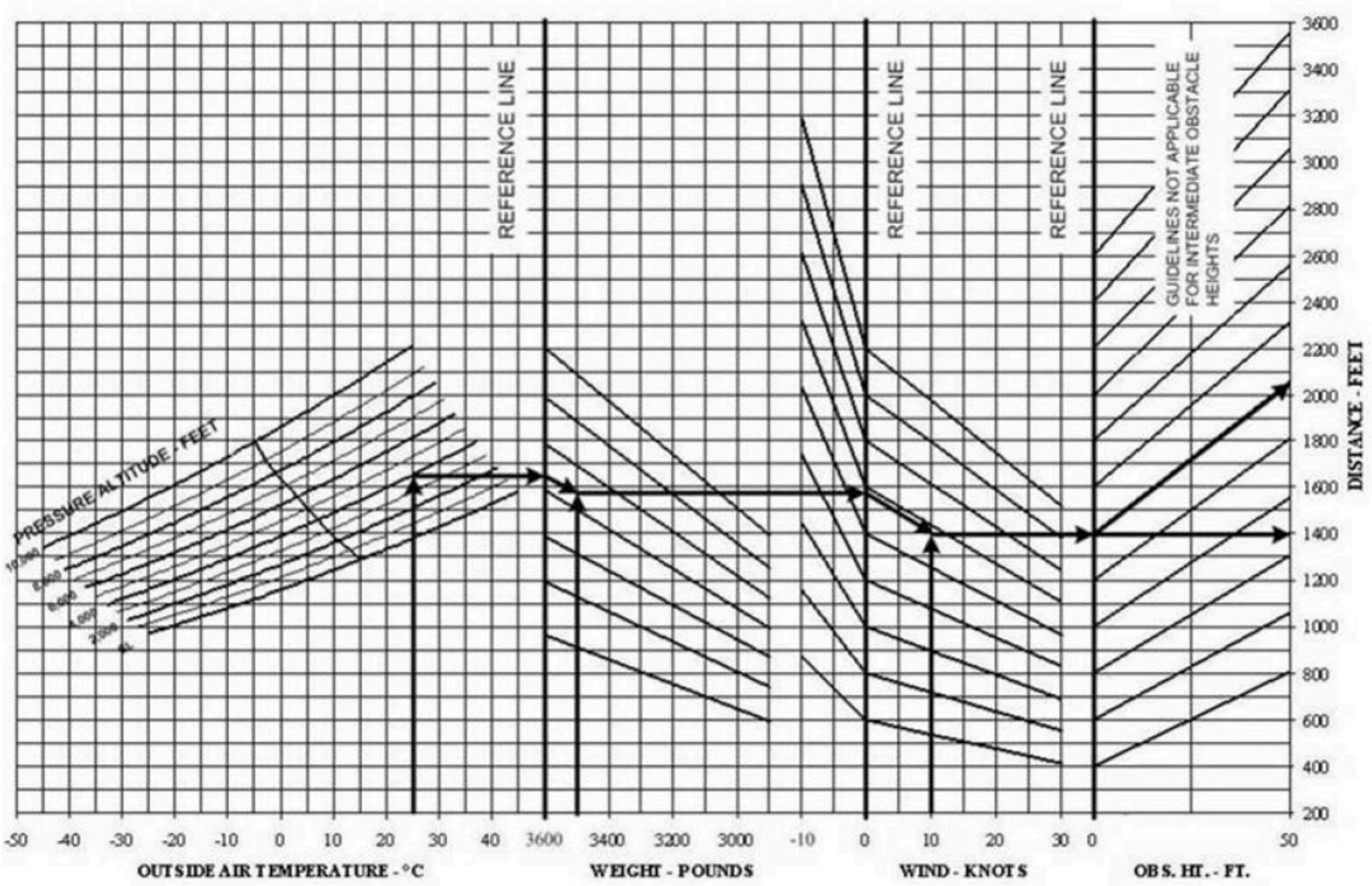
1% in ground roll for each 0.1% in runway grade (0.2% uphill)

30% additional ground roll for operations on grass runways

SHORT FIELD TAKEOFF DISTANCE (12º - TAKEOFF FLAPS)

ASSOCIATED CONDITIONS		EXAMPLE	
Power	Takeoff Power Set Before Brake Release	OAT	25°C
Flaps	12° (Takeoff position)	Pressure Altitude (PA)	4000 ft
Runway	Paved, Level, Dry Surface	Takeoff Weight	3500 lbs
Takeoff Speed	See Speed Schedule in Figure 5 - 11.	Headwind Component	10 Knots
		Ground Roll = 1400 ft (427 m) **50 ft Obstacle = 2050 ft (625 m)**	

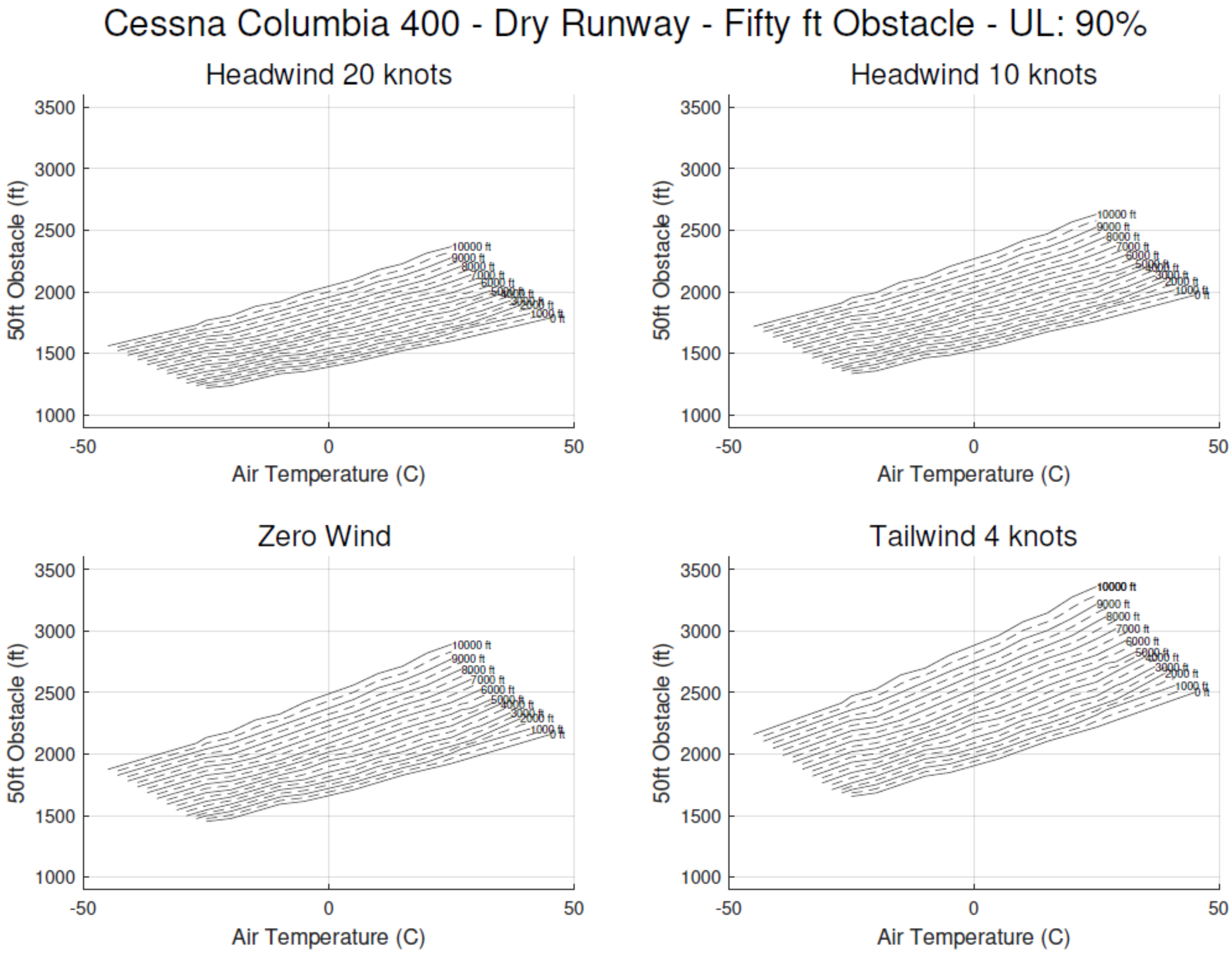
Runway Slope Correction: Add 1% to ground roll for every 0.1° (0.2%) of uphill slope. For operation on a known level, smooth, mowed grass runway, which is either wet or dry but does not include standing water, the ground roll distance obtained from this takeoff performance chart must be multiplied by a factor of 1.3 to obtain the correct field length. In the above example, the ground roll distance would be 1.3 x 1400 ft = 1820 ft (555 m). The total distance to clear a 50-ft obstacle would be 2470 ft (753 m) in this instance.



Source: Columbia Aircraft Co.

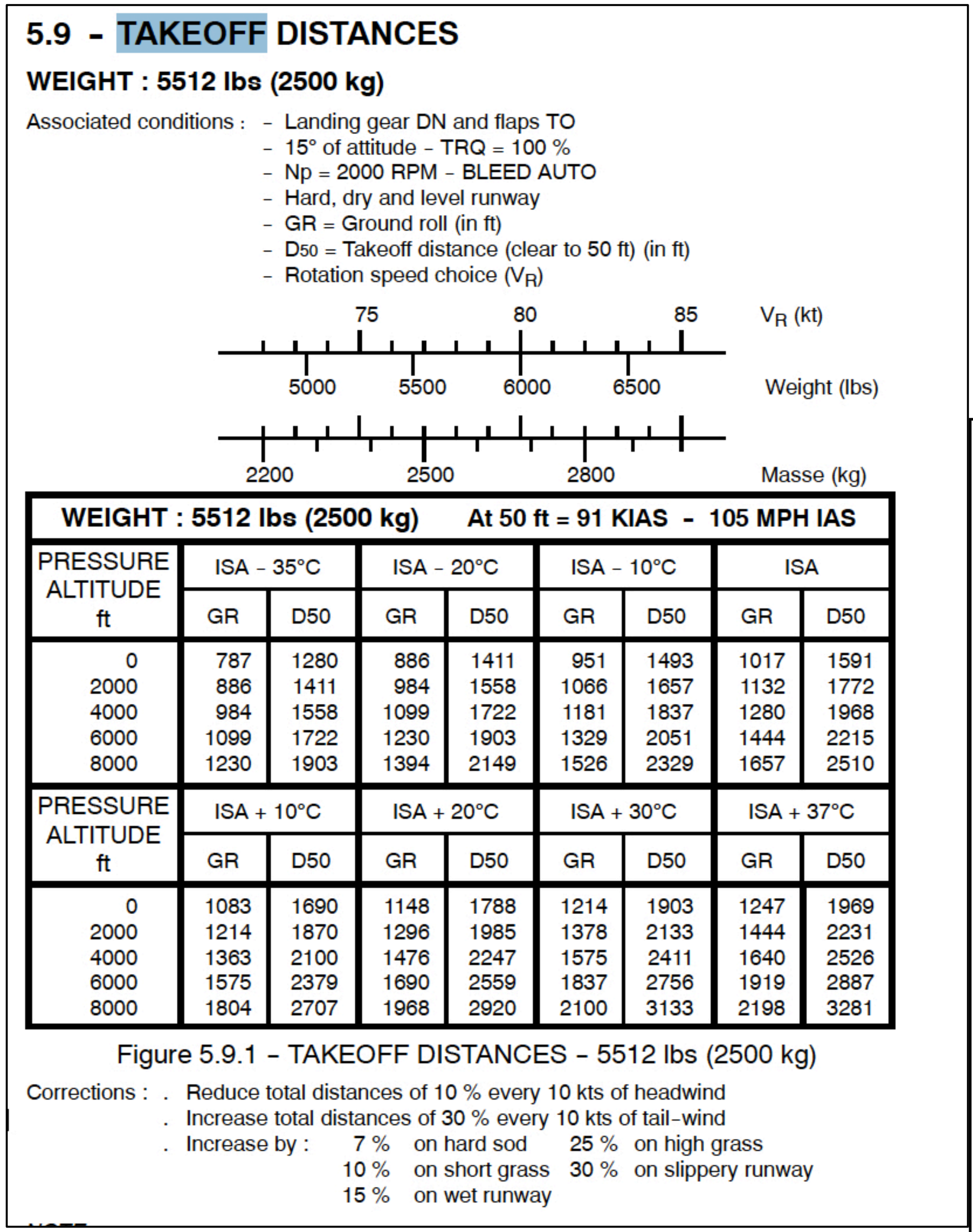
Runway Length and Temperature Effects for General Aviation Aircraft: Columbia 400

50% increase in takeoff distance to clear a 50-foot obstacle when airport elevation increases from Sea Level to 8,000 feet (at 25 deg. C and zero wind conditions)



Source of Data : Columbia 400 Airplane Flight Manual. Plots: Virginia Tech Air Transportation Systems Lab

Runway Length Presentation for Small Business Turboprop Aircraft: Daher/Socata 850



5.9 - TAKEOFF DISTANCES

WEIGHT : 5512 lbs (2500 kg)

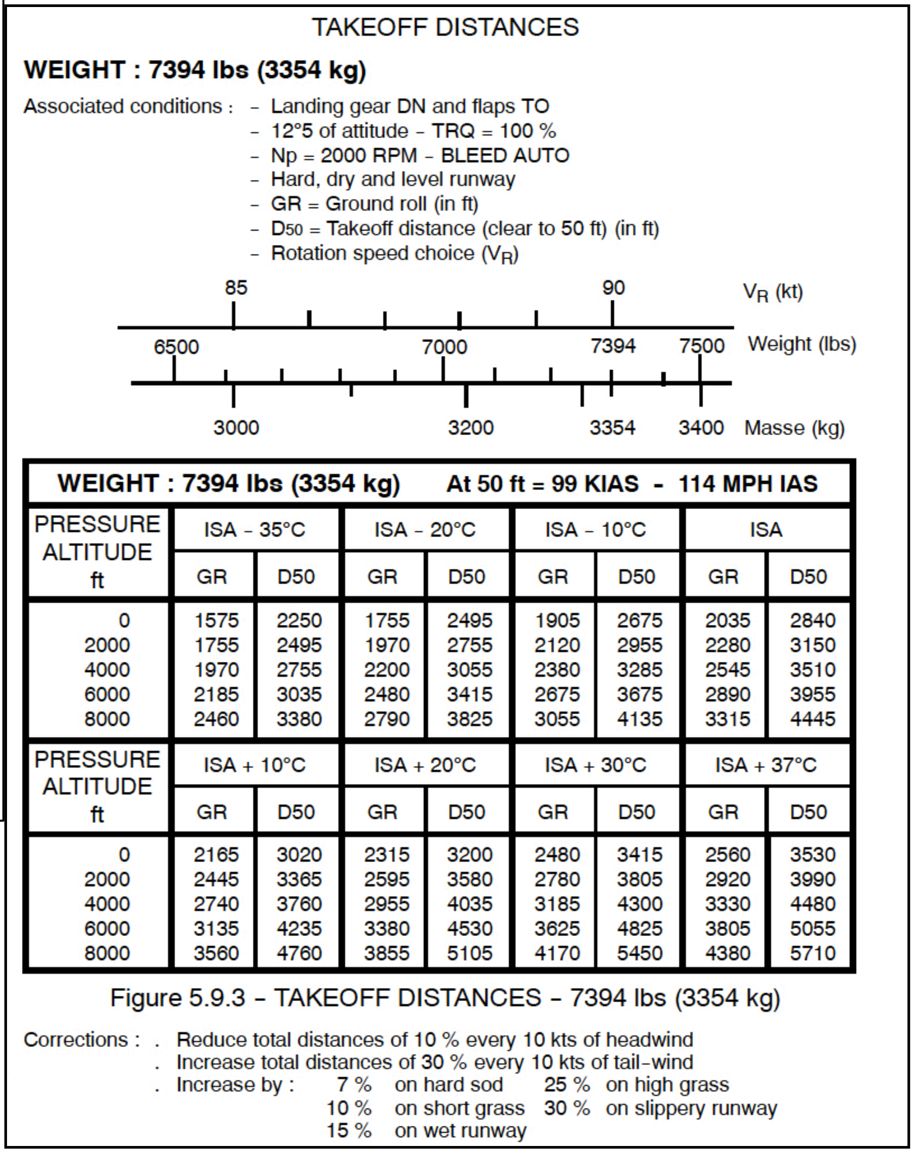
Associated conditions :
- Landing gear DN and flaps TO
- 15° of attitude - TRQ = 100 %
- Np = 2000 RPM - BLEED AUTO
- Hard, dry and level runway
- GR = Ground roll (in ft)
- D_{50} = Takeoff distance (clear to 50 ft) (in ft)
- Rotation speed choice (V_R)

WEIGHT : 5512 lbs (2500 kg)	**At 50 ft = 91 KIAS - 105 MPH IAS**							
PRESSURE ALTITUDE ft	ISA - 35°C		ISA - 20°C		ISA - 10°C		ISA	
	GR	D50	GR	D50	GR	D50	GR	D50
0	787	1280	886	1411	951	1493	1017	1591
2000	886	1411	984	1558	1066	1657	1132	1772
4000	984	1558	1099	1722	1181	1837	1280	1968
6000	1099	1722	1230	1903	1329	2051	1444	2215
8000	1230	1903	1394	2149	1526	2329	1657	2510
PRESSURE ALTITUDE ft	ISA + 10°C		ISA + 20°C		ISA + 30°C		ISA + 37°C	
	GR	D50	GR	D50	GR	D50	GR	D50
0	1083	1690	1148	1788	1214	1903	1247	1969
2000	1214	1870	1296	1985	1378	2133	1444	2231
4000	1363	2100	1476	2247	1575	2411	1640	2526
6000	1575	2379	1690	2559	1837	2756	1919	2887
8000	1804	2707	1968	2920	2100	3133	2198	3281

Figure 5.9.1 - TAKEOFF DISTANCES - 5512 lbs (2500 kg)

Corrections :
. Reduce total distances of 10 % every 10 kts of headwind
. Increase total distances of 30 % every 10 kts of tail-wind
. Increase by : 7 % on hard sod; 25 % on high grass; 10 % on short grass; 30 % on slippery runway; 15 % on wet runway

Daher/Socata TMB 850 Aircraft



TAKEOFF DISTANCES

WEIGHT : 7394 lbs (3354 kg)

Associated conditions :
- Landing gear DN and flaps TO
- 12°5 of attitude - TRQ = 100 %
- Np = 2000 RPM - BLEED AUTO
- Hard, dry and level runway
- GR = Ground roll (in ft)
- D_{50} = Takeoff distance (clear to 50 ft) (in ft)
- Rotation speed choice (V_R)

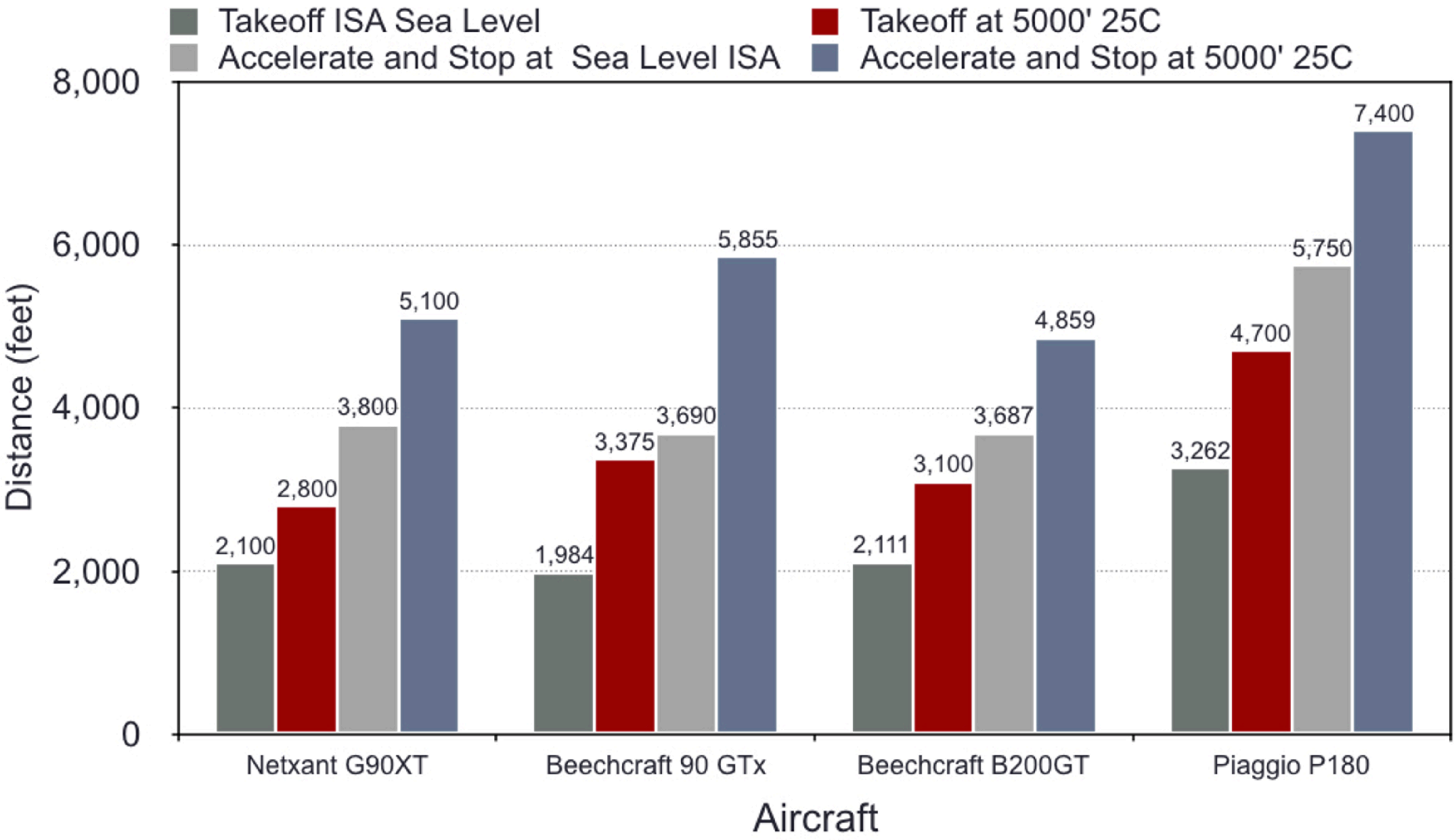
WEIGHT : 7394 lbs (3354 kg)	**At 50 ft = 99 KIAS - 114 MPH IAS**							
PRESSURE ALTITUDE ft	ISA - 35°C		ISA - 20°C		ISA - 10°C		ISA	
	GR	D50	GR	D50	GR	D50	GR	D50
0	1575	2250	1755	2495	1905	2675	2035	2840
2000	1755	2495	1970	2755	2120	2955	2280	3150
4000	1970	2755	2200	3055	2380	3285	2545	3510
6000	2185	3035	2480	3415	2675	3675	2890	3955
8000	2460	3380	2790	3825	3055	4135	3315	4445
PRESSURE ALTITUDE ft	ISA + 10°C		ISA + 20°C		ISA + 30°C		ISA + 37°C	
	GR	D50	GR	D50	GR	D50	GR	D50
0	2165	3020	2315	3200	2480	3415	2560	3530
2000	2445	3365	2595	3580	2780	3805	2920	3990
4000	2740	3760	2955	4035	3185	4300	3330	4480
6000	3135	4235	3380	4530	3625	4825	3805	5055
8000	3560	4760	3855	5105	4170	5450	4380	5710

Figure 5.9.3 - TAKEOFF DISTANCES - 7394 lbs (3354 kg)

Corrections :
. Reduce total distances of 10 % every 10 kts of headwind
. Increase total distances of 30 % every 10 kts of tail-wind
. Increase by : 7 % on hard sod; 25 % on high grass; 10 % on short grass; 30 % on slippery runway; 15 % on wet runway

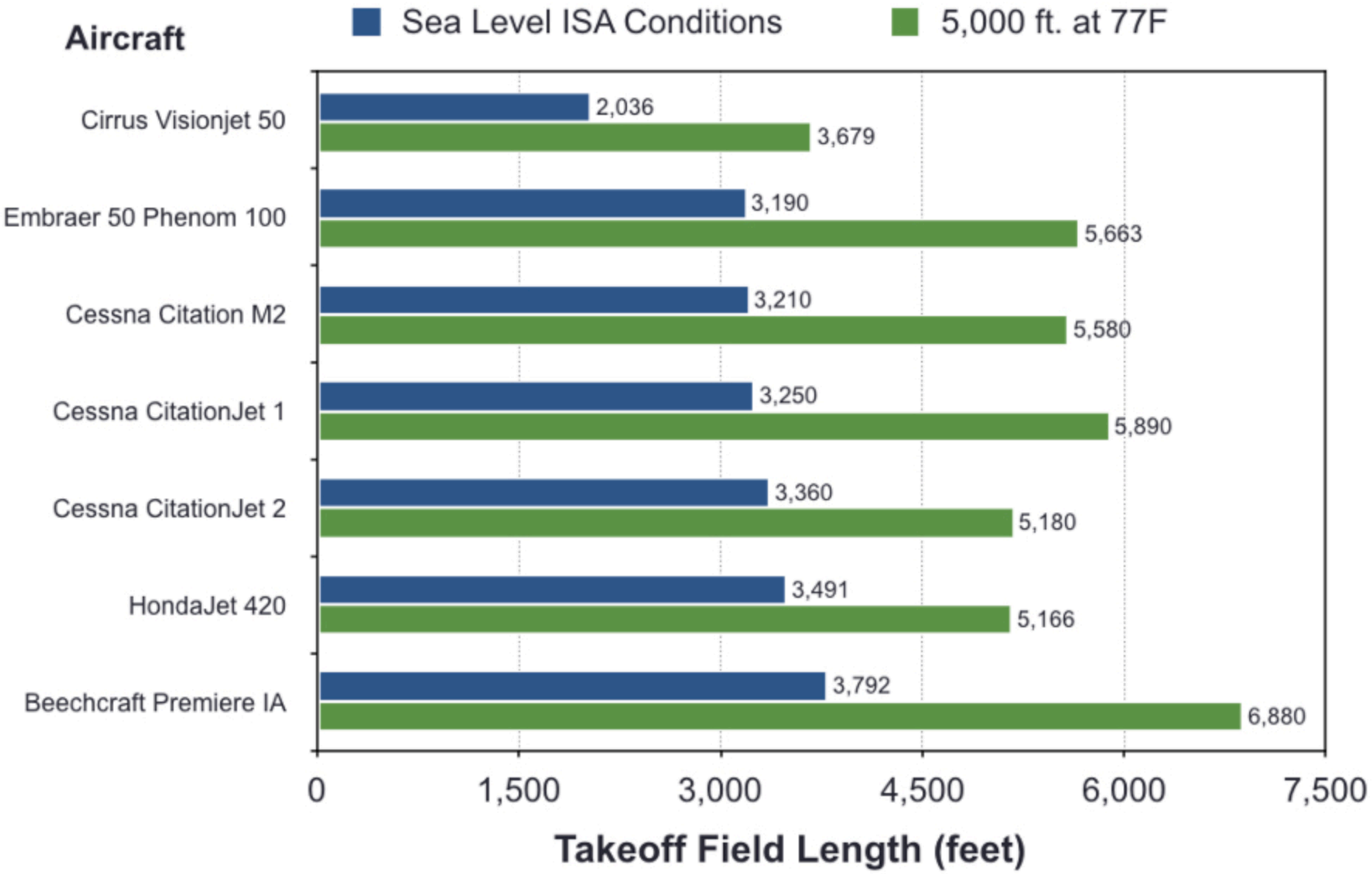
59% increase in takeoff distance to clear a 50-foot obstacle when airport elevation increases from Sea Level to 8,000 feet (at ISA+20 deg.C and W=7394 lb)

Runway Length Requirements with Airport Elevation for Business Turboprop Aircraft



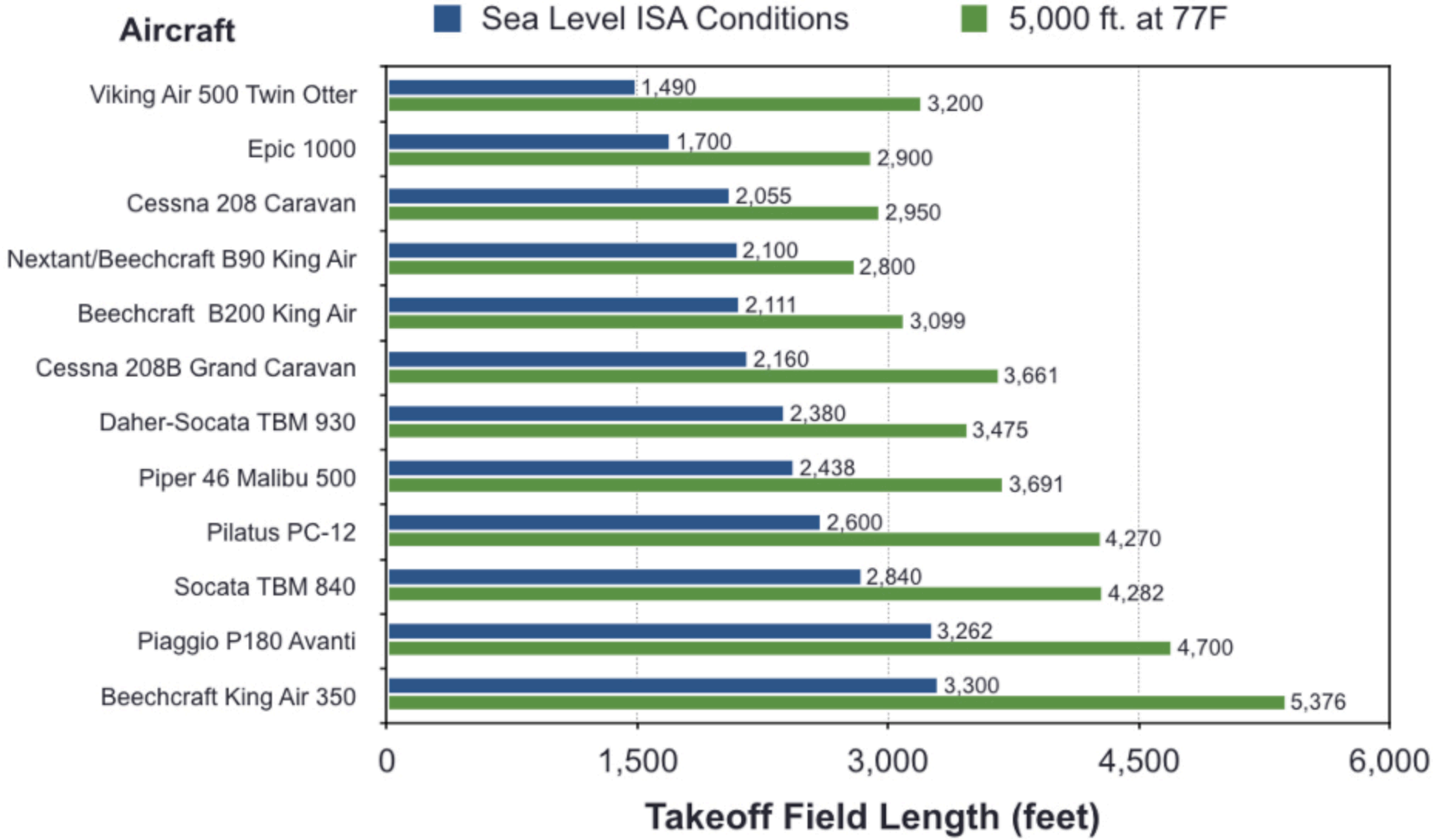
Data Source: Business and Commercial Aviation (2019)

Takeoff Field Length Requirements with Airport Elevation for Light Business Jet Aircraft (12,500 lb. or less)



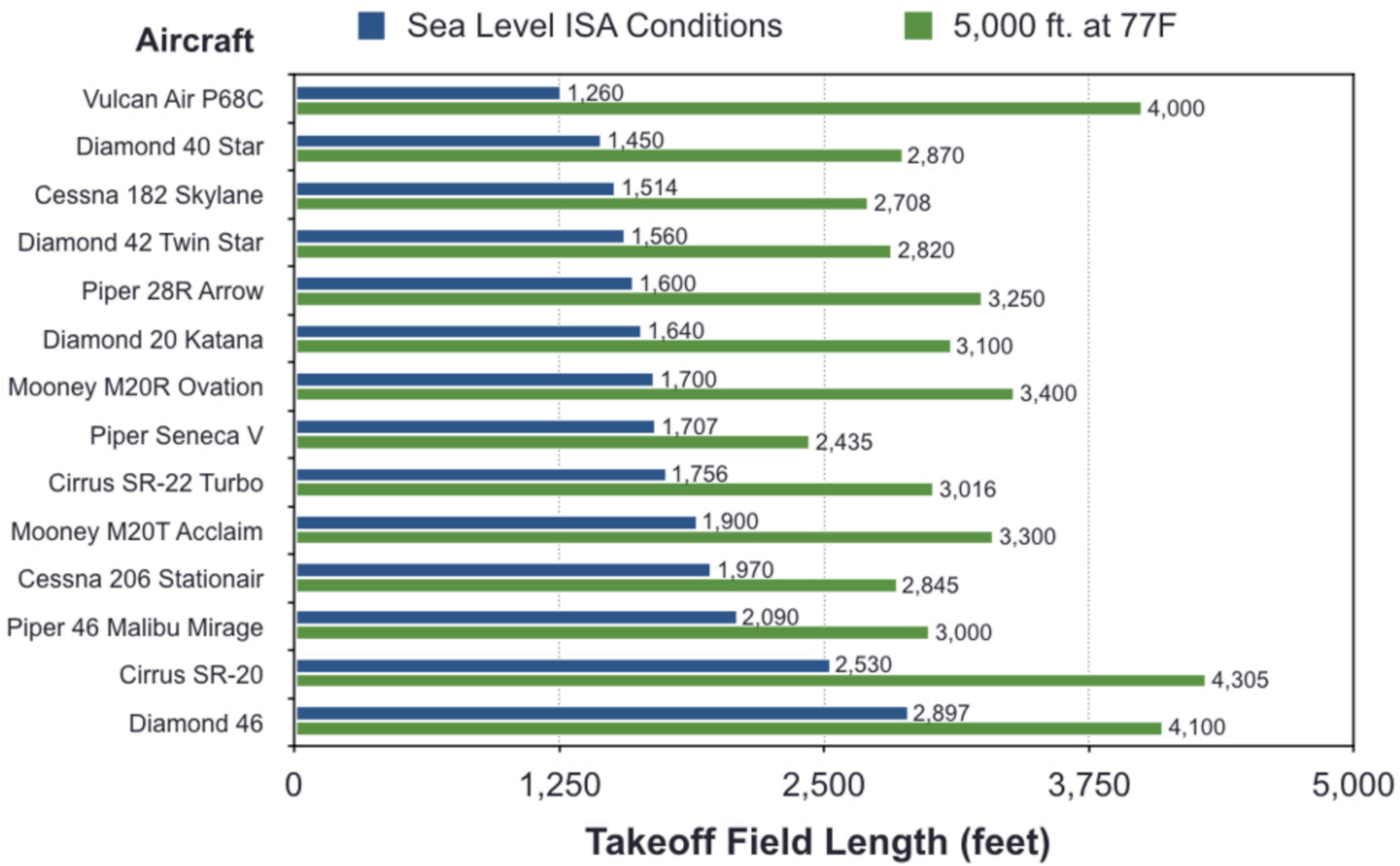
Data Source: Business and Commercial Aviation (2019)

Takeoff Field Length Requirements with Airport Elevation for Turboprop Aircraft (12,500 lb. or less)



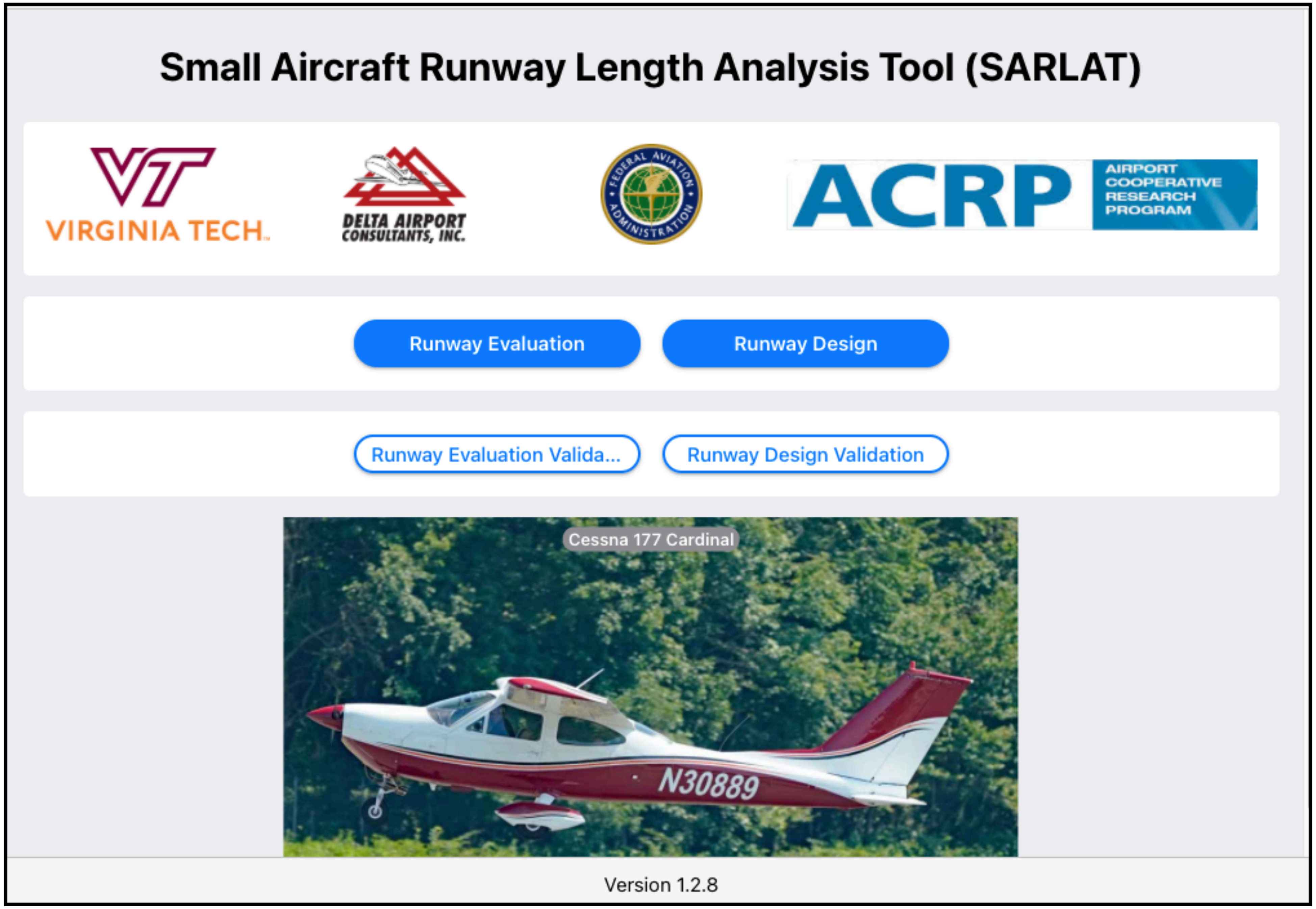
Data Source: Business and Commercial Aviation (2019)

Takeoff Field Length Requirements with Airport Elevation for Turboprop Aircraft (12,500 lb. or less)



Data Source: Business and Commercial Aviation (2019)

A Small Aircraft Runway Length Analysis Tool (SARLAT)



Small Aircraft Runway Length Analysis Tool (SARLAT)

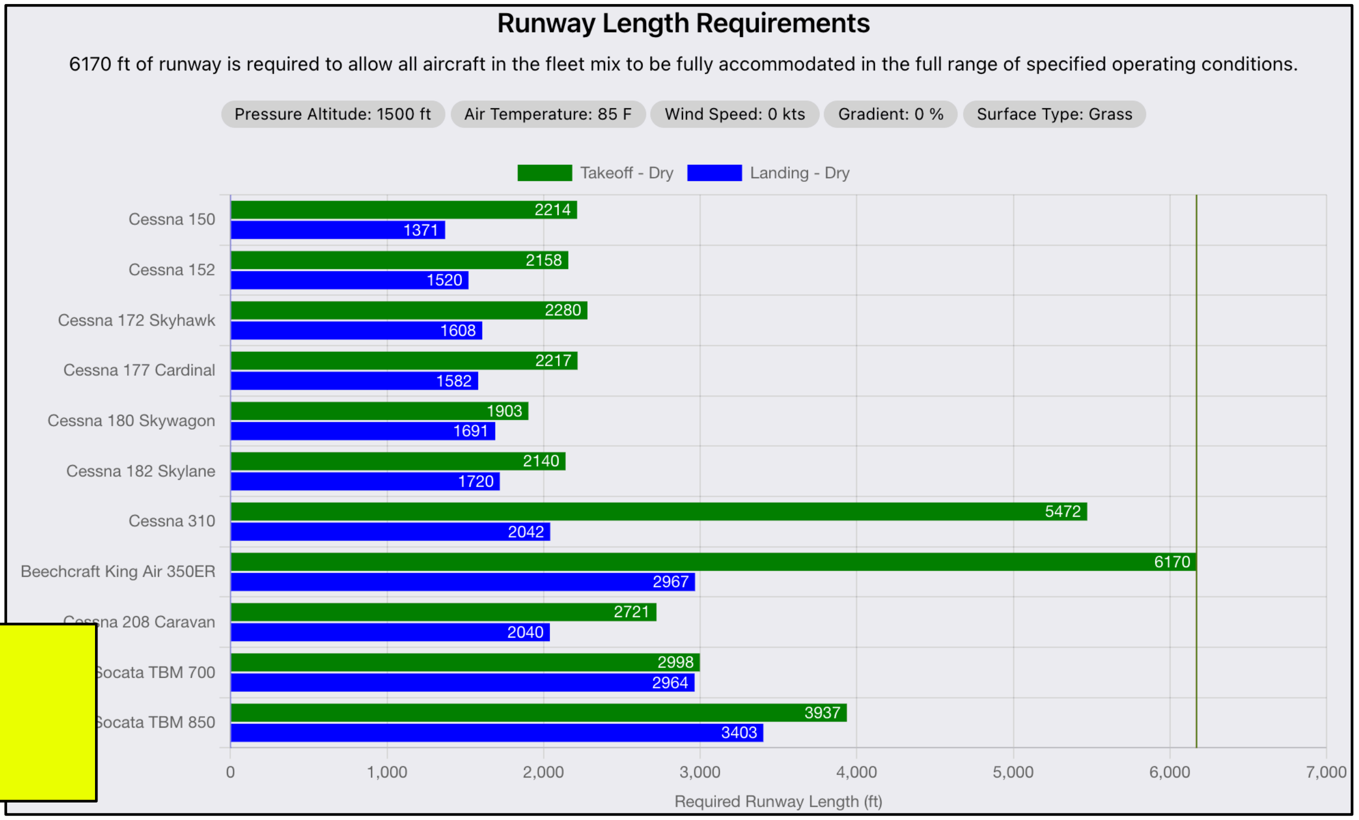
Link to get the SARLAT tool: https://www.trb.org/Main/Blurbs/182838.aspx

SARLAT Tool

- Stand-alone tool
- Considers individual aircraft performance
- Consider all airport design factors
  - Temperature
  - Wind conditions
  - Airport elevation
  - Aircraft climb limits (if applicable)

Small Aircraft Runway Length Analysis Tool (SARLAT)

Version 1.2.8



Runway Length Requirements

6170 ft of runway is required to allow all aircraft in the fleet mix to be fully accommodated in the full range of specified operating conditions.

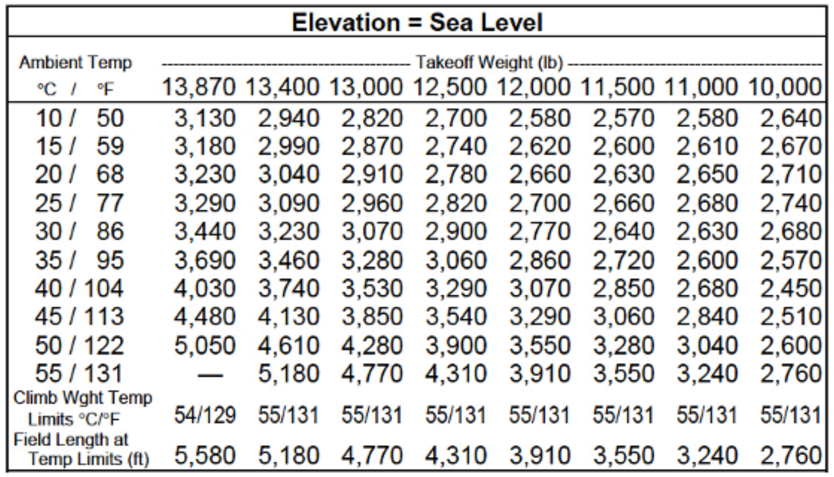
Pressure Altitude: 1500 ft
Air Temperature: 85 F
Wind Speed: 0 kts
Gradient: 0 %
Surface Type: Grass

SARLAT uses Javascript and Matlab
Runs on Windows and Mac OS systems

Translate Aircraft Performance Characteristics into a Common Format

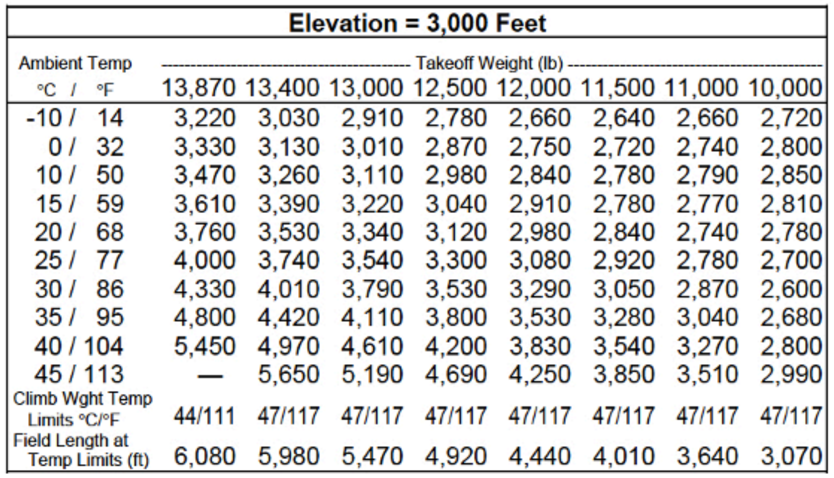
Cessna Citation Jet 3 Data

- Consider individual aircraft performance
- Consider all airport design factors
    - Temperature
    - Wind conditions
    - Airport elevation
    - Aircraft climb limits (if applicable)
    - Aircraft useful load
- Produce runway length requirements for both takeoff and landing conditions



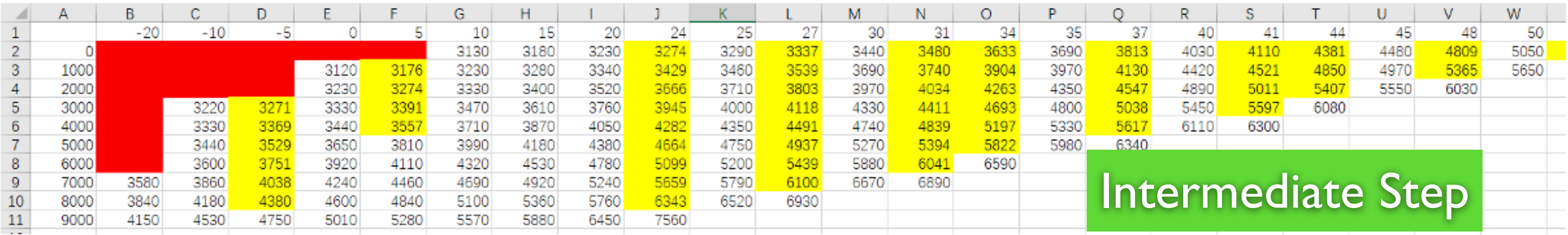
Elevation = Sea Level

Ambient Temp °C / °F	Takeoff Weight (lb) 13,870	13,400	13,000	12,500	12,000	11,500	11,000	10,000
10 / 50	3,130	2,940	2,820	2,700	2,580	2,570	2,580	2,640
15 / 59	3,180	2,990	2,870	2,740	2,620	2,600	2,610	2,670
20 / 68	3,230	3,040	2,910	2,780	2,660	2,630	2,650	2,710
25 / 77	3,290	3,090	2,960	2,820	2,700	2,660	2,680	2,740
30 / 86	3,440	3,230	3,070	2,900	2,770	2,640	2,630	2,680
35 / 95	3,690	3,460	3,280	3,060	2,860	2,720	2,600	2,570
40 / 104	4,030	3,740	3,530	3,290	3,070	2,850	2,680	2,450
45 / 113	4,480	4,130	3,850	3,540	3,290	3,060	2,840	2,510
50 / 122	5,050	4,610	4,280	3,900	3,550	3,280	3,040	2,600
55 / 131	—	5,180	4,770	4,310	3,910	3,550	3,240	2,760
Climb Wght Temp Limits °C/°F	54/129	55/131	55/131	55/131	55/131	55/131	55/131	55/131
Field Length at Temp Limits (ft)	5,580	5,180	4,770	4,310	3,910	3,550	3,240	2,760



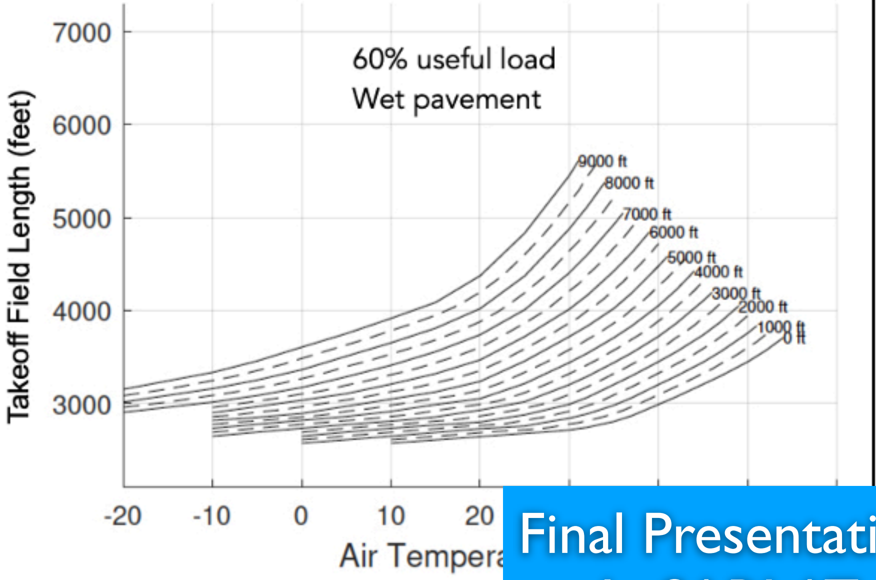
Elevation = 3,000 Feet

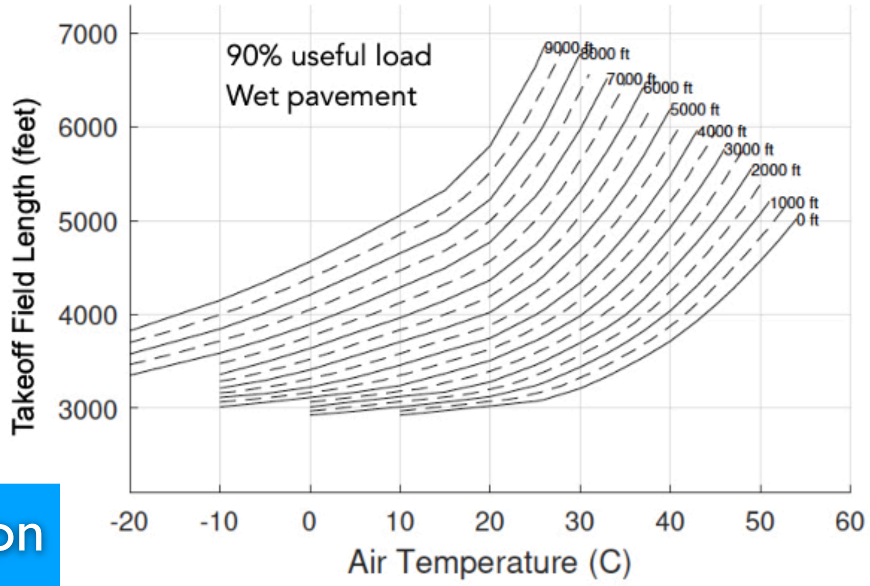
Ambient Temp °C / °F	Takeoff Weight (lb) 13,870	13,400	13,000	12,500	12,000	11,500	11,000	10,000
-10 / 14	3,220	3,030	2,910	2,780	2,660	2,640	2,660	2,720
0 / 32	3,330	3,130	3,010	2,870	2,750	2,720	2,740	2,800
10 / 50	3,470	3,260	3,110	2,980	2,840	2,780	2,790	2,850
15 / 59	3,610	3,390	3,220	3,040	2,910	2,780	2,770	2,810
20 / 68	3,760	3,530	3,340	3,120	2,980	2,840	2,740	2,780
25 / 77	4,000	3,740	3,540	3,300	3,080	2,920	2,780	2,700
30 / 86	4,330	4,010	3,790	3,530	3,290	3,050	2,870	2,600
35 / 95	4,800	4,420	4,110	3,800	3,530	3,280	3,040	2,680
40 / 104	5,450	4,970	4,610	4,200	3,830	3,540	3,270	2,800
45 / 113	—	5,650	5,190	4,690	4,250	3,850	3,510	2,990
Climb Wght Temp Limits °C/°F	44/111	47/117	47/117	47/117	47/117	47/117	47/117	47/117
Field Length at Temp Limits (ft)	6,080	5,980	5,470	4,920	4,440	4,010	3,640	3,070



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1		-20	-10	-5	0	5	10	15	20	24	25	27	30	31	34	35	37	40	41	44	45	48	50
2	0						3130	3180	3230	3274	3290	3337	3440	3480	3633	3690	3813	4030	4110	4381	4480	4809	5050
3	1000				3120	3176	3230	3280	3340	3429	3460	3539	3690	3740	3904	3970	4130	4420	4521	4850	4970	5365	5650
4	2000				3230	3274	3330	3400	3520	3666	3710	3803	3970	4034	4263	4350	4547	4890	5011	5407	5550	6030	
5	3000		3220	3271	3330	3391	3470	3610	3760	3945	4000	4118	4330	4411	4693	4800	5038	5450	5597	6080			
6	4000		3330	3369	3440	3557	3710	3870	4050	4282	4350	4491	4740	4839	5197	5330	5617	6110	6300				
7	5000		3440	3529	3650	3810	3990	4180	4380	4664	4750	4937	5270	5394	5822	5980	6340						
8	6000		3600	3751	3920	4110	4320	4530	4780	5099	5200	5439	5880	6041	6590								
9	7000	3580	3860	4038	4240	4460	4690	4920	5240	5659	5790	6100	6670	6890									
10	8000	3840	4180	4380	4600	4840	5100	5360	5760	6343	6520	6930											
11	9000	4150	4530	4750	5010	5280	5570	5880	6450	7560													

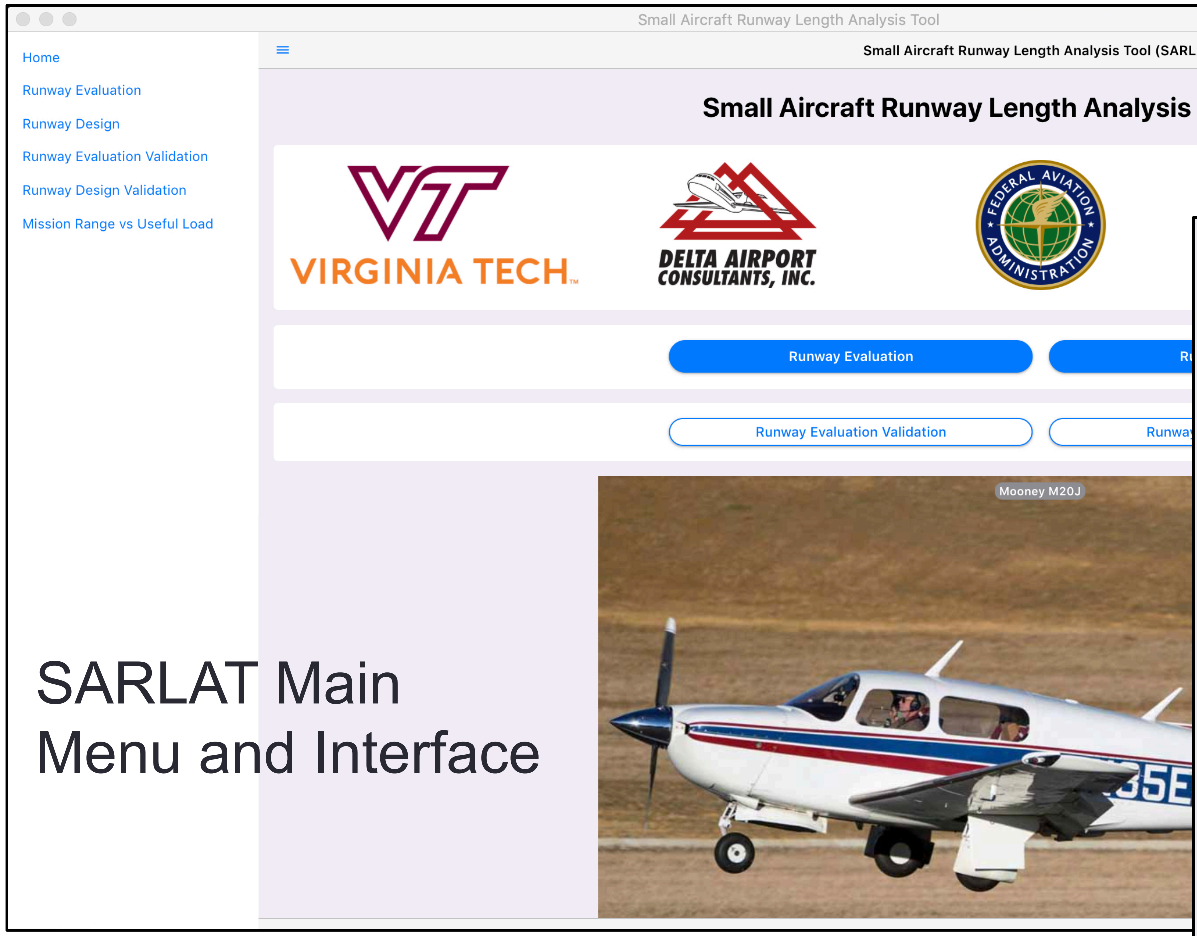
Intermediate Step





Final Presentation In SARLAT

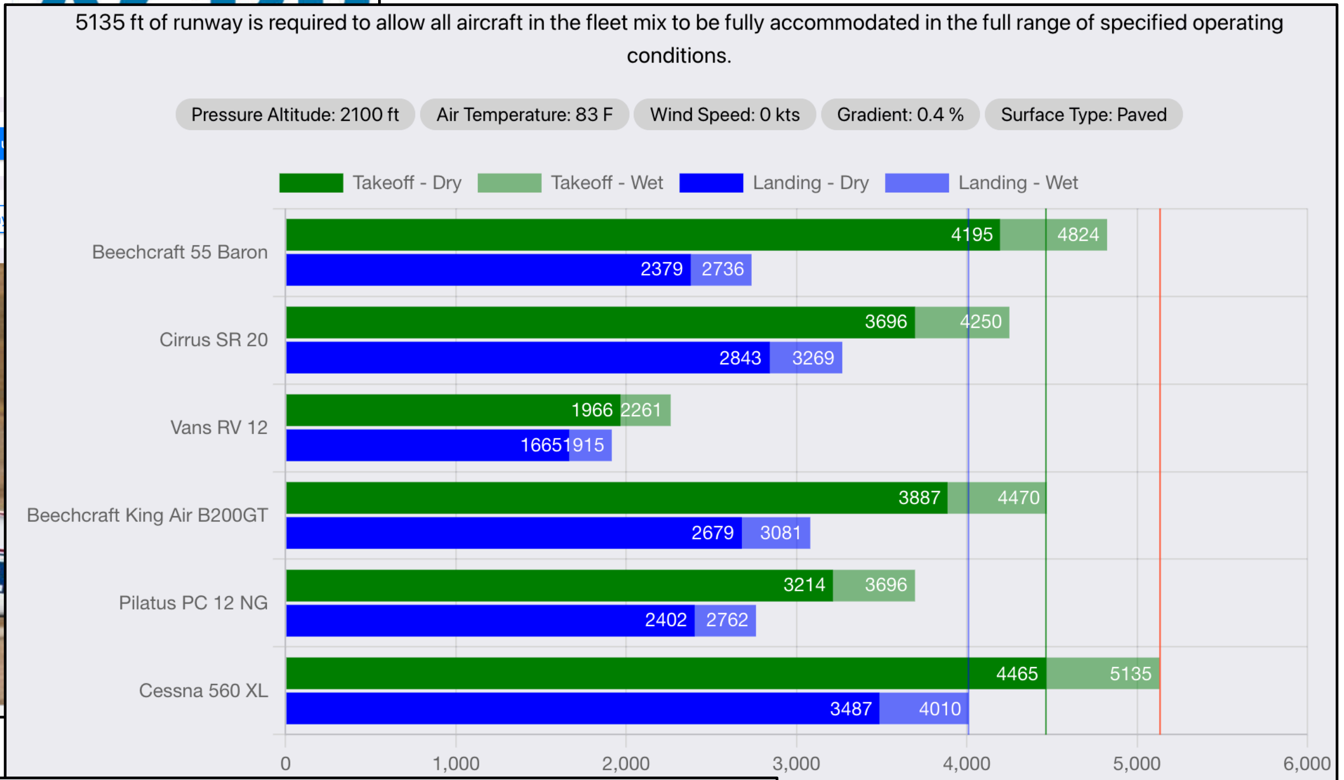
Integrate SARLAT into a Stand-Alone Computer Tool



Small Aircraft Runway Length Analysis Tool (SARLAT)

SARLAT Main Menu and Interface

Runway Design Output



5135 ft of runway is required to allow all aircraft in the fleet mix to be fully accommodated in the full range of specified operating conditions.

Pressure Altitude: 2100 ft | Air Temperature: 83 F | Wind Speed: 0 kts | Gradient: 0.4 % | Surface Type: Paved

Runway Takeoff and Landing Restrictions

Pressure Altitude: 2000 ft | Air Temperature: 86 F | Wind Speed: 0 kts | Runway Length: 5500 ft | Gradient: 0.4 % | Surface Type: Paved

Aircraft Name	Aircraft Mix	Takeoff Weight (Useful Load)		Landing at Maximum Landing Weig				
				No Correction		Part 135 Eligible		P
		Dry	Wet	Dry	Wet	Dry	Wet	Dry
Piston								
Cessna 172 Skyhawk	20%	2300 lbs 100 %	2300 lbs 100 %	✓	✓			
Cessna 402B	5%	6300 lbs 100 %	6300 lbs 100 %	✓	✓			
Cirrus SR 20	10%	3150 lbs 100 %	3150 lbs 100 %	✓	✓			
Turboprop								
Beechcraft King Air 350ER	25%	15189 lbs 79 %	13114 lbs 45 %	✓	✓			✓

Runway Evaluation Output

SARLAT Modes of Operation

The Small Aircraft Runway Length Analysis Tool has **four modes of operation described below:**

- **Analysis modes:**

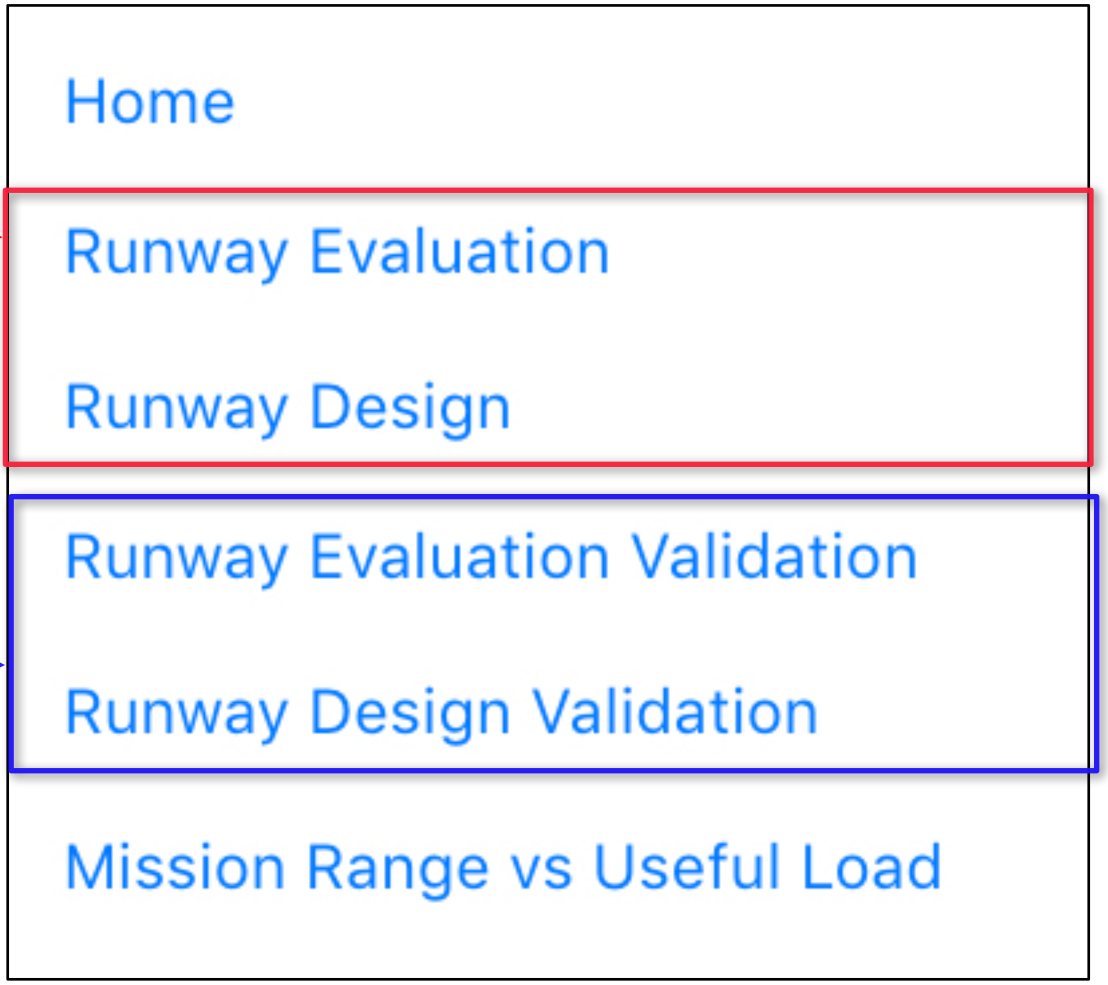
a) Evaluation of an existing runway

b) Design of a new runway

- **Validation modes:**

a) Evaluation of an existing runway

b) Design of a new runway



- Use the **Analysis Modes** to evaluate or design a new runway
- Use the **Validation Modes** to validate and visualize the runway performance of individual aircraft for a set of airport conditions