Lecture 8

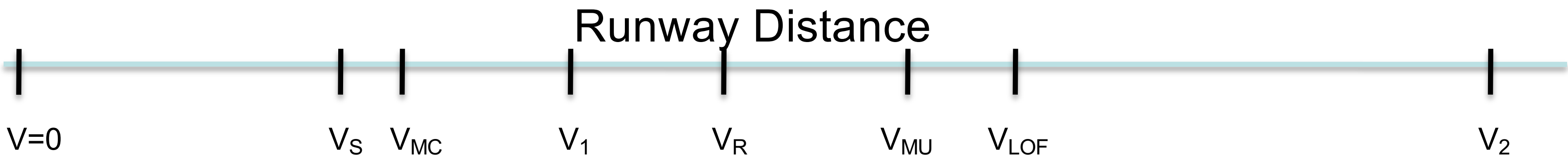
Takeoff and Landing Performance


Image Courtesy of USAF

Piper Cherokee – Photo by Ahunt

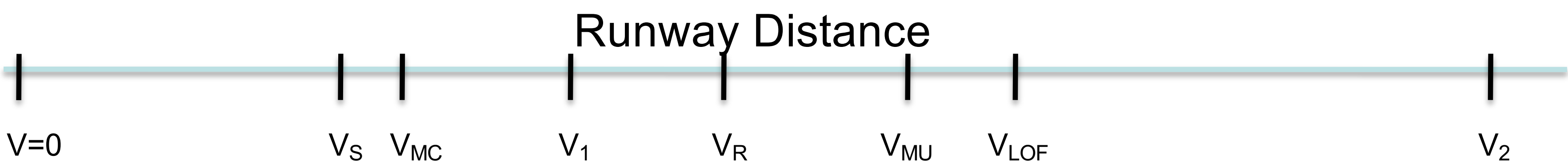
Image Courtesy of US Navy

Takeoff Overview



- **V=0: The aircraft is stationary at the end of the runway**
- **V_S: The stall speed while in take-off configuration**
- **V_{MC}: Minimum control speed. If an engine fails, the aircraft is able to maintain straight flight at that that speed**
- **V_1: Critical engine failure speed, or decision speed. (V_1 must be greater than V_{MC}.) Should an engine fail below this speed, the aircraft can be safely stopped on the remaining runway. Should an engine fail above this speed, there may be insufficient runway to stop, so the aircraft must continue its takeoff**

Takeoff Overview (cont.)



- **V_R : Rotation speed. (V_R >= V_1, but must be 5% > V_{MC}.) At this speed, the pilot can pull back on the stick to begin rotating the aircraft and increasing the angle of attack**

- **V_{MU}: Minimum un-stick speed. The minimum speed at which the aircraft can lift off safely without striking its tail on the ground**

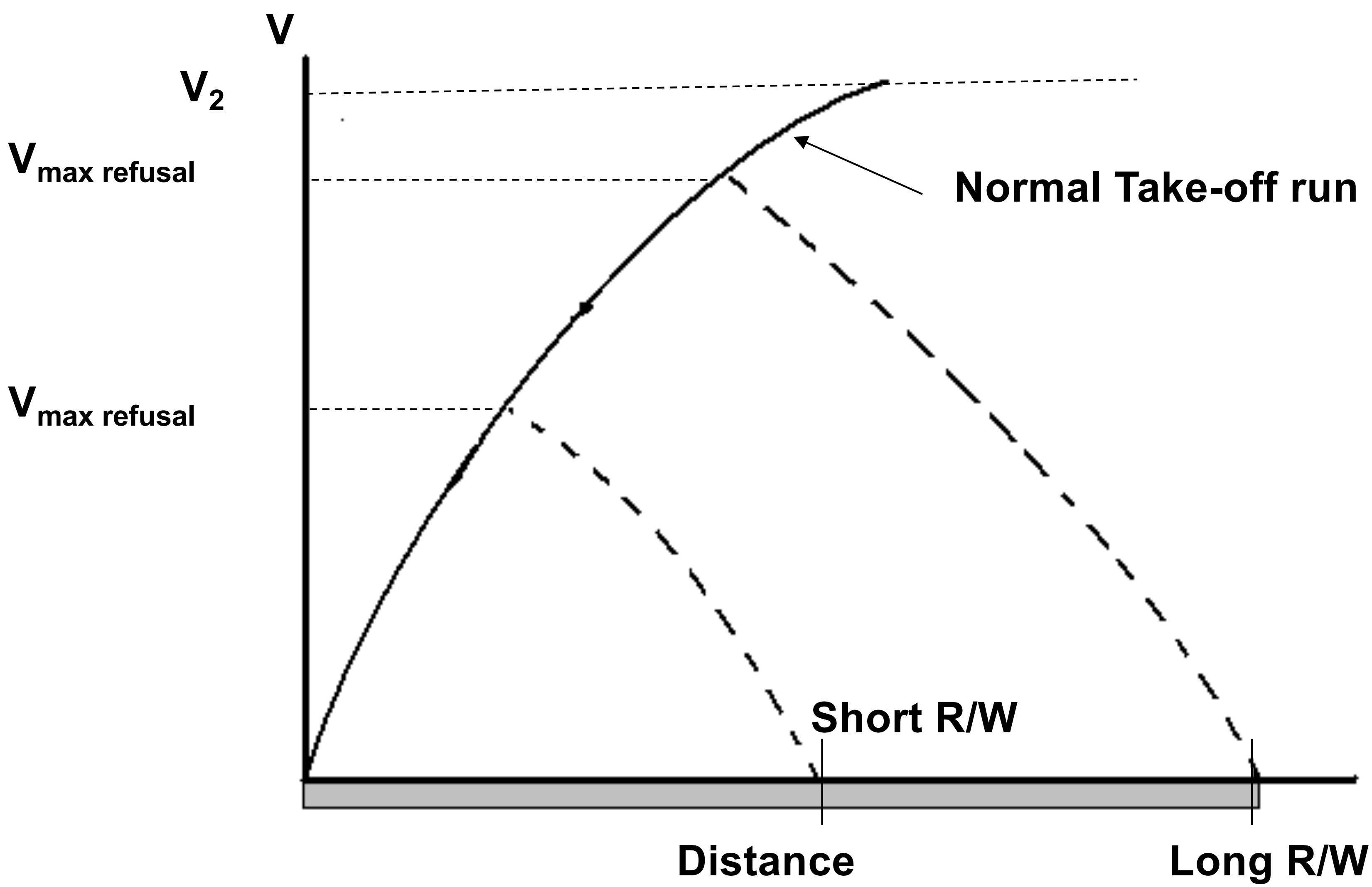
- **V_{LOF}: Lift-off speed. Slightly faster than V_{MU}, so lift-off occurs at a lower pitch attitude (lower angle of attack) than at V_{MU}**

- **V_2: Take-off climb speed. The aircraft continues to accelerate after lift-off to the take-off climb while it climbs to the screen height (35 or 50 ft depending on the aircraft class). $V_2 > 1.2\ V_S$ and $V_2 > 1.1V_{MC}$**

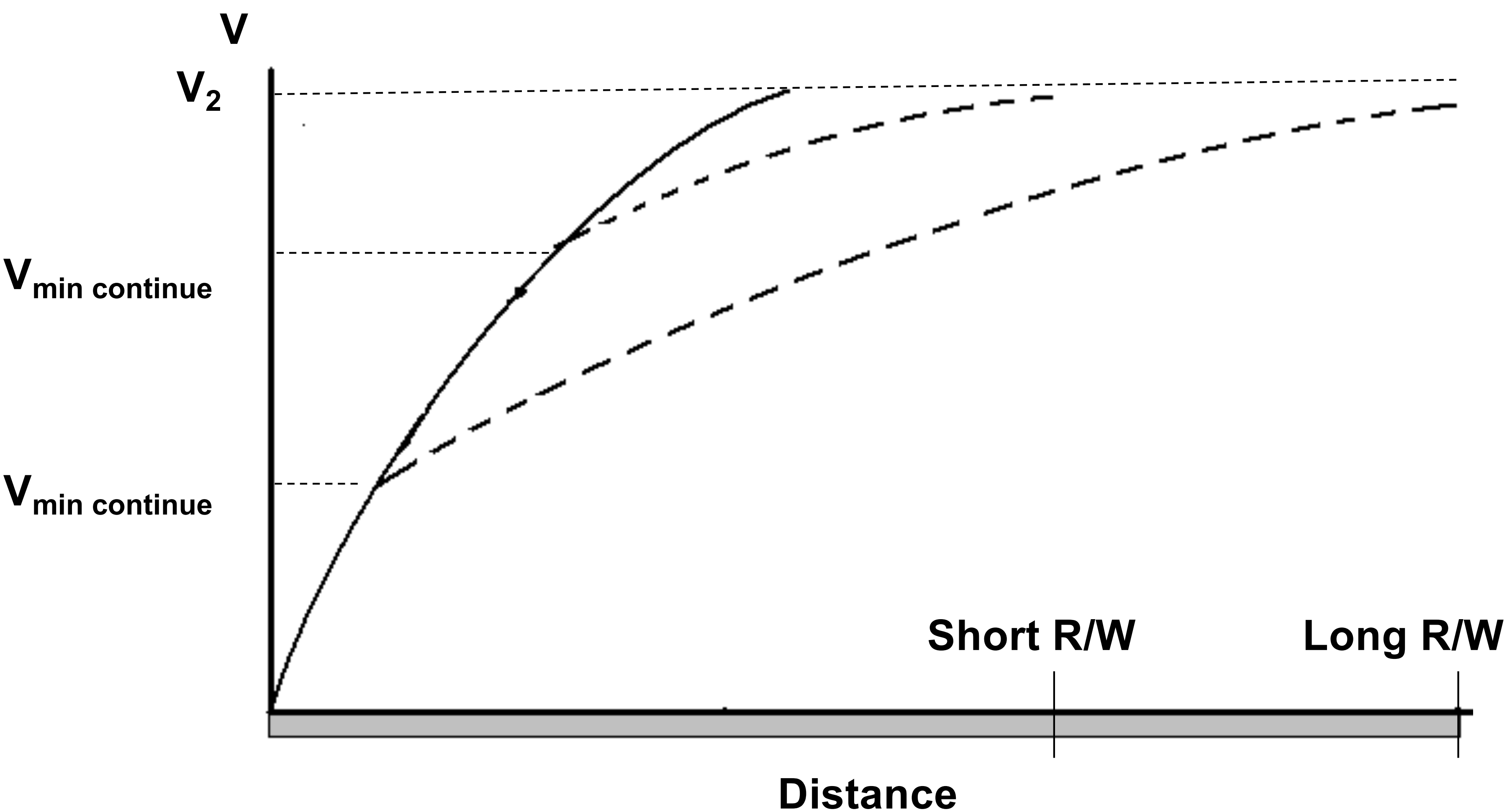
Engine Failure on Take-off

- **Critical safety issue with takeoff is an engine out condition**
  - **Engine out could occur at any time during takeoff**
  - **Pilot must know what to do if one of his engines fails**
  - **Decisions must be made quickly**

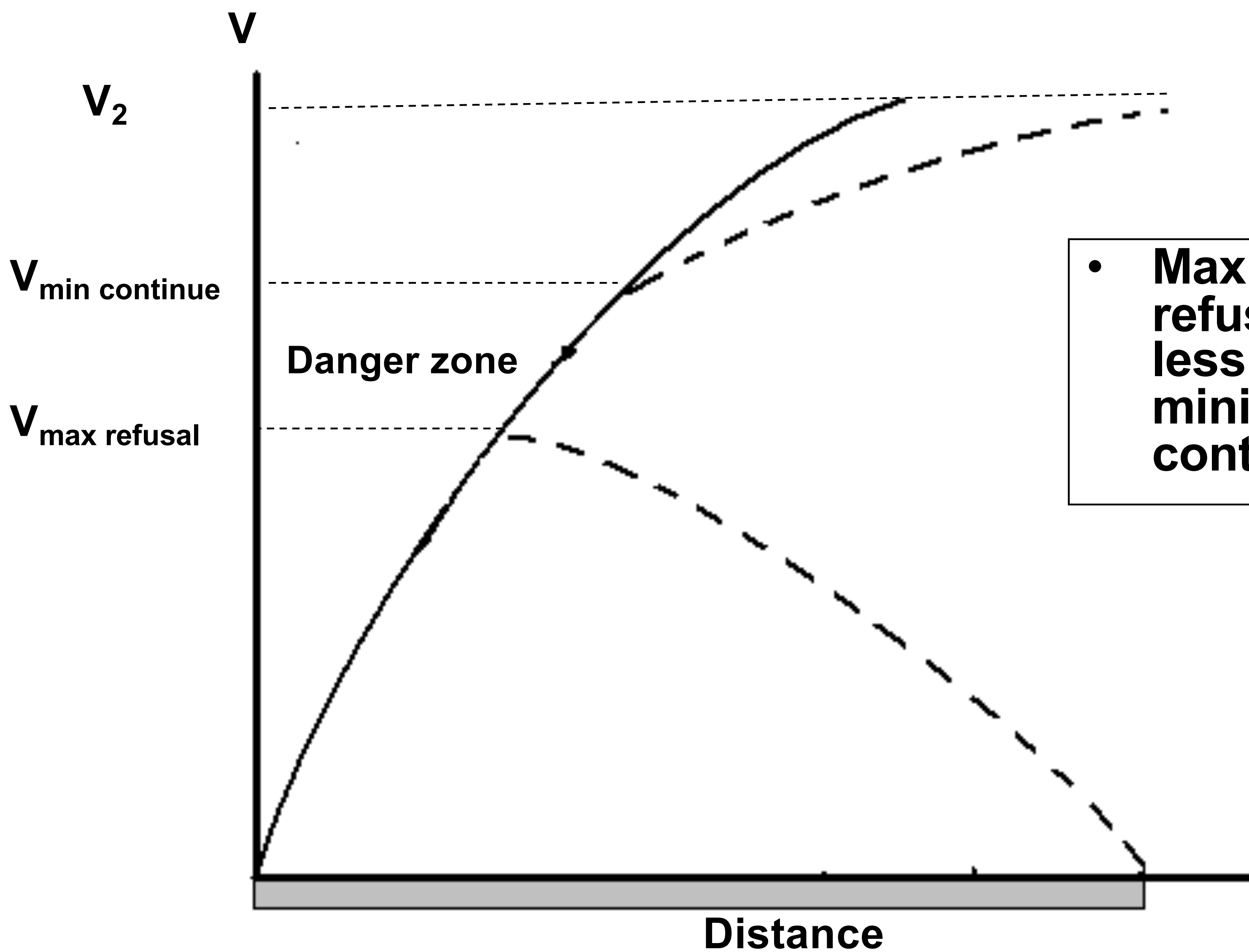
Rejected Take-off



Continued Take-off

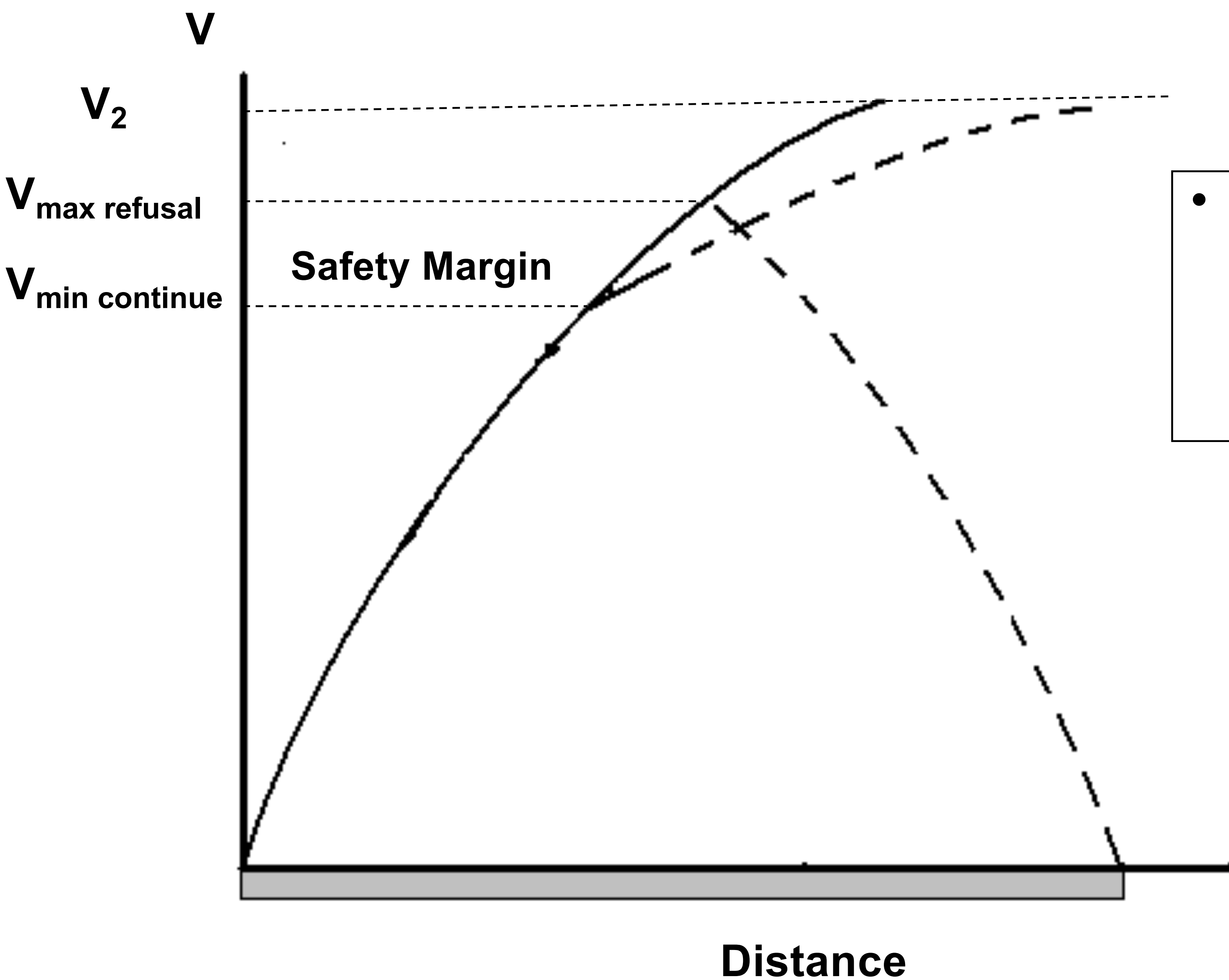


Unsafe Take-off



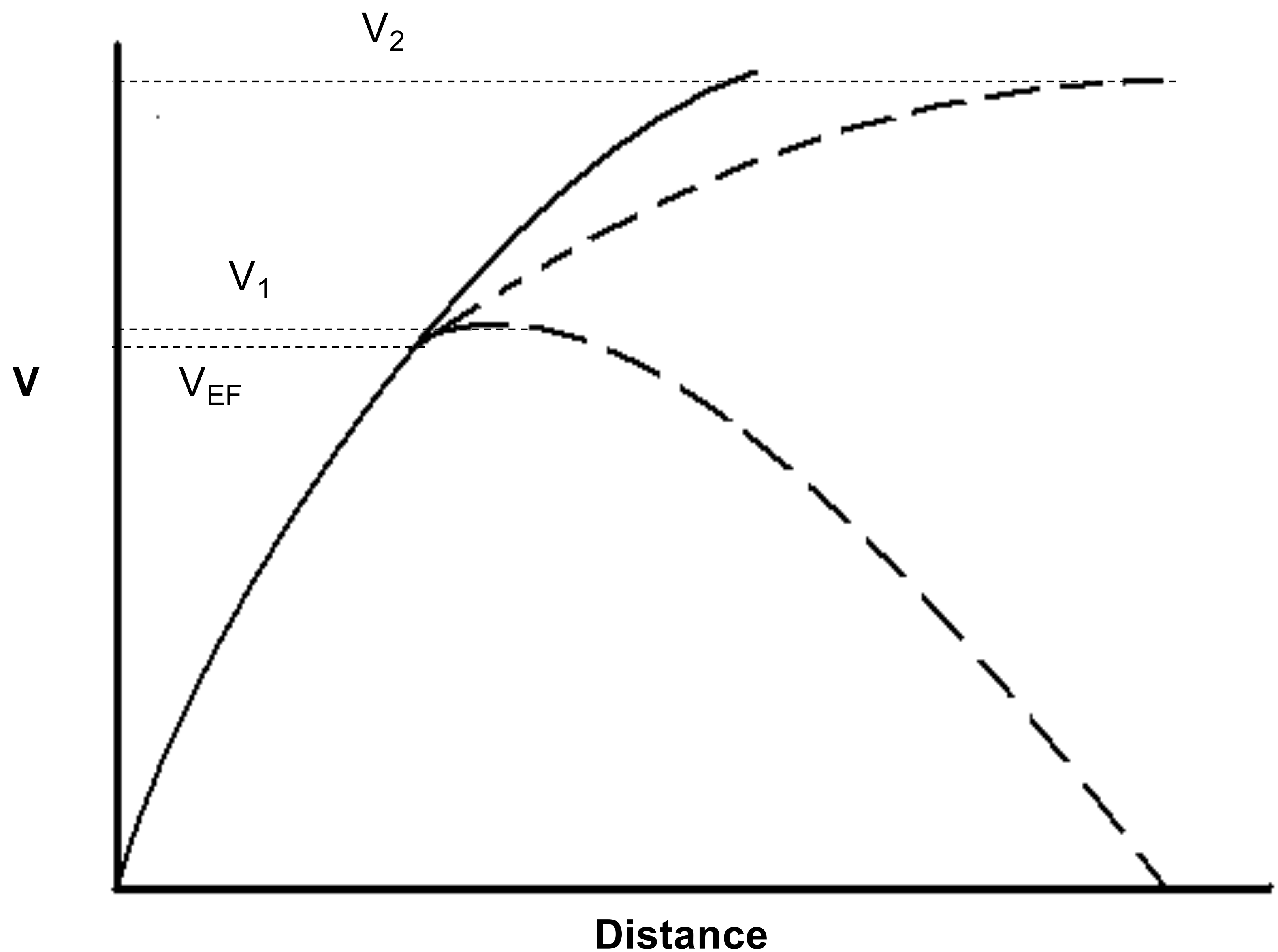
- **Maximum refusal speed is less than minimum continue speed.**

Safe Take-off



- **Max Refusal speed greater than minimum continue speed.**

Balanced Field Length



Balanced Field Length

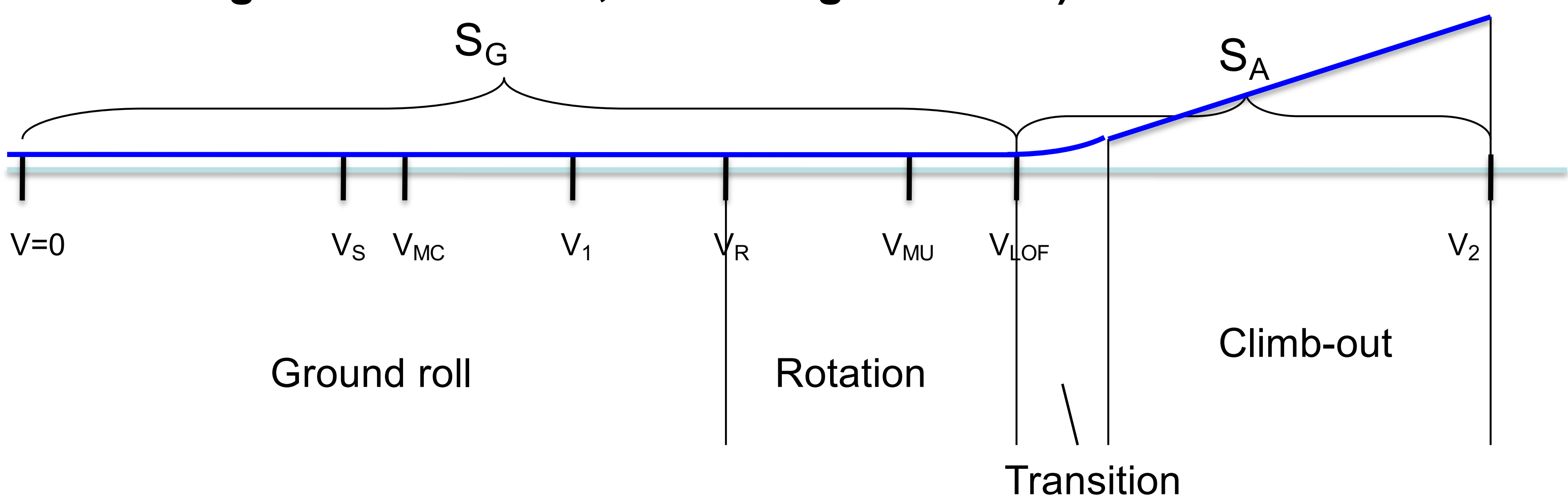
- **Balanced field length (Critical field length): When min continue speed equals max refusal speed**
  - **It takes the same distance to either stop or go following an engine failure**

- **Balanced field length used to determine V1 speed**
  - **If engine failure occurs above V1, pilot must take off**
  - **Below V1, pilot must abort take-off, idle engines, apply max brake**

Estimating Take-off Distance

Take-off distance can be split into 4 sections:

- **Ground roll**
  - **1. acceleration on the ground – nose wheel on ground**
  - **2. acceleration on the ground while rotating to lift-off attitude**
- **Air Distance**
  - **3. After lift-off, transitioning to climb attitude**
  - **4. straight flight path, climbing to required obstacle height (35ft for cargo & commercial, 50ft for light aircraft)**



Ground Roll

- **Equations of Motion:**

$$T - D_G - \mu_G (W - L_G) = m\dot{V} \longrightarrow \frac{dV}{dt} = \frac{g}{W}\left(T - D_G - \mu_G (W - L_G)\right) = a_G$$

- **Thrust, drag and lift all vary with velocity**
  - **Thrust profile usually known**
  - **Usually can assume that lift and drag coefficients remain constant during roll (no change in AoA), and that lift and drag are proportional to V²**
  - **Ground effect will alter aero coefficients:**

$$D_G = q_\infty S\left(C_{D,0} + GKC_{L_G}^2\right)$$

From McCormick:

$$\boxed{G = \frac{(16h/b)^2}{1 + (16h/b)^2}}$$

- **Friction coefficient depends on runway conditions**
  - **Rolling drag on hard runway: μ = 0.02 – 0.05**
  - **Heavy braking: μ = 0.3 – 0.4**

Ground Roll (cont.)

- **Wind speed must be accounted for:**

$$\frac{dS_G}{dt} = V - V_{headwind}$$

- **Integrate ground velocity to determine take-off distance:**

$$dS_G = \frac{V - V_{headwind}}{a_G} dV \longrightarrow S_G = \int_{V_{headwind}}^{V_{LOF}} \frac{V - V_{headwind}}{a_G} dV$$

Estimating Ground Roll Distance

- **There are a variety of ways to approximate the ground roll distance**
  - **If we knew how acceleration profile (how it varied with velocity), we could integrate numerically to obtain ground distance (most accurate)**

$$S_G = \int_{V_{headwind}}^{V_{LOF}} \frac{V - V_{headwind}}{g\left\{\left(\frac{T}{W} - \mu_G\right) - \frac{\left(C_{D_G} - \mu_G C_{L_G}\right)\bar{q}}{W/S}\right\}} dV$$

  - **If we assume that the net force varies linearly with V^2 all the way to V_{LOF}, then we can make the approximation that the average acceleration occurs at the average V^2 value**
    Assuming $V_{headwind} << V_{LOF}$,

$$V^2 = \frac{\left(0 + V_{LOF}^2\right)}{2} \longrightarrow V = \frac{V_{LOF}}{\sqrt{2}} \cong 0.7 V_{LOF}$$

Estimating Ground Roll Distance

- **If we use the average acceleration, we can treat it as a constant, then we can integrate V to obtain $V^2 = 2*a*d$ relation. Assuming $V_{headwind} << V_{LOF}$,**

$$S_G \approx \frac{1}{a_{g,at\,0.7V_{LOF}}} \int_{V_{headwind}}^{V_{LOF}} \left(V - V_{headwind}\right) dV \approx \frac{1}{a_{g,at\,0.7V_{LOF}}} \frac{\left(V_{LOF} - V_{headwind}\right)^2}{2}$$

$$\approx \frac{1}{2a_{g,V=0.7V_{LOF}}} \left(V_{LOF} - V_{headwind}\right)^2$$

$$S_G = \frac{\left(V_{LOF} - V_{headwind}\right)^2}{2g\left\{\left(\frac{T}{W} - \mu_g\right) - \frac{\left(C_{D_g} - \mu_g C_{L_g}\right)\bar{q}}{W/S}\right\}_{atV=0.7V_{LOF}}}$$

Take-off Ground Distance

- **Effects of Weight**
  - **Larger mass leads to lower acceleration**
  - **Increased weight also requires higher stall speed**
  - **Increased friction force**
- **Effects of wind**

$$\frac{S_{G1}}{S_{G2}} = \frac{V_{LO}^2}{\left(V_{LO} - V_W\right)^2}$$

- **Runway slope**

$$T = D_G - \mu_G (W - L_G) + mg \sin\gamma$$

- **Pressure and temperature**
  - **Hot or high condition increases true airspeed at V_{LO}**
  - **Hot or high condition reduces thrust (reduced density)**

Determining Air Distance

- **Airborne distance can be approximated by the energy balance in the airborne phase:**
  - **ΔE = Excess Thrust * distance travelled**

$$\Delta E = (T - D)_{avg} S_A$$

$$\Delta E = (K.E + P.E)_{h_{screen}} - (K.E + P.E)_{L.O}$$

$$S_A = \frac{mg}{(T - D)_{avg}} \left[\frac{V_2^2 - V_{LOF}^2}{2g} + h_{screen} \right]$$

Landing Rules

- **Civil landing regulations (FAR 23, FAR 25):**
  - **Requires that the landing distance from 50ft obstacle, while stabilized at a speed of $V_A = 1.3V_{S,approach}$ be determined**
  - **Touchdown speed not specified, but normally it is around $1.15V_{S,approach}$**
  - **Balked landings at the 50 ft. obstacle must be possible**

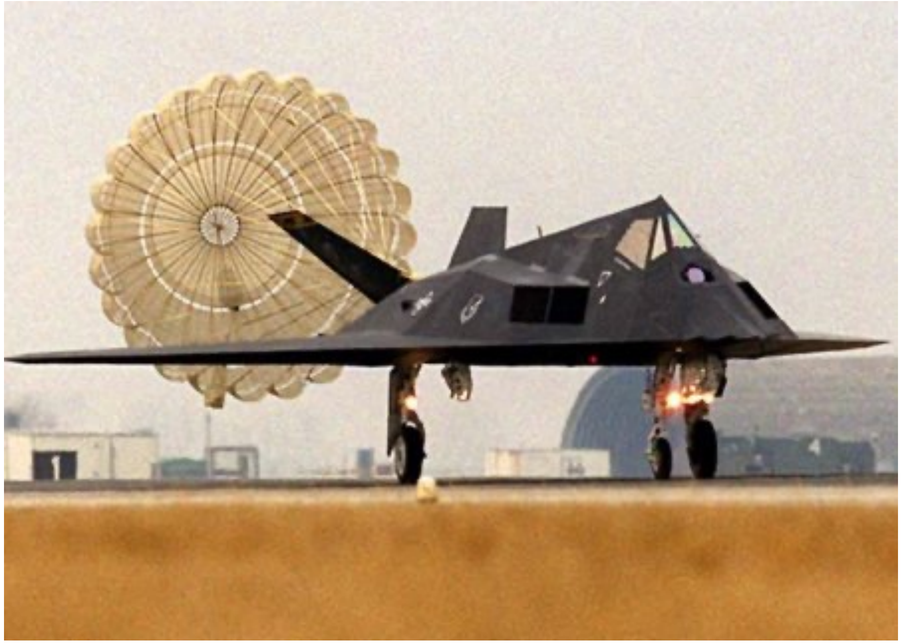
Ground Roll

- **Ground distance can be split into two sections:**
  $S_{LG} = +S_{LND} + S_{LR}$
- **S_{LR}: ground roll during rotation**
  - **Vehicle will rotate to nose-gear down attitude**
  - **Velocity will decrease from V_{TD} to V_{LR}**

$$S_{LR} = \int_{V_{TD} \pm V_W}^{V_{LR} \pm V_W} \frac{V \pm V_W}{g\left\{\left(\frac{T}{W} - \mu_G\right) - \frac{\left(C_{D_G} - \mu_G C_{L_G}\right)\bar{q}}{W/S} - \Phi\right\}} dV$$

- **S_{LND} : ground roll with nose-gear down**
  - **Velocity will decrease from V_{LR} to 0**

$$S_{LND} = \int_{V_{LR} \pm V_W}^{\pm V_W} \frac{V \pm V_W}{g\left\{\left(\frac{T}{W} - \mu_G\right) - \frac{\left(C_{D_G} - \mu_G C_{L_G}\right)\bar{q}}{W/S} - \Phi\right\}} dV$$



Same equation as takeoff ground roll

Ground Roll Distance

- **If acceleration profiles are known, the integrals on the previous slide can be evaluated to determine the ground distance**

- **Approximate method**

  – **We can also estimate the average acceleration (just as we did with takeoff):**

$$\left[T - D - \mu(W - L)\right]_{avg} = \left[T - D - \mu(W - L)\right]_{0.7V_{TD}}$$

  – **Estimate rotation phase time based on aircraft size:**
    - **N = 1sec for small aircraft**
    - **N = 3 sec for larger transport aircraft**

  – **Ground roll distance can then be computed using**

$$S_{LG} = \frac{V_{TD}^2}{2a_{0.7V_{TD}}} + NV_{TD}$$

Aircraft Carriers

References

1. C.E.Lan, J. Roskam, *Airplane Aerodynamics and Performance*, Design Analysis Research Corporation, 1997
2. McCormick, B.W., *Aerodynamics, Aeronautics and Flight Mechanics*, 2nd edition, Wiley & Sons, 1995
3. E. Field, MAE 154S Lecture Notes, 2000