Contaminated and Slippery Runways

Agenda:

- **Basic Regulations and Definitions**
- **Physics of Contaminated Runways**
- **Operational Practice**
- **Operational Data/Applications**
- **Other Considerations**

Contaminated runway

- More than 25% of the runway is covered by slush, standing water, snow covered, Ice covered or compacted snow

Regulatory Requirements

- **FAA Operators**

Historically

No definitive regulatory requirements for contaminated or slippery runway performance adjustments in Part 25 or 121

Current (737-6/7/8/900) -

Wet runway is part of AFM certification basis

No definitive regulatory requirements for contaminated or slippery (non-wet)

Regulatory Requirements

- FAA Guidelines:
  - Current approved guidelines published in Advisory Circular 91-6A, May 24, 1978
  - Provides guidelines for operation with standing water, slush, snow or ice on runway
  - Does not provide for wet runways
  - Proposed Advisory Circular 91-6B (draft)

Regulatory Requirements

- JAA Operators - New certifications
  - Specific requirements covered in the AFM
  - Includes performance based on various runway conditions (wet, compact snow, wet ice, slush, dry snow)
- JAROPS 1
  - Requires operational contaminated/slippery runway data based on possibility of an engine failure

Proposed Advisory Circular 91-6B:

- Guidelines for takeoff and landing with water, slush, snow or ice on runway
  - Defines contaminated runway
  - Defines braking coefficient used for accelerate-stop distance calculation
  - Includes wet runway
  - Reverse thrust credit for accelerate-stop
- Did not specifically address, but were adopted in the advisory data of the time
  - 15-foot screen height for accelerate-go

JAR-OPS 1 / AMJ15X1591:

- Guidelines for takeoff and landing with water, slush, snow or ice on runway
  - Defines contaminated runway
  - Defines braking coefficient and contaminant drag to be used in calculations
  - Includes wet runway
  - 15-foot screen height for accelerate-go
  - Reverse thrust credit for accelerate-stop

Dry, Damp, and Wet Runways are NOT Contaminated

- Dry: Neither wet or contaminated (JAR-OPS 1.480)
  - FAA - No definitive definition
- Damp: Surface is not dry, but moisture on the surface does not give a shiny appearance (JAR-OPS 1.480)
- Wet: - FAA - neither dry nor contaminated (Draft AC 91-6B)
  - Shiny in appearance, depth less than 3 mm of water (JAR-OPS 1.480)

Runways are CONTAMINATED When:*

- More than 25% of the surface to be used is covered by standing water or slush more than 1/8 inch (3 mm) deep

OR

- Has an accumulation of snow or ice

*As defined by *FAA Advisory Circular 91-6B*

Additional considerations:

- **If the contaminants are lying on that portion of the runway where the high speed part of the takeoff roll will occur, it may be appropriate to consider the runway contaminated.**
  (Draft AC 91-6B)

- **Do NOT takeoff when the depth of standing water or slush is more than:**

  1/2 inch (13 mm) deep

Boeing Contaminated Runway Takeoff Performance

- Slush / Standing Water Data
  - Acceleration/deceleration capability

- Slippery runway
  - Deceleration capability

    Ice covered, compacted snow, or wet

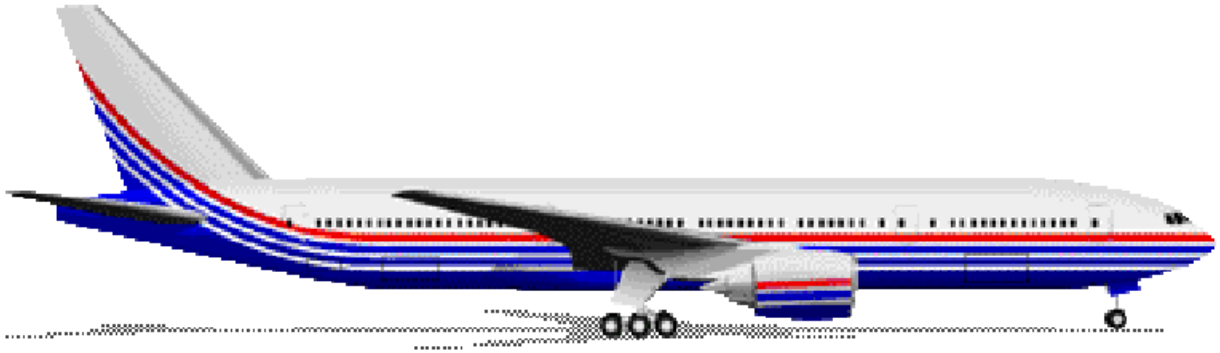
Agenda:

- Basic Regulations and Definitions
- **Physics of Contaminated Runways**
- Operational Practice
- Operational Data/Applications
- Other Considerations

Takeoff Distance Is Proportional to $\frac{1}{a}$

- Large Acceleration (a) ⇨ Short Takeoff Distance
- Small Acceleration (a) ⇨ Long Takeoff Distance

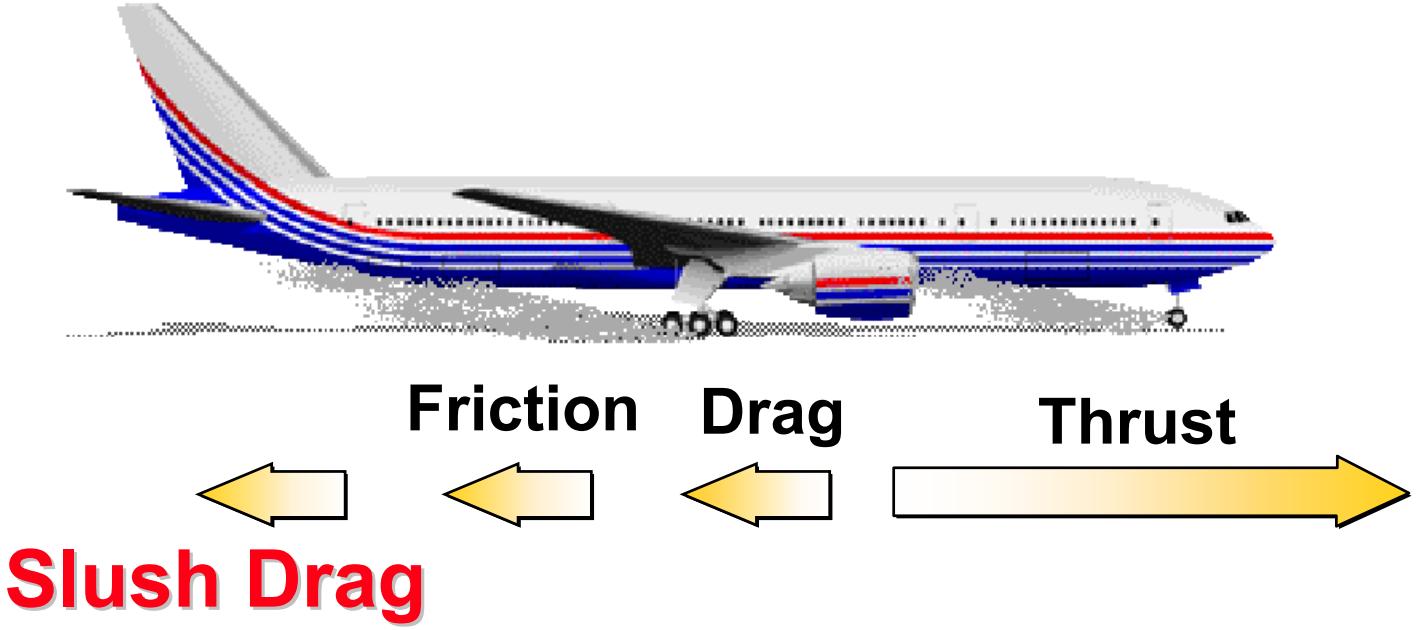
Dry Runway Acceleration



Friction Drag Thrust

$$a = \frac{g}{W}\left[\text{Thrust} - \text{Drag} - \text{Friction}\right]$$

Acceleration with Slush/Standing Water



$$a = \frac{g}{W}\left[\text{Thrust} - \text{Drag} - \text{Friction} - \text{Slush Drag}\right]$$

$$F_{Slush} = 1/2\ \rho\ V_g^2 C_{D\ Slush} A_{Tire}$$

ρ = Slush Density, 1.65 slugs/ft3
Equal to Specific Gravity of 0.85

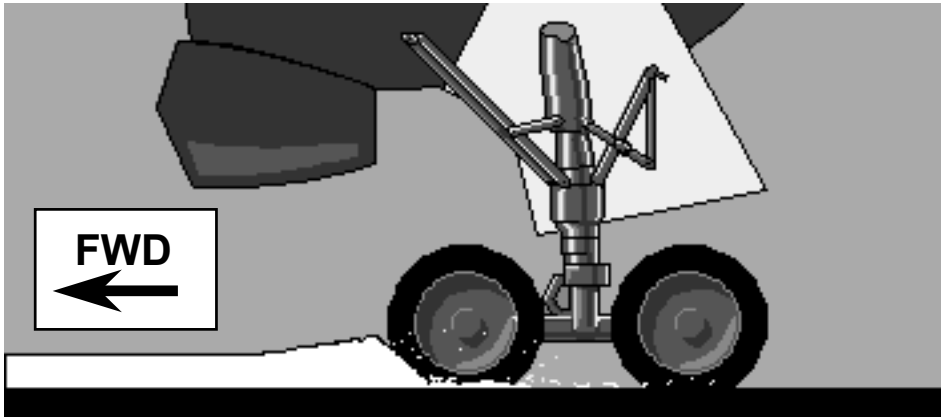
V_g = Ground Speed - Feet per Second

$C_{D\ Slush}$ = Slush Drag Coefficient for airplane's specific gear arrangement

A_{Tire} = Reference Area for Slush Force Calculation

Data Sources: FAA/NACA Convair 880 Tests 1962
NASA Langley Load Track Tests - 1960,1962

$C_{D\ Slush}$ Accounts for Displacement and Impingement

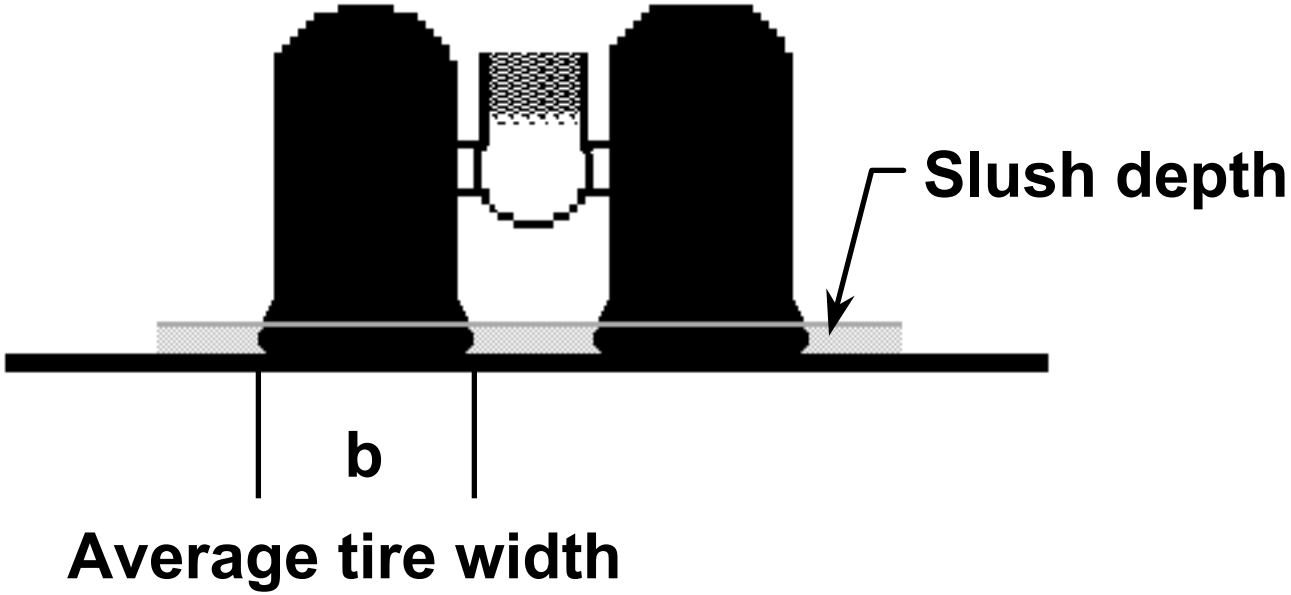


Displacement Drag

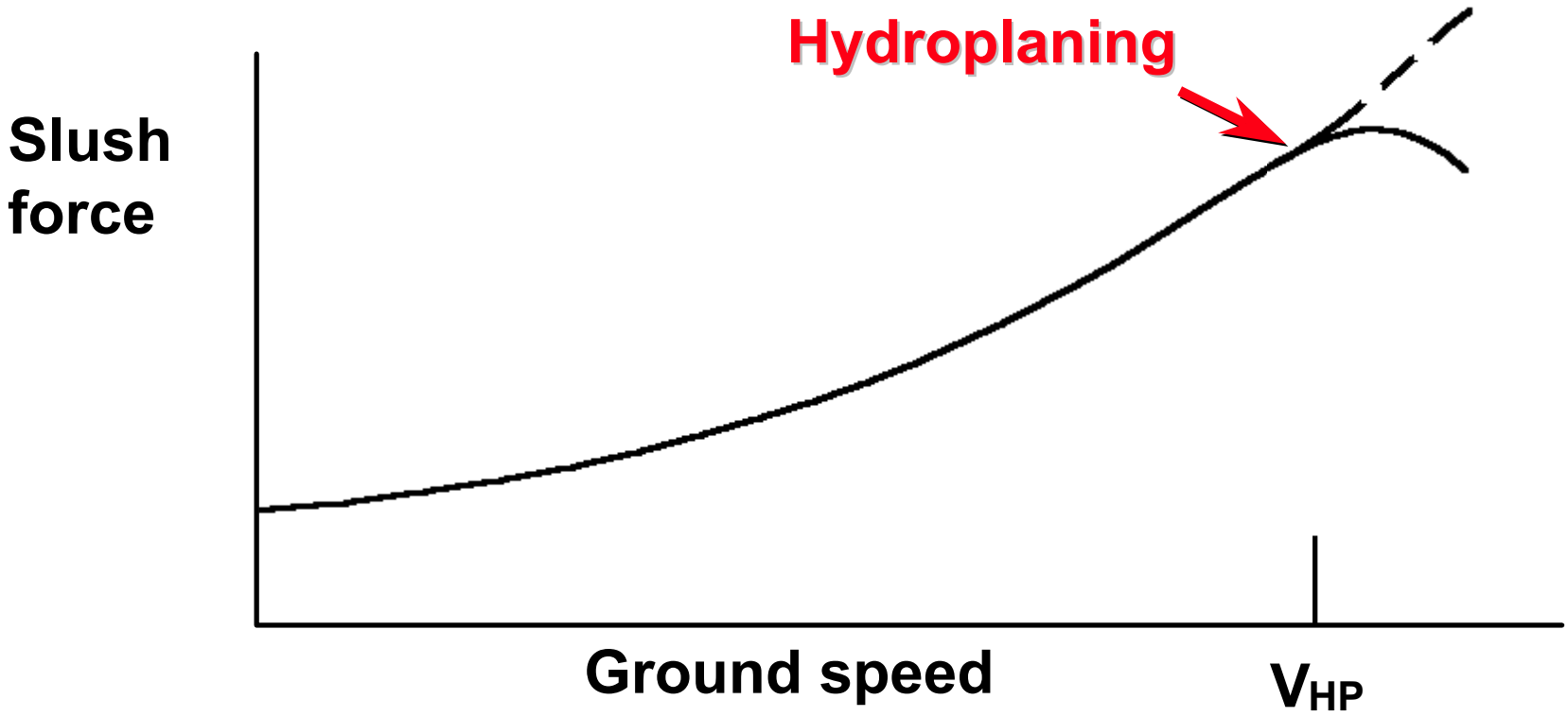
Impingement Drag

Tire Reference Area for Slush Calculation

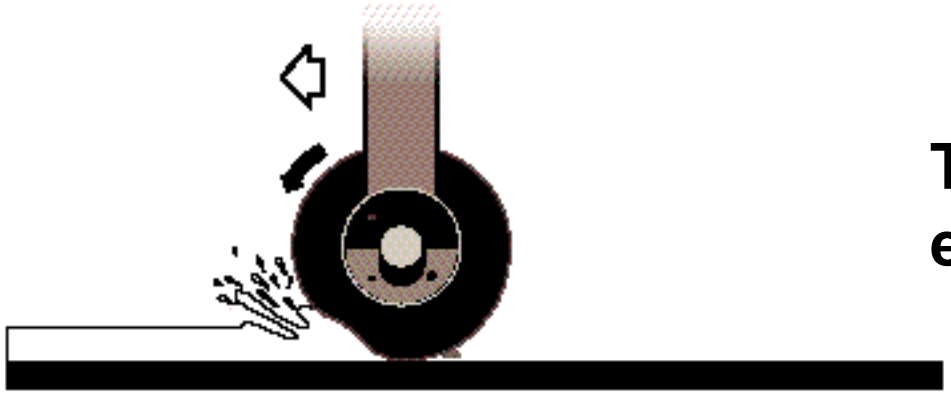
$$A_{Tire} = (\Sigma\, b_{main} + \Sigma\, b_{nose}) \times \text{Slush Depth}$$



Slush Force



Hydroplaning



Tire Pressure in psi evaluated for Main Gear

$$V_{HP} = 8.63\sqrt{\frac{\text{Tire Pressure}}{\text{Specific Gravity}}}$$

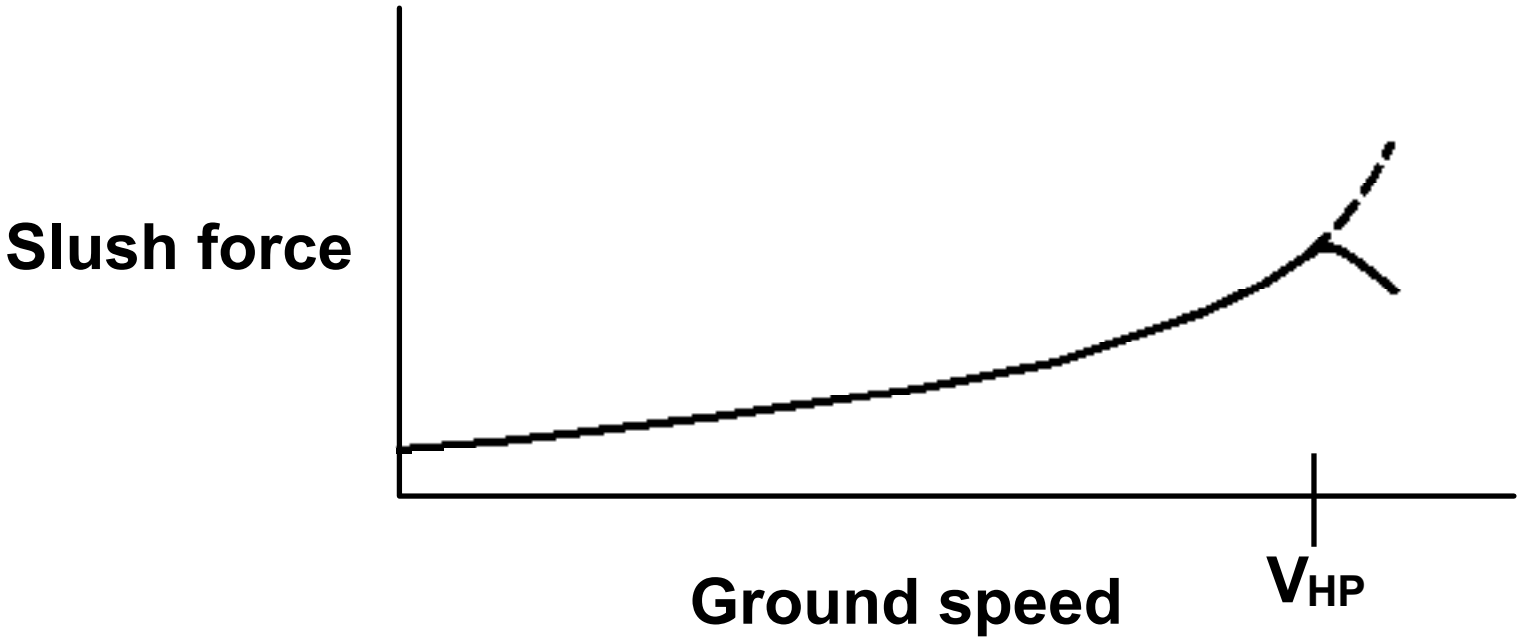
80's, 90's method

$$= 8.63\sqrt{\text{Tire Pressure}}$$

Current method

Slush Force Including Hydroplaning

$$F_s = (1/2\ \rho\ C_{D_{Slush}} V_g^2\ A_{Tire}) \times f_{HP}$$

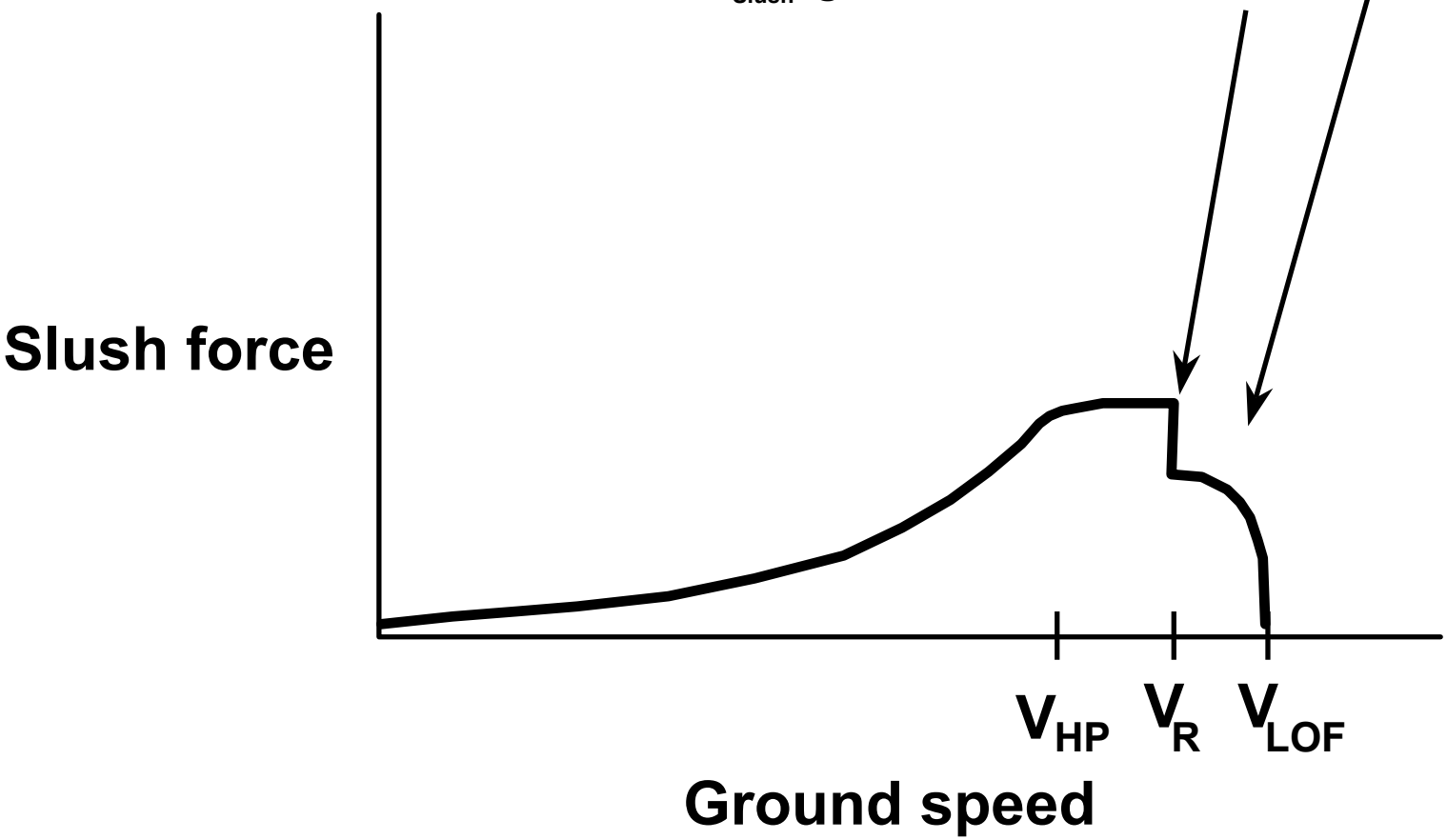


$$f_{HP} = \left[\frac{1.6V_{HP} - V_g}{.6V_{HP}}\right]^{\left(\frac{2.5V_g}{V_{HP}} - 1.5\right)}$$

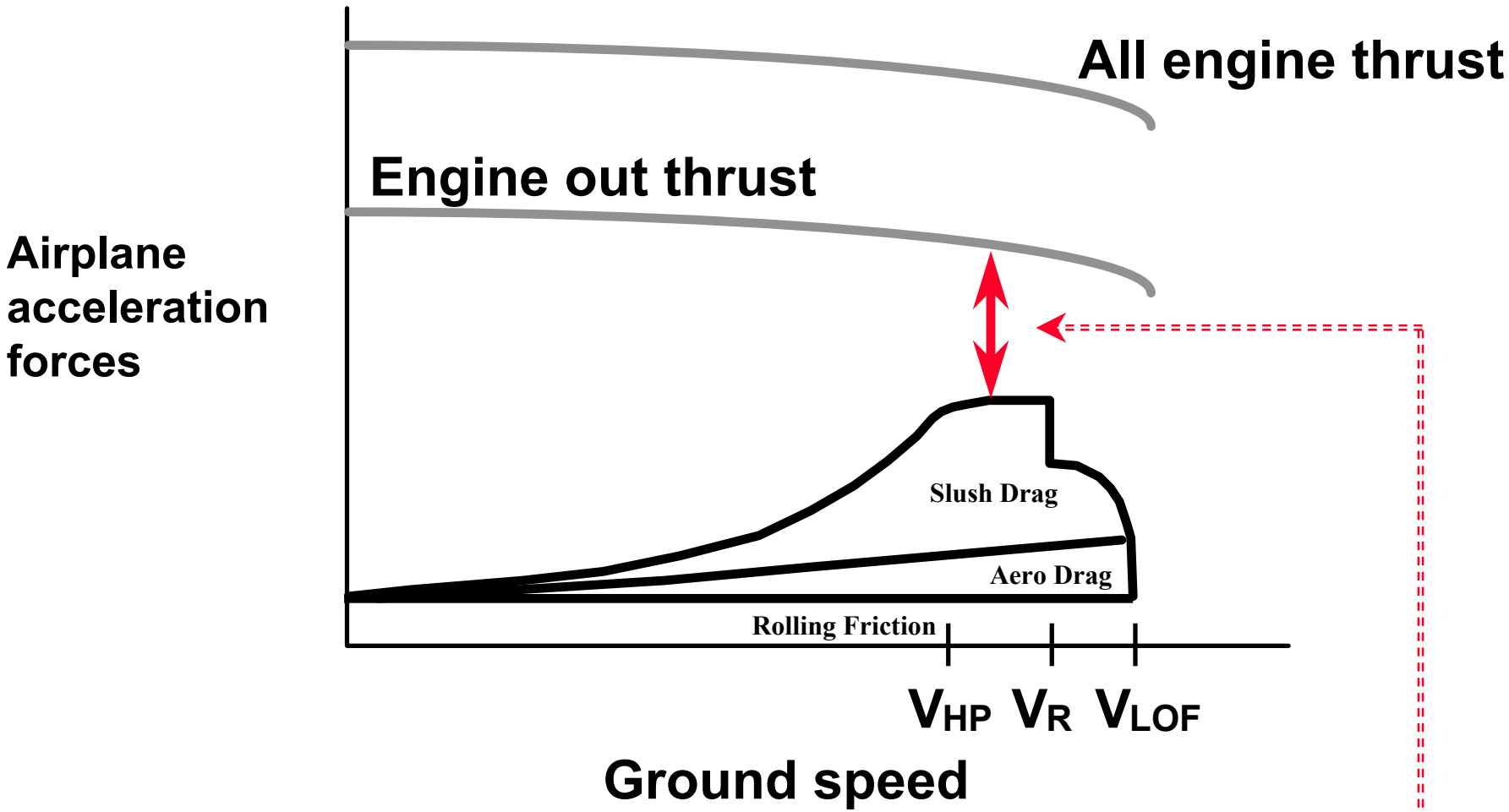
This factor is applied at speeds above the hydroplaning speed.

Slush Force From Rotation to Liftoff

$$F_s = (1/2\ \rho\ C_{D_{Slush}} V_g^2\ A_{Tire}) \times f_{HP} \times f_R \times f_{LOF}$$



Force Variation With Speed



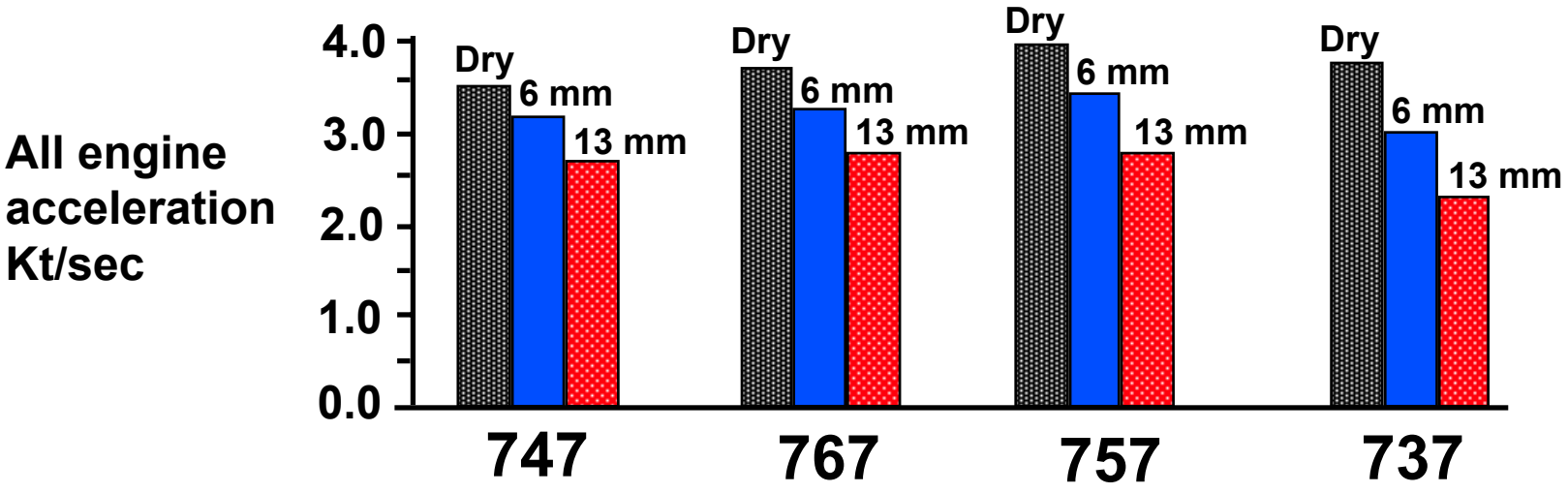
Total Acceleration Force = Thrust - (Slush force + Aero drag + Friction)

All Engine Acceleration Capability

130 Knots

6 mm of slush - 10-20 % reduction in all engine acceleration

13 mm of slush - 20-40 % reduction in all engine acceleration

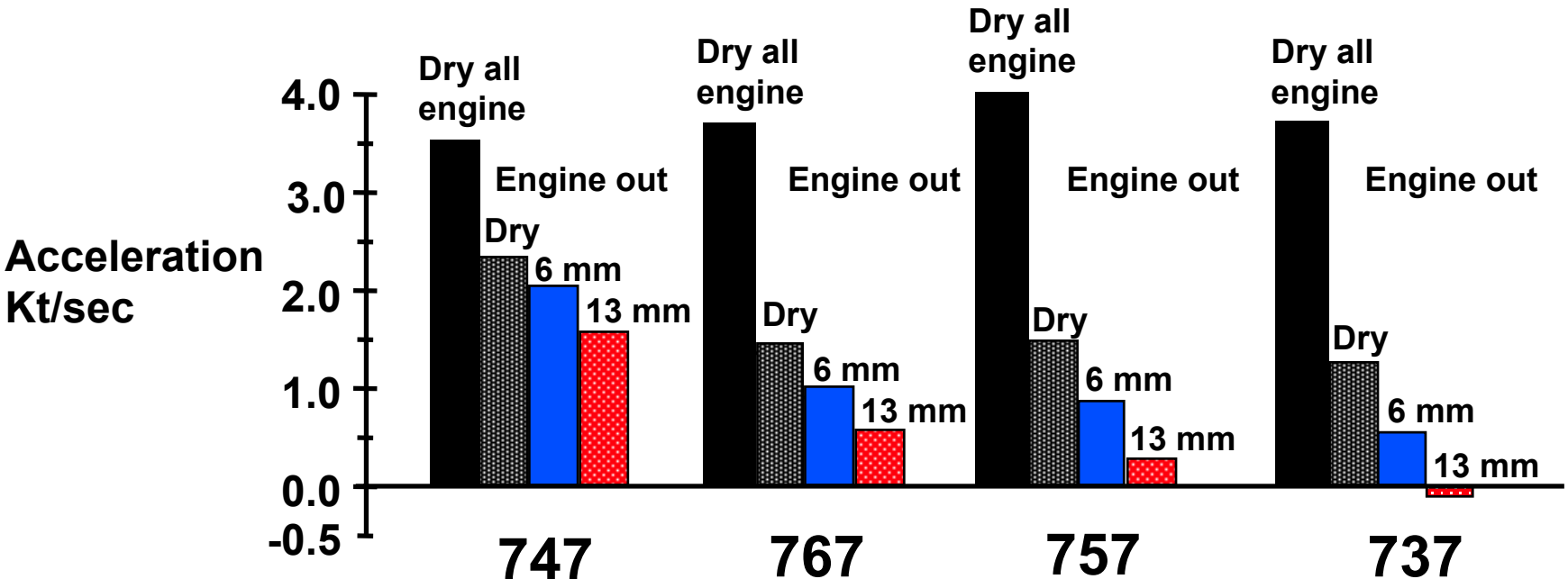


Engine Out Acceleration Capability

130 Knots

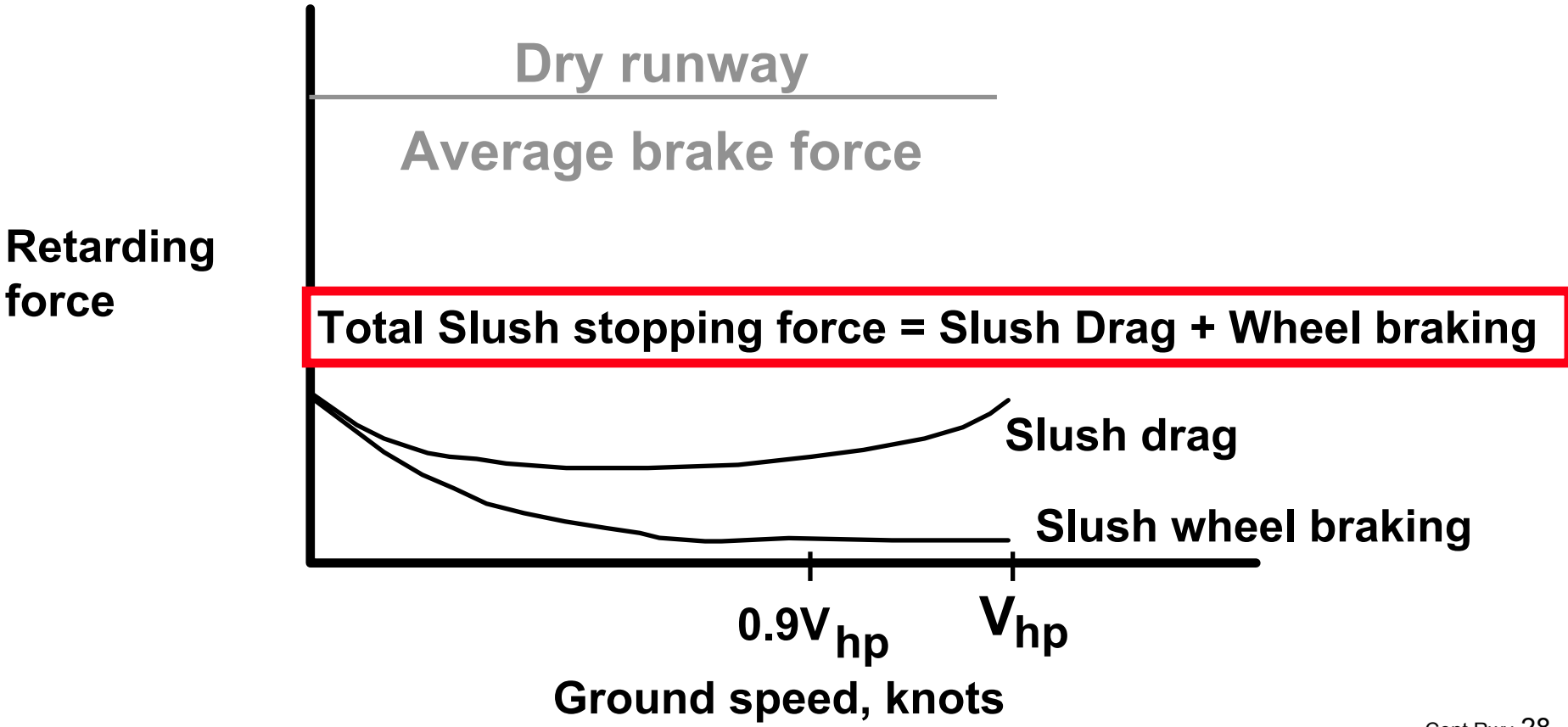
6 mm of slush - 15-50 % reduction in engine out acceleration

13 mm of slush - 30-110 % reduction in engine out acceleration



Effect of Slush On Airplane Stopping

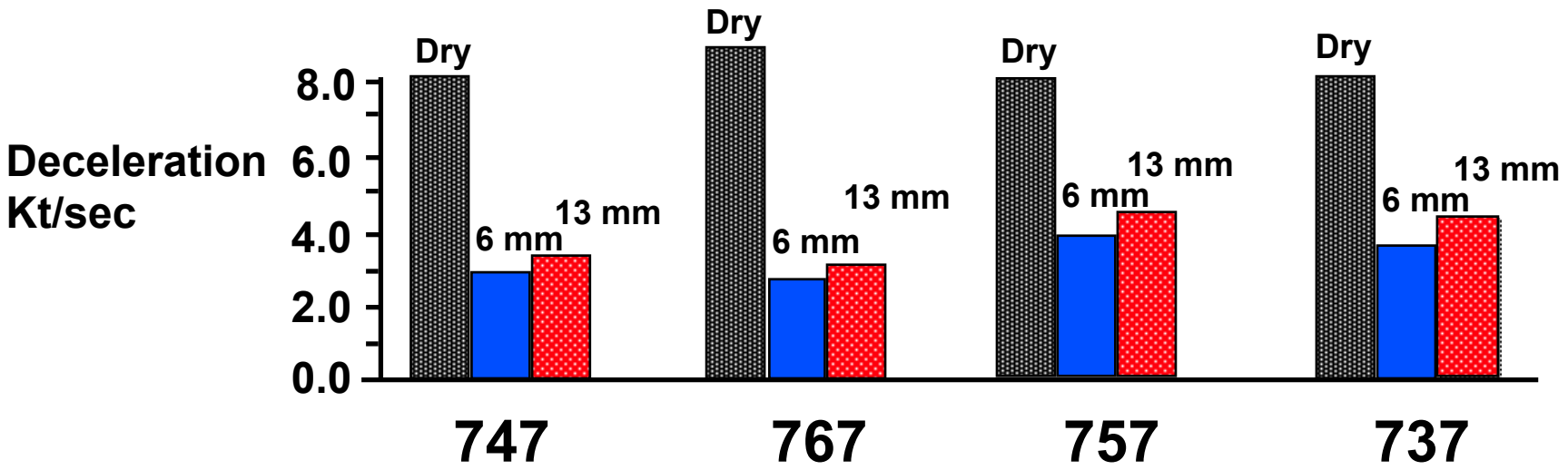
- Tire to ground friction reduced due to slush
- Retarding slush drag acts to slow the airplane



One Engine Inoperative Deceleration Capability

130 Knots

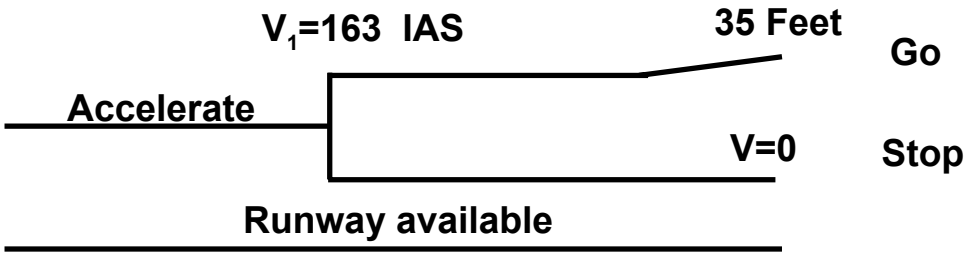
- Dry - AFM performance - includes maximum braking, spoilers, idle thrust
- Slush - includes wheel braking, spoilers, reverse thrust, and slush drag



Effect of Slush - All Engine

767-300 - 182,800 kg, V_1 = 163 IAS

Baseline - **AFM balance field length - 9520 Feet**



Effect of using dry runway performance on slush covered runway

All engine performance- 6 mm slush

Margin 15%

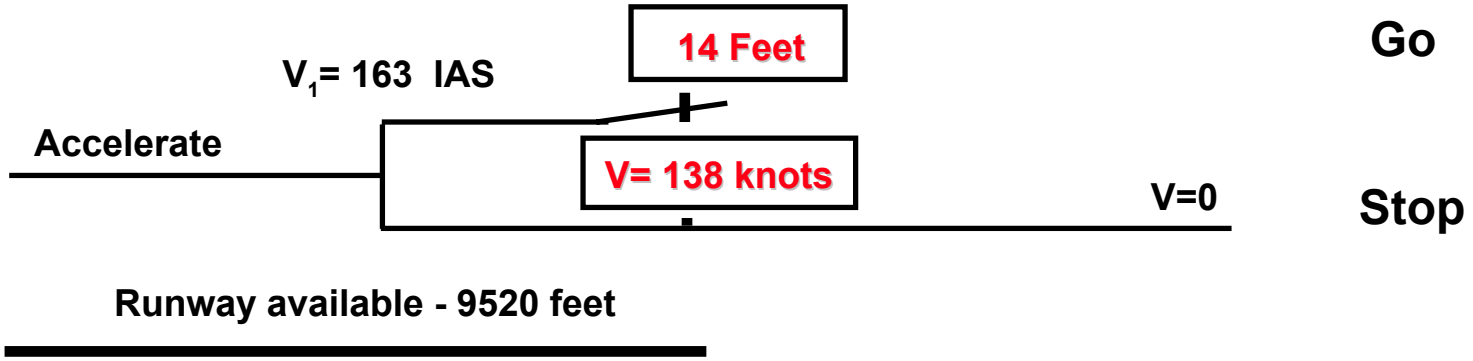
All engine performance- 13 mm slush

Margin 5%

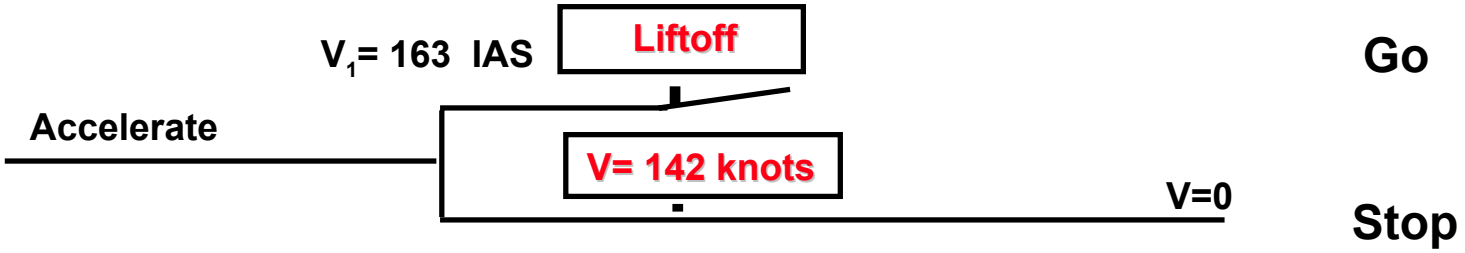
Effect of Slush - Engine Out

767-300 - 182,800 kg, V_1 = 163 IAS

- **Effect of using dry runway performance on slush covered runway**
- **Engine out performance - 6 mm slush**



- **Engine out performance - 13 mm slush**



Agenda:

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- Physics of Contaminated Runways
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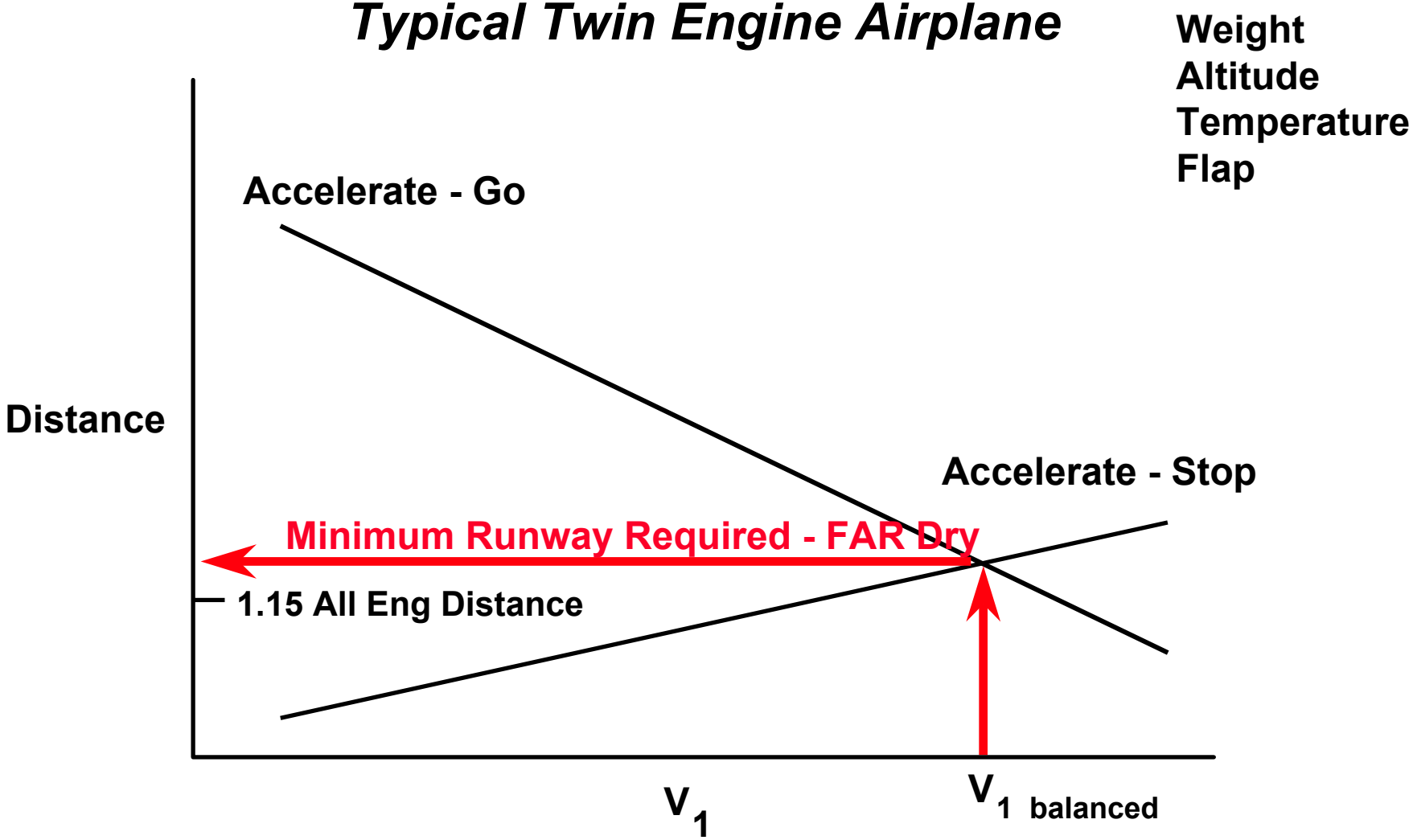
Boeing Contaminated Runway Data Adjustments - Choices

- All engines operating
  - Weight reduction
  - No V_1 adjustment provided
  - Preserves 15% margin
- Engine failure is considered - JAROPS 1
  - Weight reduction and V_1 adjustment provided
  - Credit for reverse thrust
  - 15 foot screen height

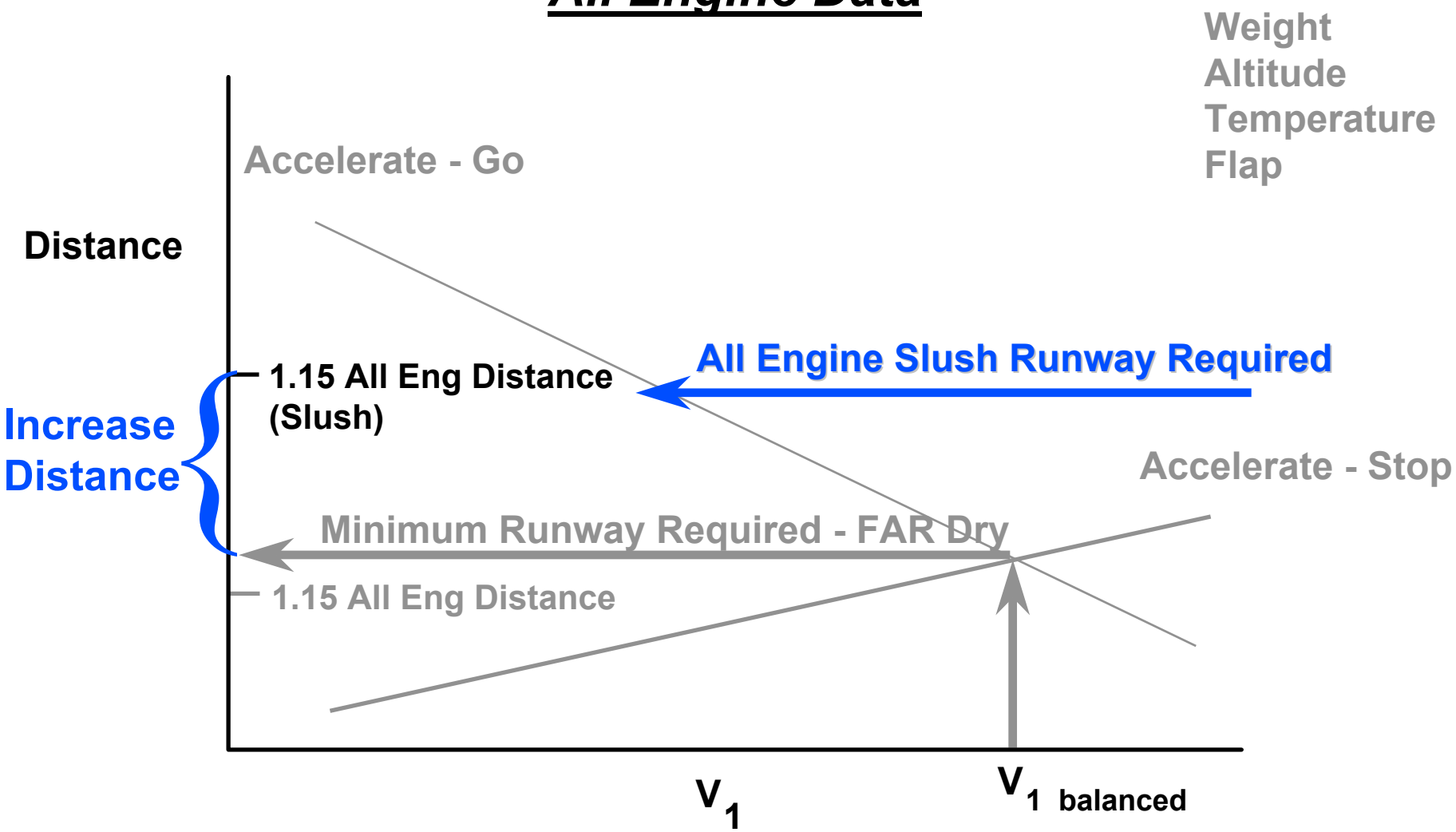
Data presented in airplane *Operations Manual, FPPM,* and *PEM*

FAR Dry Field Length

Typical Twin Engine Airplane

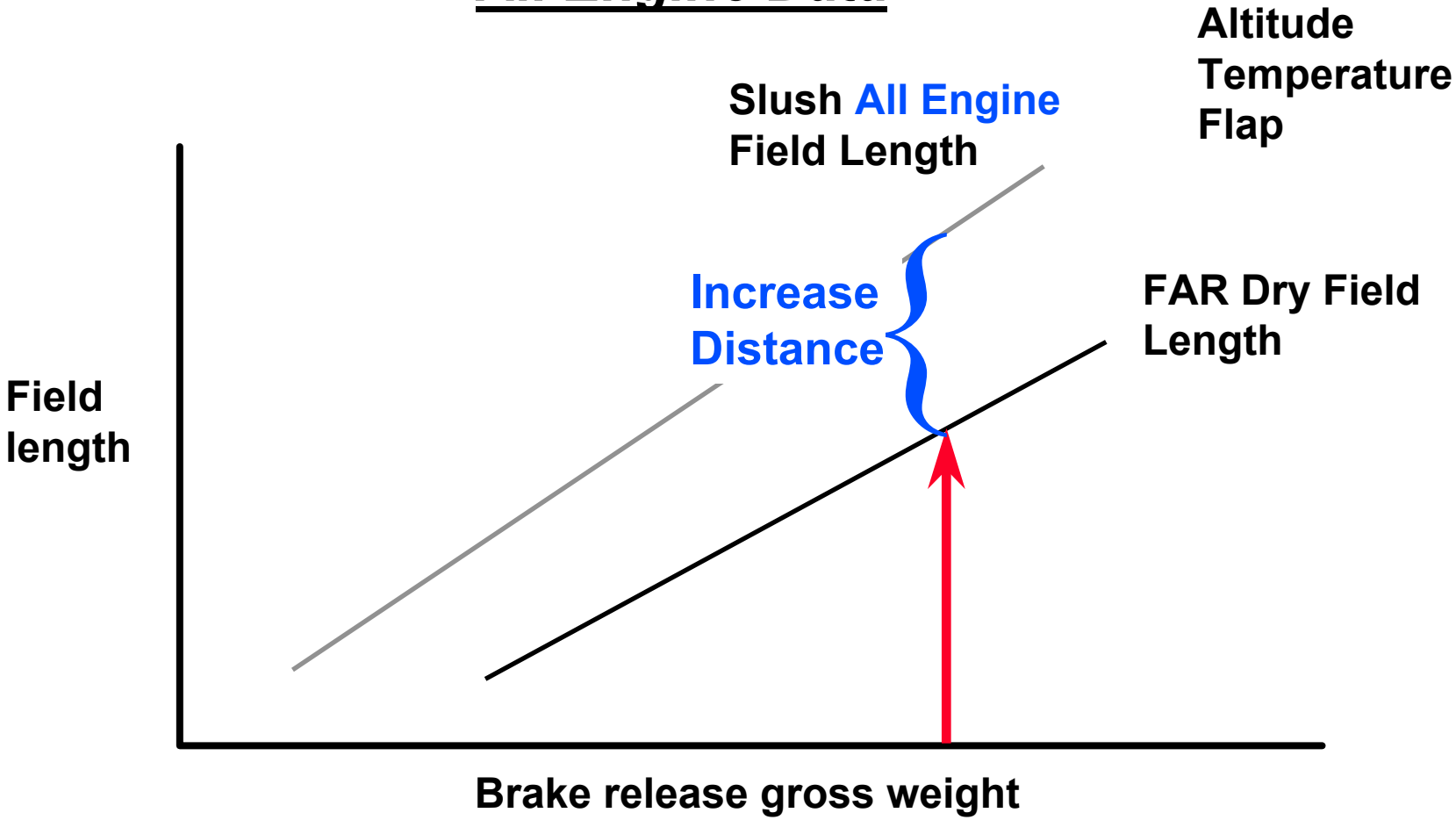


Contaminated Runway Case
All Engine Data



Constant Field Length Weight Reduction

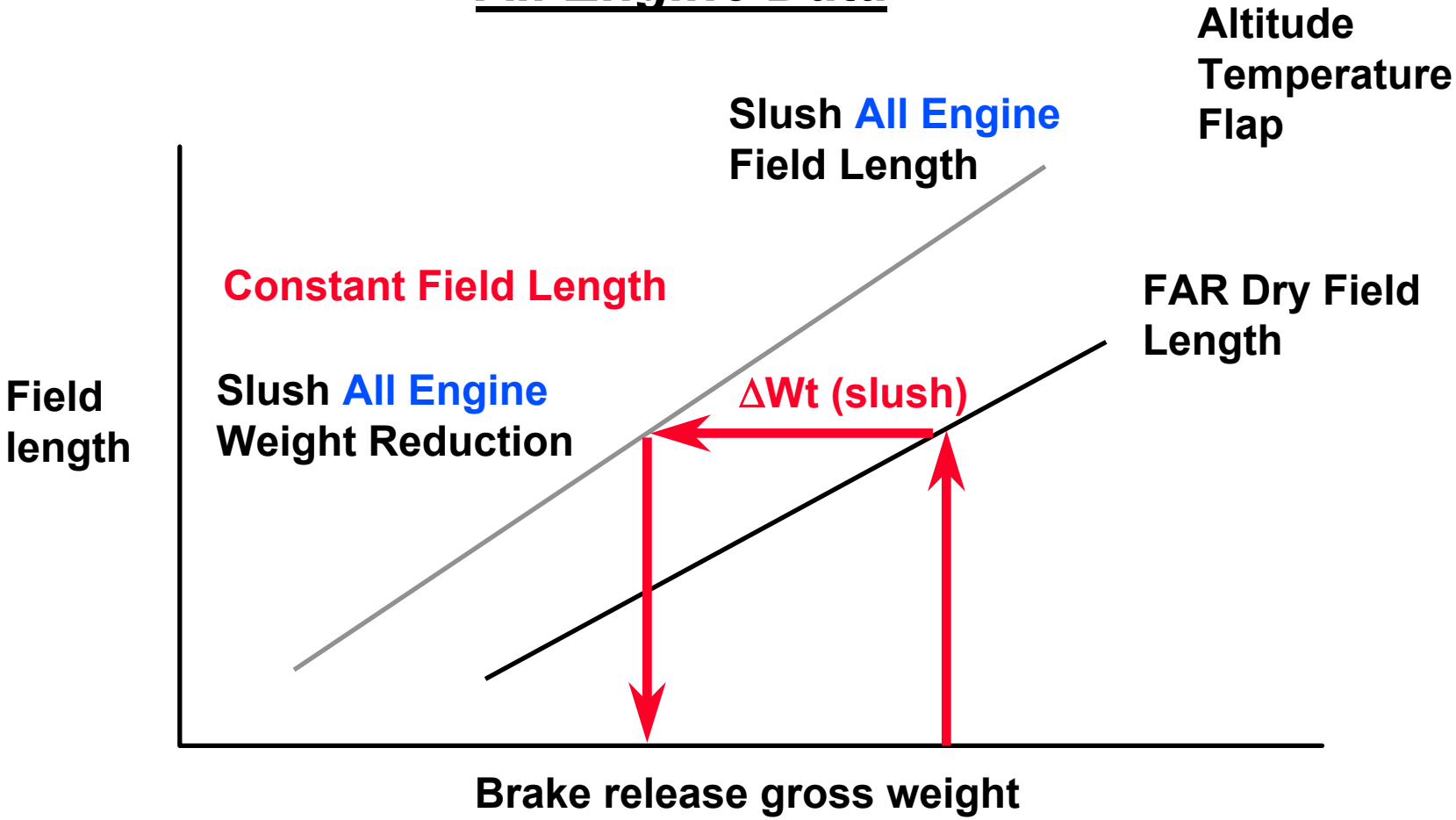
All Engine Data



Note: Stop has not been considered nor has continued takeoff following engine failure

Constant Field Length Weight Reduction

All Engine Data



Note: Stop has not been considered nor has continued takeoff following engine failure

Sample Ops Manual Slush/Standing Water Page

All Engine Data - 737-500 / 20K Rating

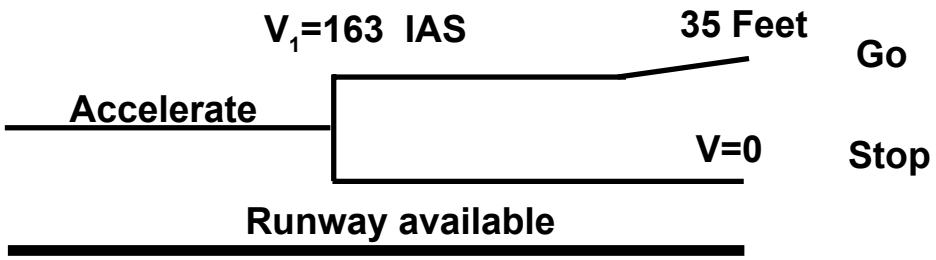
WEIGHT REDUCTIONS - 1000 kg

Dry Field /Obstacle Limit Weight 1000 kg	0.25 in (6 mm) Slush/Standing Water Depth			0.50 in (13 mm) Slush/Standing Water Depth		
	Airport Pressure Altitude			Airport Pressure Altitude		
	S. L.	4000 ft	8000 ft	S. L.	4000 ft	8000 ft
35	0.0	0.0	0.0	0.3	0.5	1.0
40	0.0	0.0	0.1	0.8	1.2	2.1
45	0.1	0.2	0.6	1.4	1.9	3.1
50	0.3	0.5	1.1	2.0	2.7	4.2
55	0.5	0.8	1.7	2.5	3.4	5.1
60	0.6	1.1	2.1	3.2	4.3	6.2
65	0.7	1.3	2.3	4.1	5.2	7.2
70	0.8	1.4	2.2	4.9	6.1	8.3

All Engine Slush Takeoff Distance

767-300 - 182,800 kg, V_1 = 163 IAS

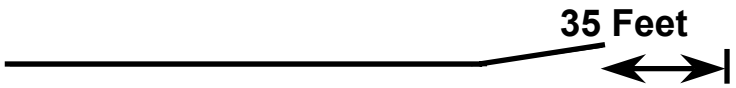
Baseline - AFM balance field length - 9520 Feet



All engine performance - 1/2 inch slush

Slush limit weight = AFM weight - Δ weight slush

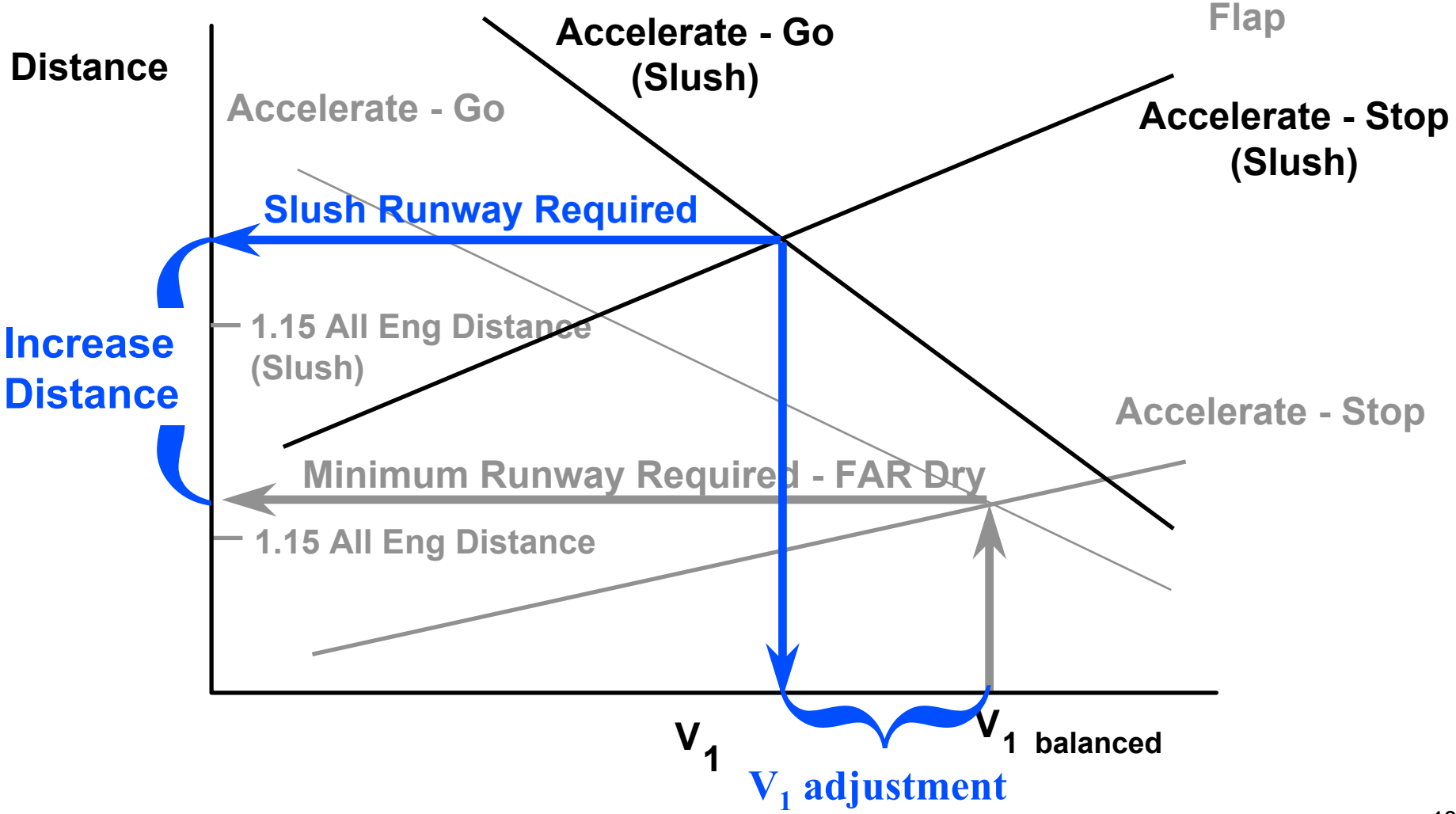
= 182,800 - 3800 = 179,000 kg



Margin 15%

Contaminated Runway Case
Engine Failure Considered

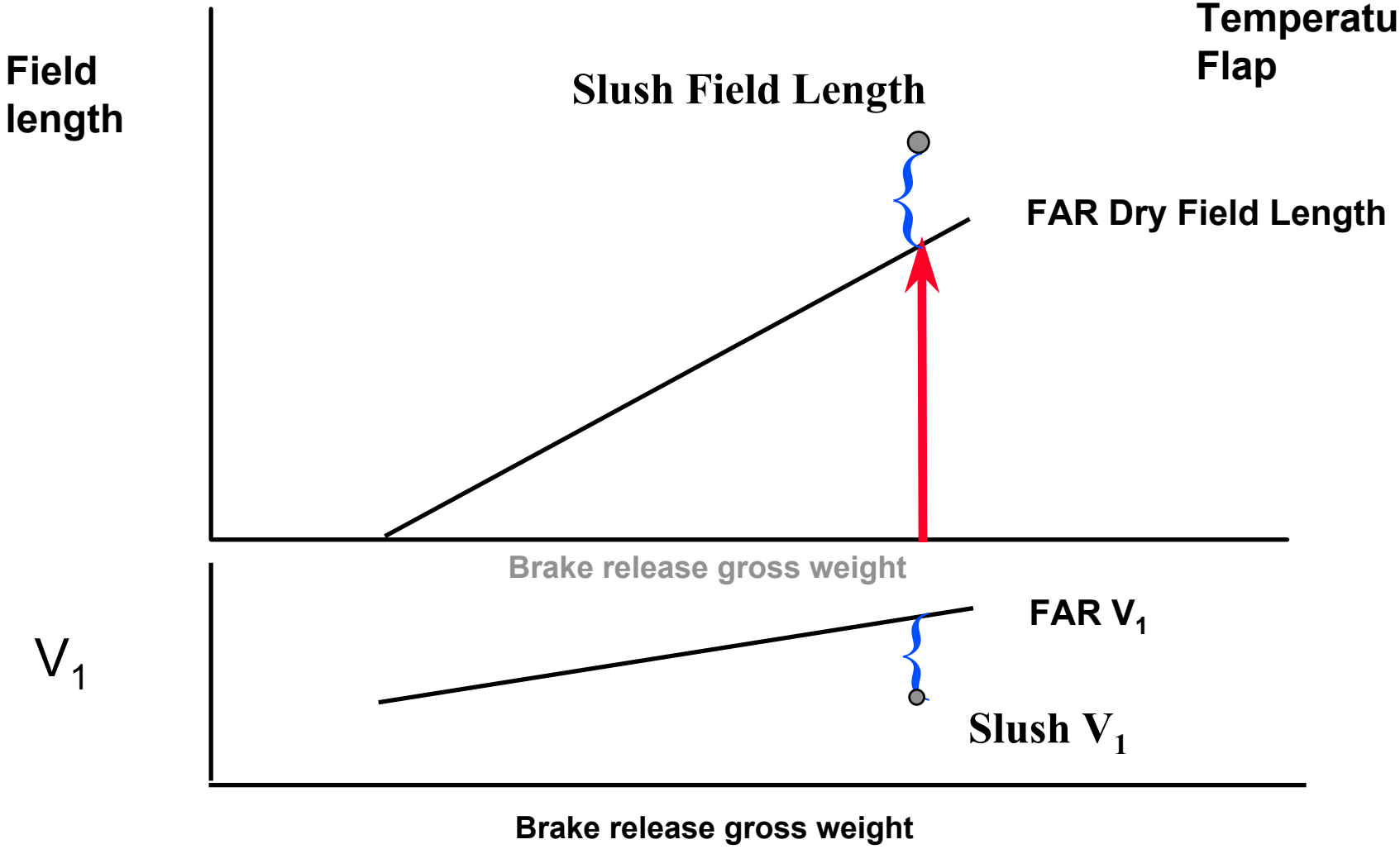
Weight
Altitude
Temperature
Flap



Constant Field Length Weight Reduction and V_1 Adj.

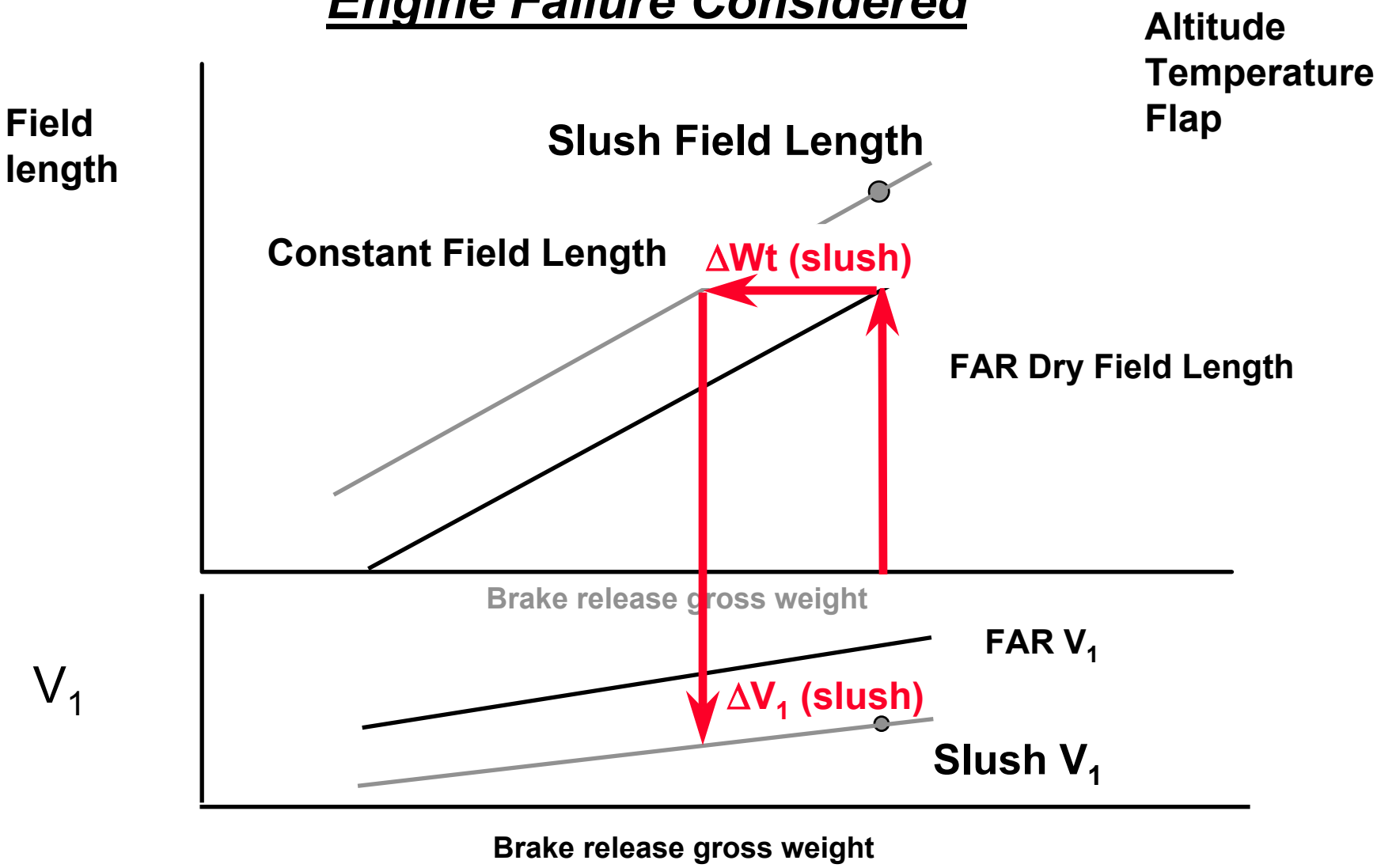
Engine Failure Considered

Altitude
Temperature
Flap



Constant Field Length Weight Reduction and V_1 Adj.

Engine Failure Considered



Sample Ops Manual Slush/Standing Water Data

Engine Failure Considered - 737-500 / 20K Rating

Weight Adjustment (1000 kg)

FIELD/OBSTACLE LIMIT WEIGHT (1000 KG)	6 MM (0.25 INCHES)		
	S.L.	4000 FT	8000 FT
68	-9.4	-10.1	-10.8
64	-8.8	-9.6	-10.4
60	-7.9	-8.8	-9.8
56	-7.1	-8.0	-9.0
52	-6.2	-7.0	-8.1
48	-5.5	-6.1	-7.2
44	-4.8	-5.3	-6.1
40	-4.5	-4.9	-5.3
36	-4.3	-4.8	-4.6

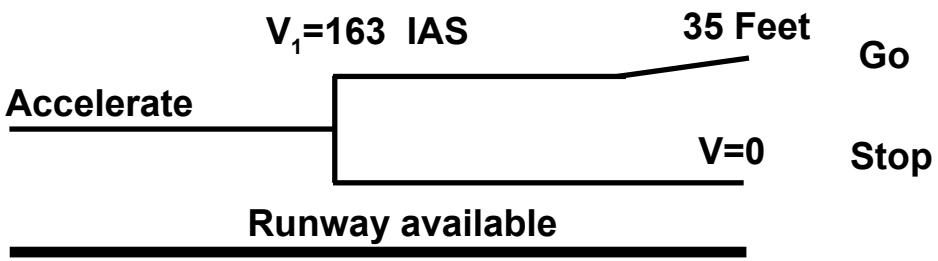
V1 Adjustment (1000 kg)

WEIGHT (1000 KG)	6 MM (0.25 INCHES)		
	S.L.	4000 FT	8000 FT
68	-3	-4	-4
64	-5	-5	-4
60	-7	-6	-5
56	-10	-8	-6
52	-13	-11	-7
48	-16	-13	-8
44	-18	-16	-11
40	-19	-17	-13
36	-19	-18	-15

Engine Out Slush Takeoff Distance

767-300 - 182,800 kg, V_1 = 163 IAS

Baseline - AFM balance field length - 9520 Feet



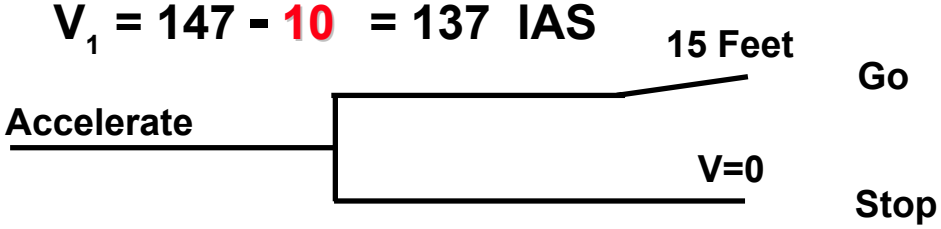
Engine out performance - 1/2 inch slush

Slush limit weight = AFM weight - Δ weight slush

= 182,800 - 28,900 = 153,900 kg

V_1 = QRH V_1 at Actual Weight - ΔV1 Slush

V_1 = 147 - 10 = 137 IAS

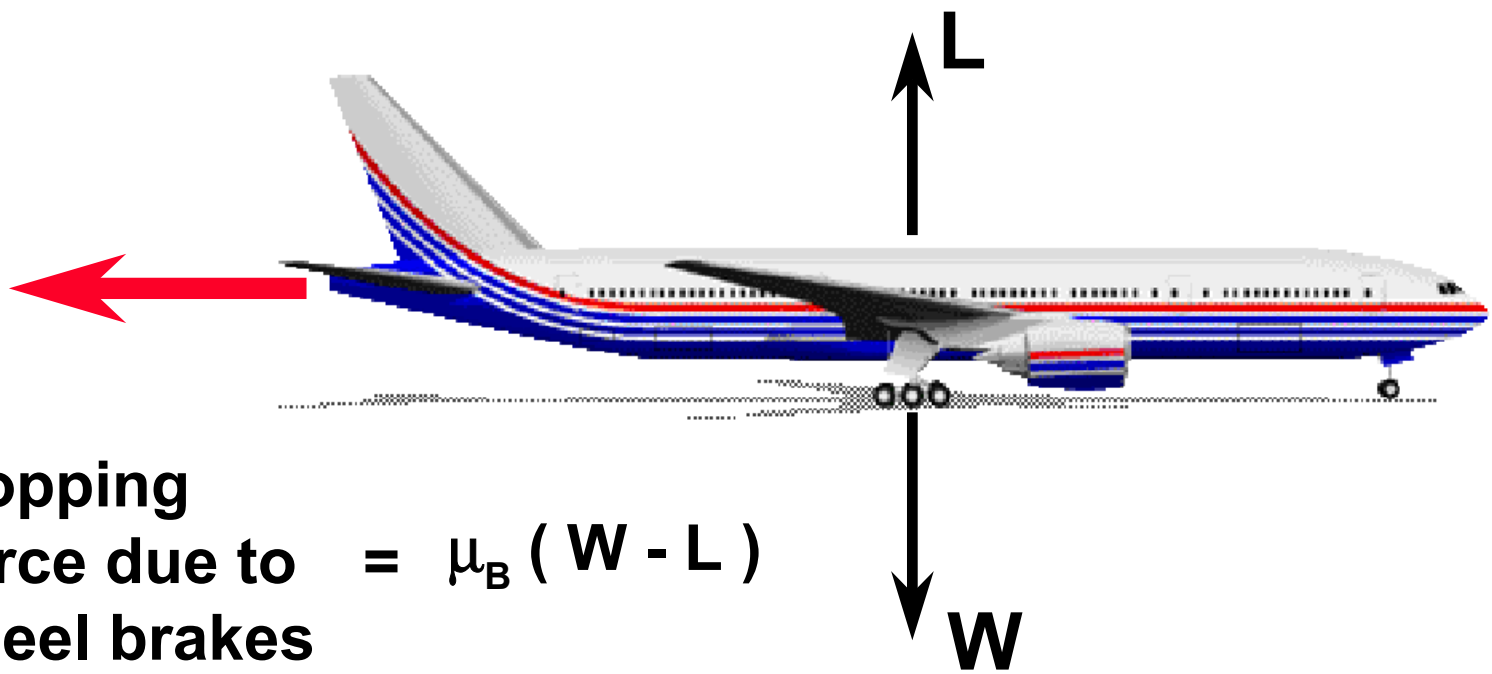


Slippery Runway

(Wet or Icy)

- No effect on acceleration
- All engine - No effect on calculation of all engine takeoff distance
- Accelerate - stop
  - Reduce tire to ground friction
  - Credit for reverse thrust
- Engine out accelerate - go
  - Go to 15-ft screen height

Airplane Braking Coefficient - μ_B



Stopping Force due to wheel brakes = μ_B (W - L)

μ_B = Average ***airplane*** ***braking coefficient*** during the stop

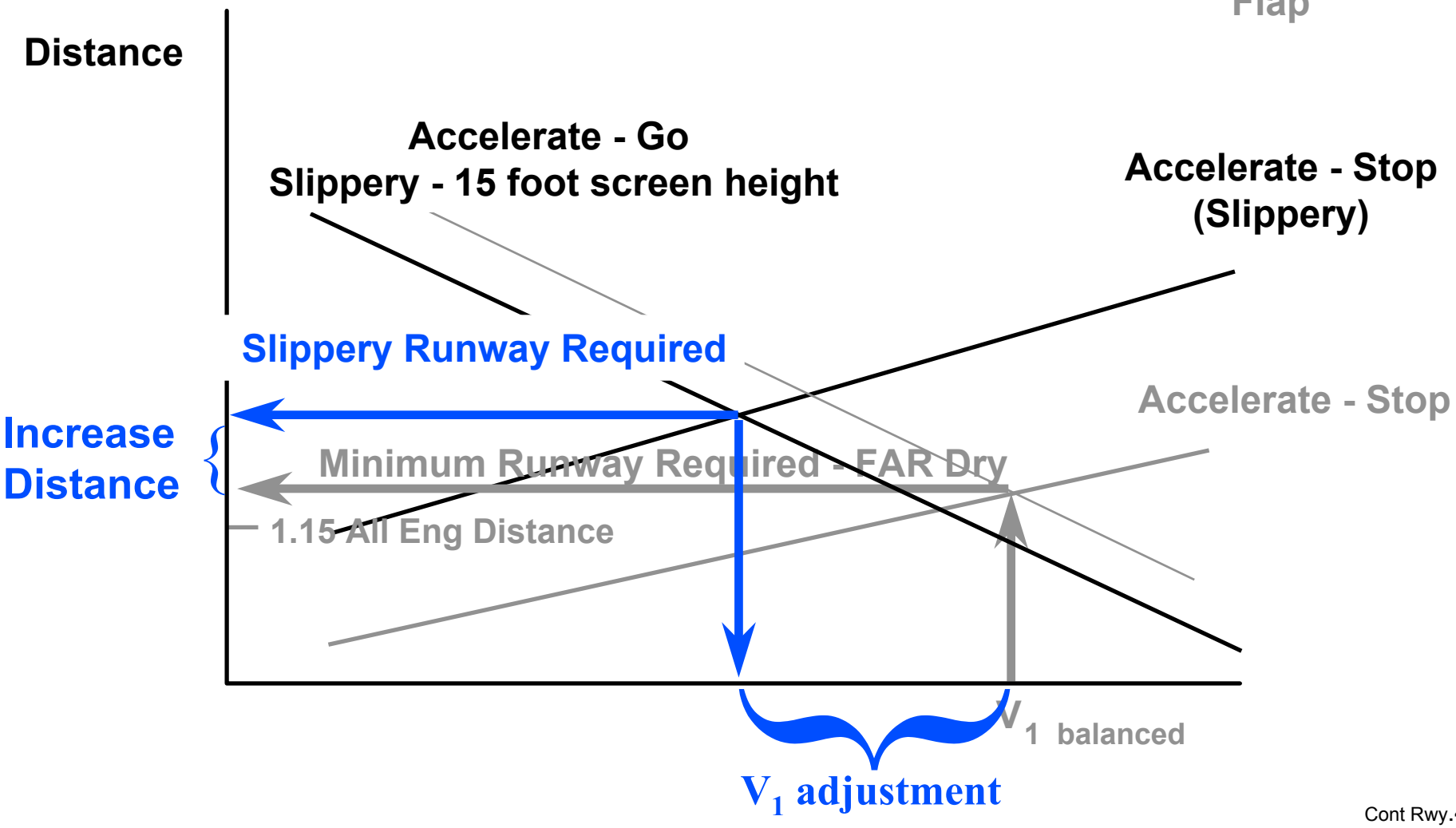
(Note: this is not tire to ground friction)

Airplane Braking Coefficient - μ_B

- Typical dry values from Boeing certification testing
  - μ_B = 0.35 to 0.41
  - Maximum manual braking, anti-skid limited region
- Boeing slippery runway data (PEM/JAROPS 1)
  - RTO - μ_B = 0.05, 0.1, 0.15, 0.2
  - Landing - μ_B = 0.05, 0.1, 0.15, 0.2
- AC 91-6B and AMJ25X1591
  - Wet can be approximated by 1/2μ_B dry max - fair
  - JAR certifications, Compact snow - μ_B = 0.20
  - Wet ice - μ_B = 0.05 - nil

Slippery Runway Case
Engine Failure Considered

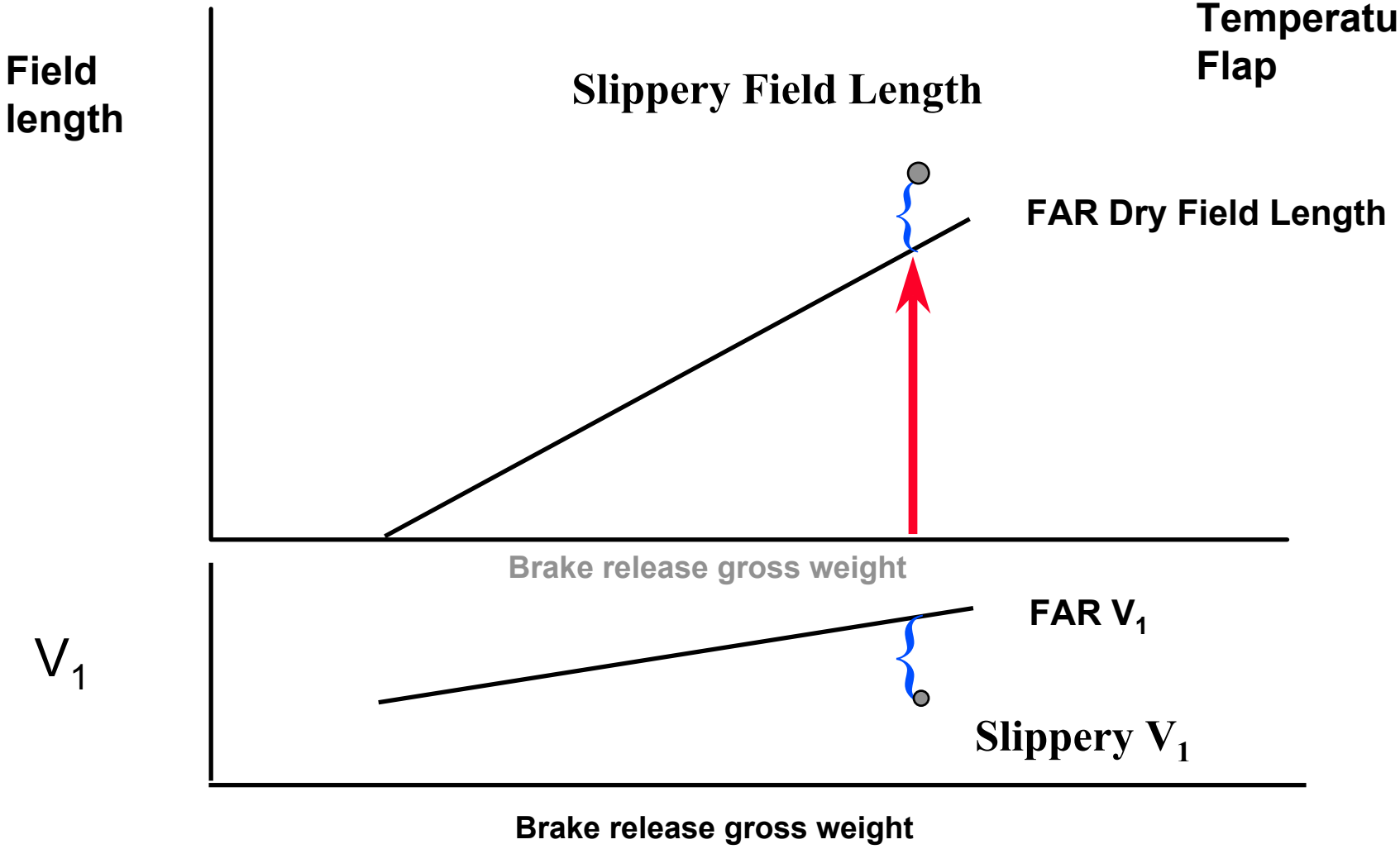
Weight
Altitude
Temperature
Flap



Constant Field Length Weight Reduction and V_1 Adj.

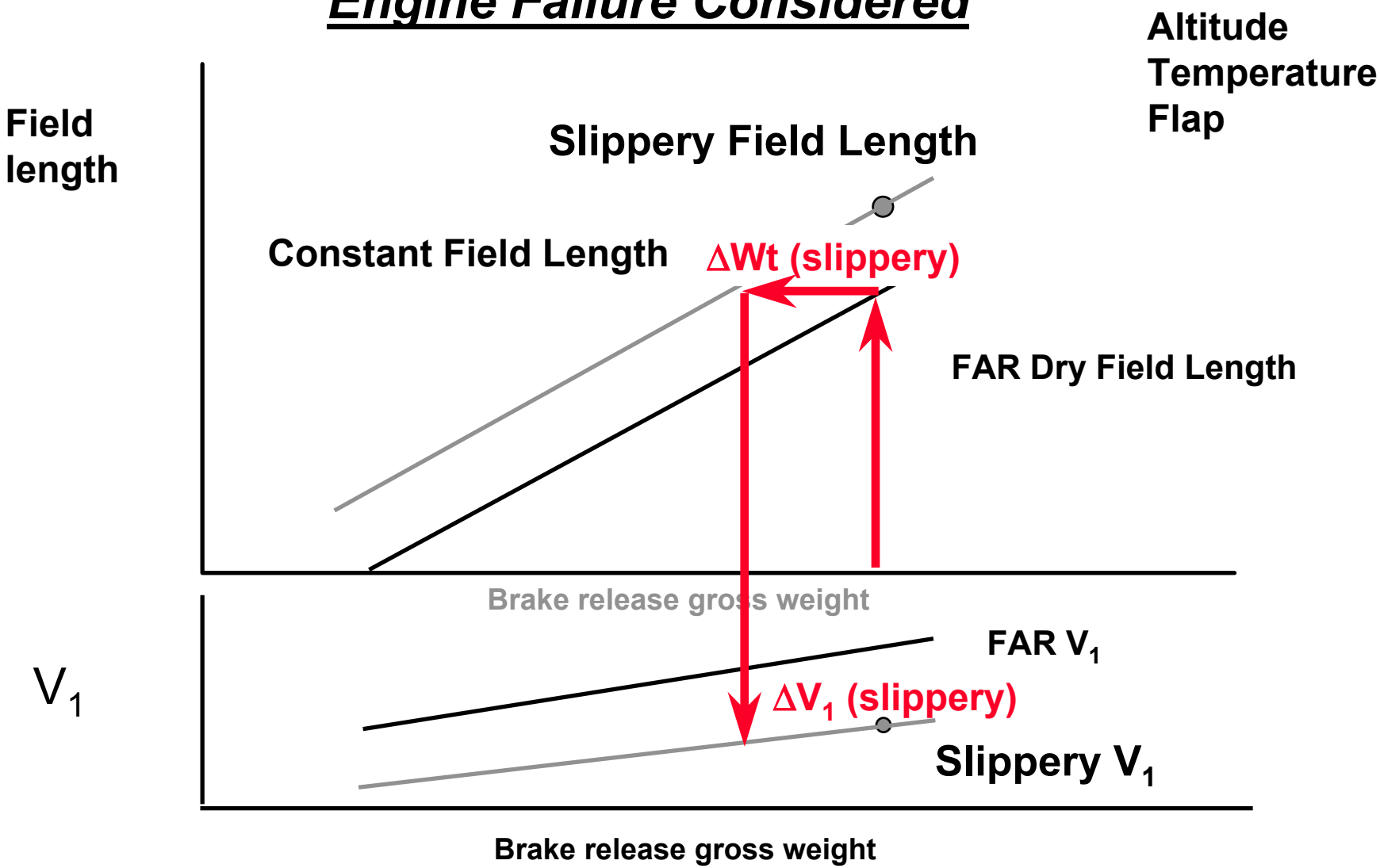
Engine Failure Considered

Altitude
Temperature
Flap



Constant Field Length Weight Reduction and V_1 Adj.

Engine Failure Considered



Slippery Runway

- **Boeing does not correlate "*friction vehicle reported runway friction*" to airplane braking coefficient.**
- **Pilot reported runway braking condition advisory information only**

	Good	Medium	Poor
Assumed Airplane Braking coefficient	0.20	0.10	0.05

Sample Ops Manual Slippery Runway Data

Engine Failure Considered - 737-500 / 20K Rating

Weight Adjustment (1000 kg)

FIELD/OBSTACLE LIMIT WEIGHT (1000 KG)	MEDIUM		
	S.L.	4000 FT	8000 FT
68	-4.1	-4.1	-4.1
64	-4.2	-4.2	-4.2
60	-4.2	-4.2	-4.2
56	-4.1	-4.1	-4.1
52	-3.8	-3.8	-3.8
48	-3.6	-3.6	-3.6
44	-3.6	-3.6	-3.6
40	-3.7	-3.7	-3.7
36	-4.1	-4.1	-4.1

V1 Adjustment (1000 kg)

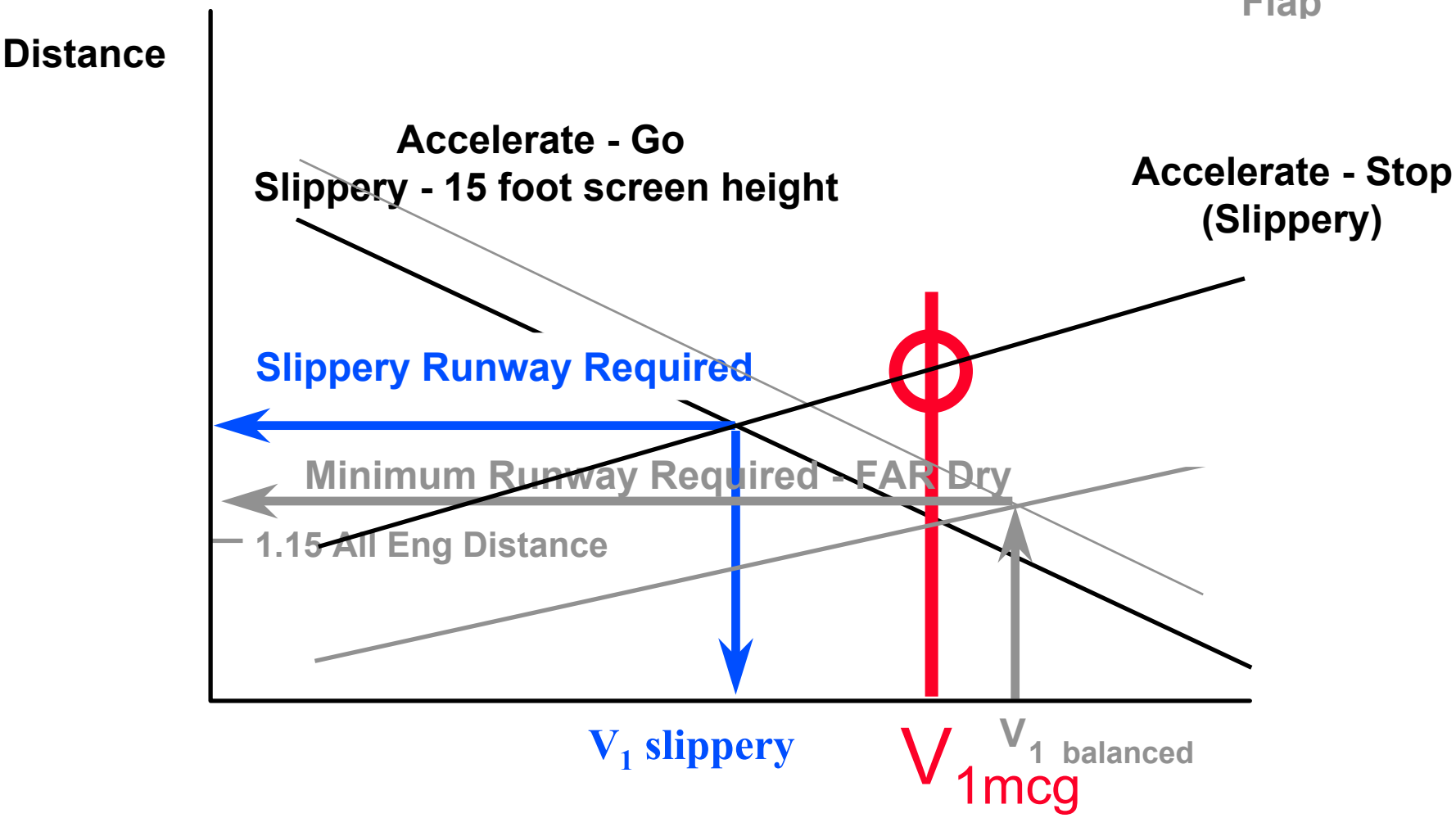
WEIGHT (1000 KG)	MEDIUM		
	S.L.	4000 FT	8000 FT
68	-10	-8	-6
64	-13	-11	-9
60	-15	-13	-11
56	-17	-15	-13
52	-19	-17	-15
48	-21	-19	-17
44	-22	-20	-18
40	-23	-21	-19
36	-25	-23	-21

V_{1MCG} Considerations

V_1 reductions associated with slippery and contaminated runways increases the possibility of being limited by V_{1MCG} considerations.

V_{1mcg} Case

Weight
Altitude
Temperature
Flap



Sample OM Slush/Standing Minimum Field Length Page

737-500 / 20K Rating

V1 = V1(MCG) LIMIT WEIGHT 1000 KG

AVAILABLE FIELD LENGTH FT	6 MM (0.25 INCHES)		
	PRESSURE ALTITUDE		
	S.L.	4000 FT	8000 FT
4200			
4600	30.7		
5000	37.6	28.1	
5400	44.5	33.7	28.1
5800	51.8	39.3	33.1
6200	59.1	44.9	38.1
6600	66.5	51.0	43.1
7000	73.8	57.1	48.3
7400		63.2	53.5

V_{1MCG} Limitation based on *Accelerate - Stop Distance*

- Distance Required to accelerate to a given velocity and stop is less for deeper slush.

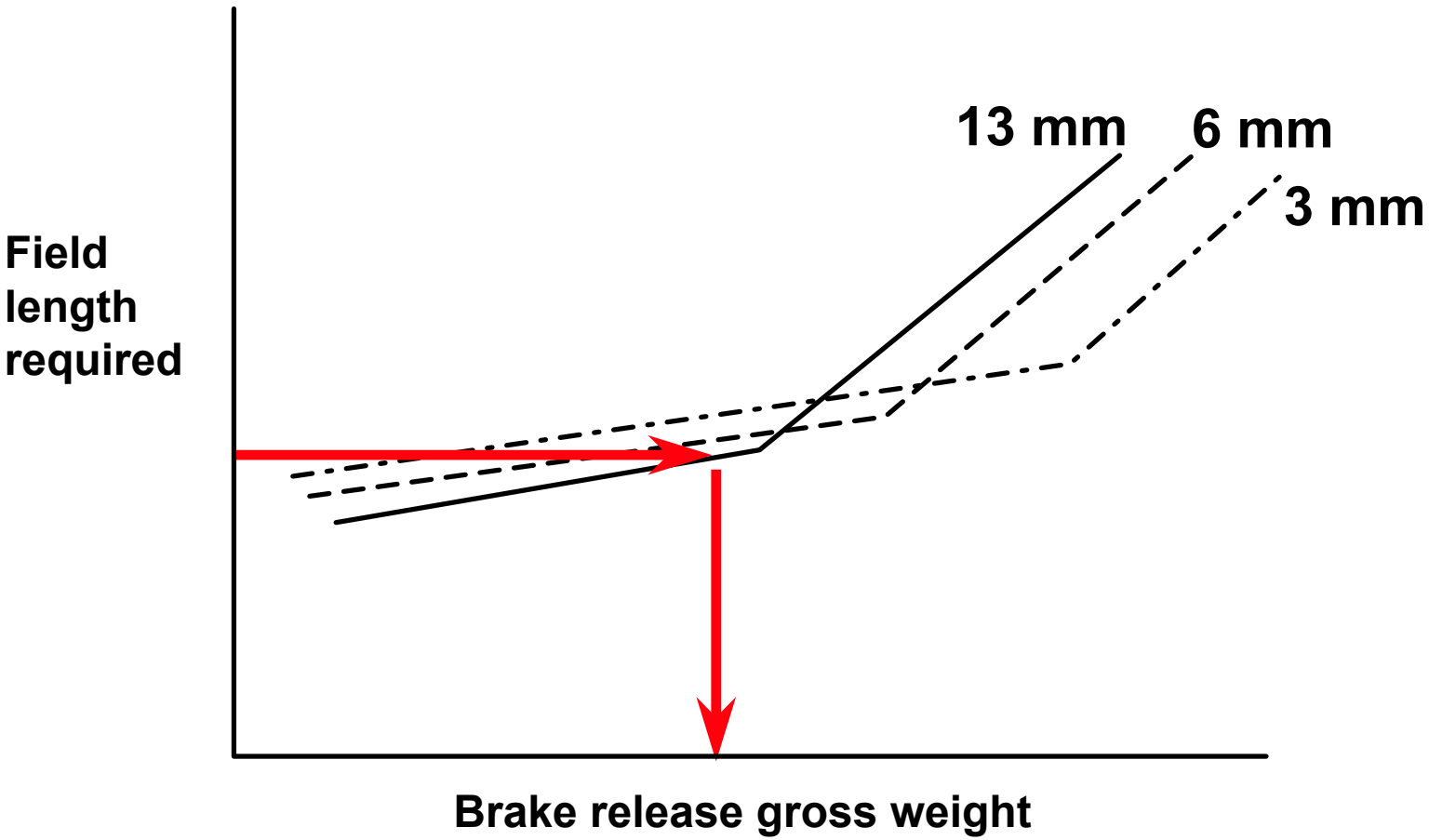
  737-500/20k rating, V_{1mcg} = 109 kias, GW = 52,000 kg

Slush Depth	Accel-stop distance to V1mcg
3 mm	6050 feet
6 mm	5800 feet
13 mm	5600 feet

- This is because the slush drag penalty on the all engine acceleration segment is less than the benefit that the slush drag provides on the stop.

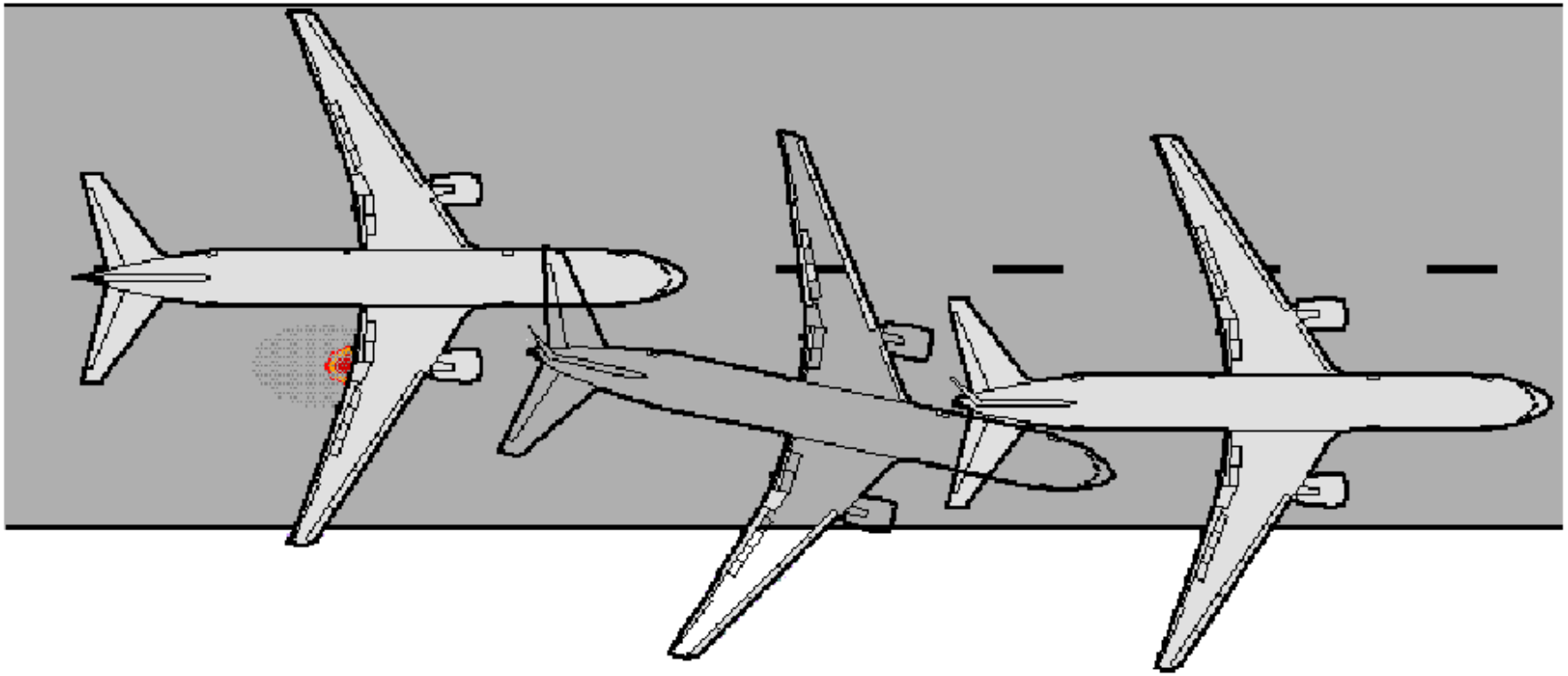
Result - Deeper slush more takeoff weight when limited by V_{1mcg}

V_{1MCG} Speed and Slush

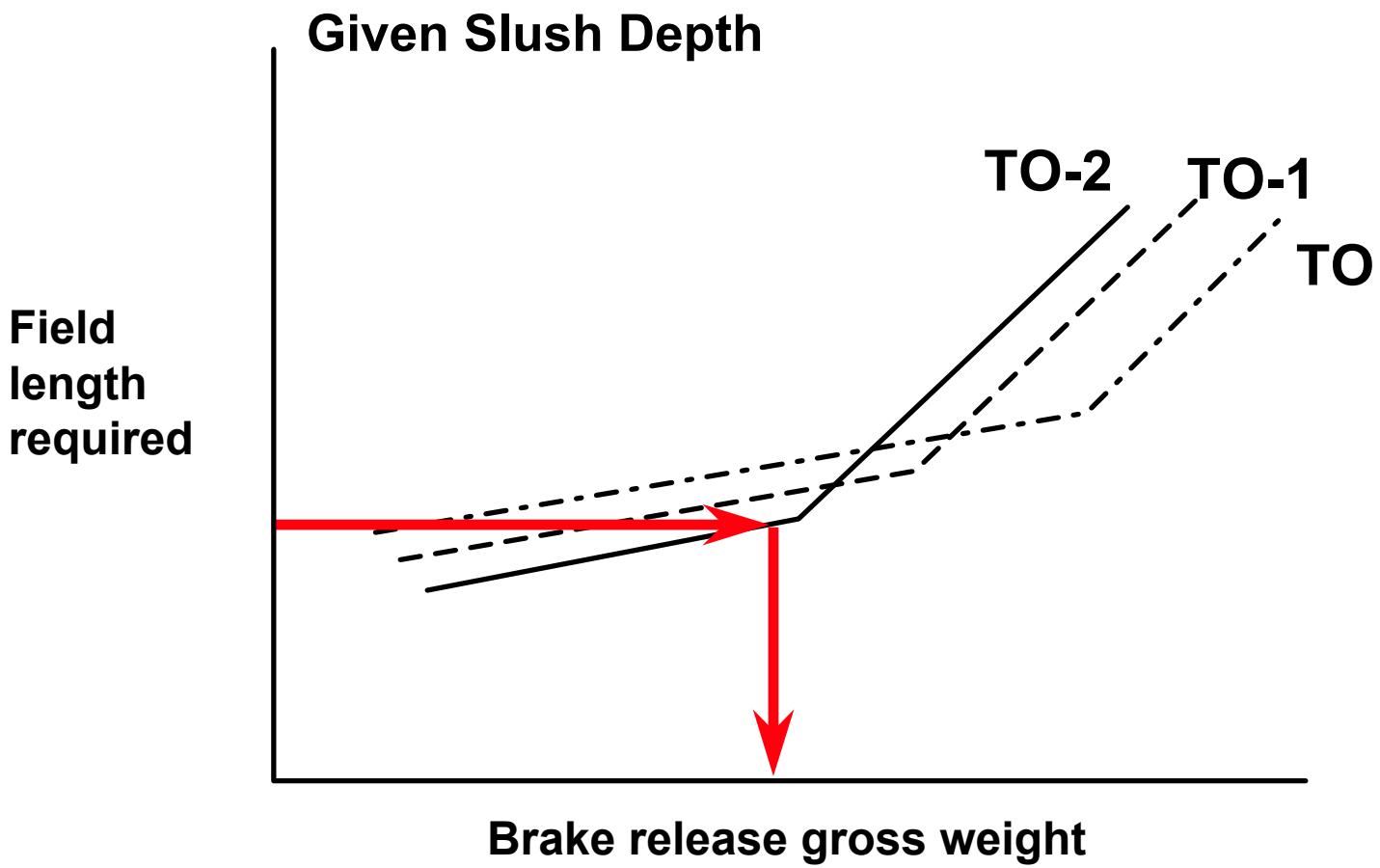


V_{1MCG} Speed, Slush and Derate

Thrust	TO	TO-1	TO-2
V_{1mcg}	126	123	117



V_{1MCG} Speed, Slush and Derate



Agenda:

- Basic Regulations and Definitions
- Physics of Contaminated Runways
- Operational Practice
- Operational Data/Applications
- Other Considerations

Operational Data

Condition: 737- 500
CFM56-3 series @ 20K engines
Runway length available = 6,000 ft
Field/obstacle limit weight = 60,000 kgs
Sea level, 0 C, flaps 5

6 mm (0.25”) of slush

Step 1 - Determine gross weight reduction

Step 2 - Determine V1mcg limit weight

Step 3 - Lowest of step 1 and 2 is limiting weight

Step 4 - Determine V1 at actual takeoff weight

Ops Manual Slush/Standing Water Page

0.25 in (6mm) Slush/Standing Water Depth

Weight Adjustment (1000 kg)

FIELD/OBSTACLE LIMIT WEIGHT (1000 KG)	6 MM (0.25 INCHES)		
	S.L.	4000 FT	8000 FT
68	-9.4	-10.1	-10.8
64	-8.8	-9.6	-10.4
60	-7.9	-8.8	-9.8
56	-7.1	-8.0	-9.0
52	-6.2	-7.0	-8.1
48	-5.5	-6.1	-7.2
44	-4.8	-5.3	-6.1
40	-4.5	-4.9	-5.3
36	-4.3	-4.8	-4.6

Operational Data

Condition: 737- 500
CFM56-3 series @ 20K engines
Runway length available = 6,000 ft
Field/obstacle limit weight = 60,000 kgs
Sea level, 0 C, flaps 5
6 mm (0.25”) of slush

Step 1 - Determine gross weight reduction
60,000 - 7900 = 52,100 kgs

Step 2 - Determine V1mcg limit weight

Step 3 - Lowest of step 1 and 2 is limiting weight

Step 4 - Determine V1 at actual takeoff weight

Ops Manual Slush/Standing Water Page

0.25 in (6mm) Slush/Standing Water Depth

V1 = V1(MCG) LIMIT WEIGHT 1000 KG

AVAILABLE FIELD LENGTH FT	6 MM (0.25 INCHES)		
	PRESSURE ALTITUDE		
	S.L.	4000 FT	8000 FT
4200			
4600	30.7		
5000	37.6	28.1	
5400	44.5	33.7	28.1
5800	51.8	39.3	33.1
6200	59.1	44.9	38.1
6600	66.5	51.0	43.1
7000	73.8	57.1	48.3
7400		63.2	53.5

Operational Data

Condition: 737- 500
CFM56-3 series @ 20K engines
Runway length available = 6,000 ft
Field/obstacle limit weight = 60,000 kgs
Sea level, 0 C, flaps 5
6 mm (0.25”) of slush

Step 1 - Determine gross weight reduction
60,000 - 7900 = 52,100 kgs

Step 2 - Determine V1mcg limit weight
55,450 kgs

Step 3 - Lowest of step 1 and 2 is limiting weight
52,100 kgs, lowest of step 1 and 2

Step 4 - Determine V1 at actual takeoff weight

Ops Manual Slush/Standing Water Page

0.25 in (6mm) Slush/Standing Water Depth

QRH/FMC Dry Runway Takeoff Speeds at 52,100 kgs

132 / 134 / 142
-13

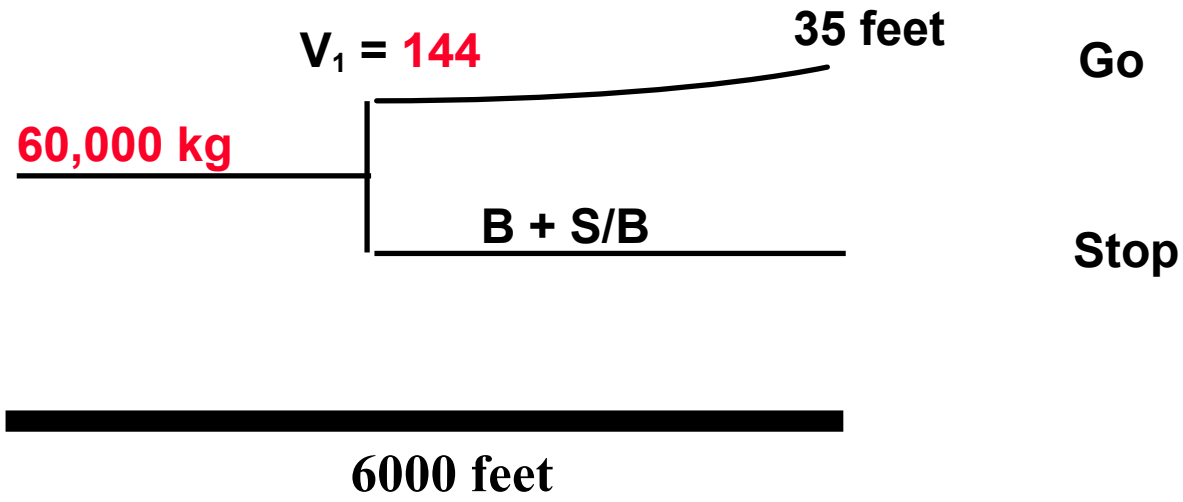
119 / 134 / 142

V1mcg for this condition is 109 kias. Not limiting.

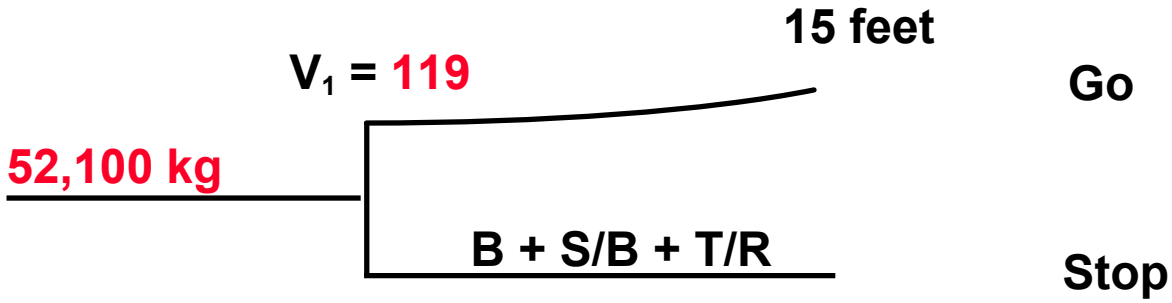
V1 Adjustment (1000 kg)

WEIGHT (1000 KG)	6 MM (0.25 INCHES)		
	S.L.	4000 FT	8000 FT
68	-3	-4	-4
64	-5	-5	-4
60	-7	-6	-5
56	-10	-8	-6
52	-13	-11	-7
48	-16	-13	-8
44	-18	-16	-11
40	-19	-17	-13
36	-19	-18	-15

Dry runway - “normal”



6 mm (0.25”) of slush



Agenda:

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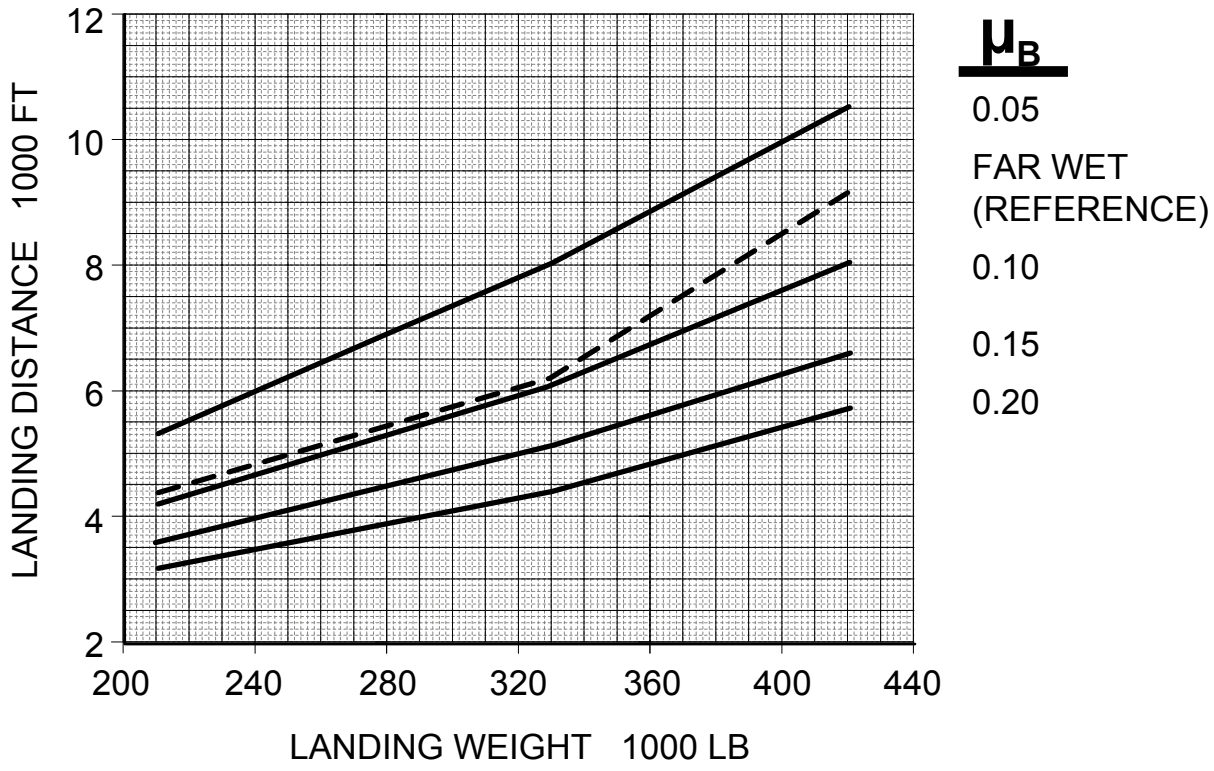
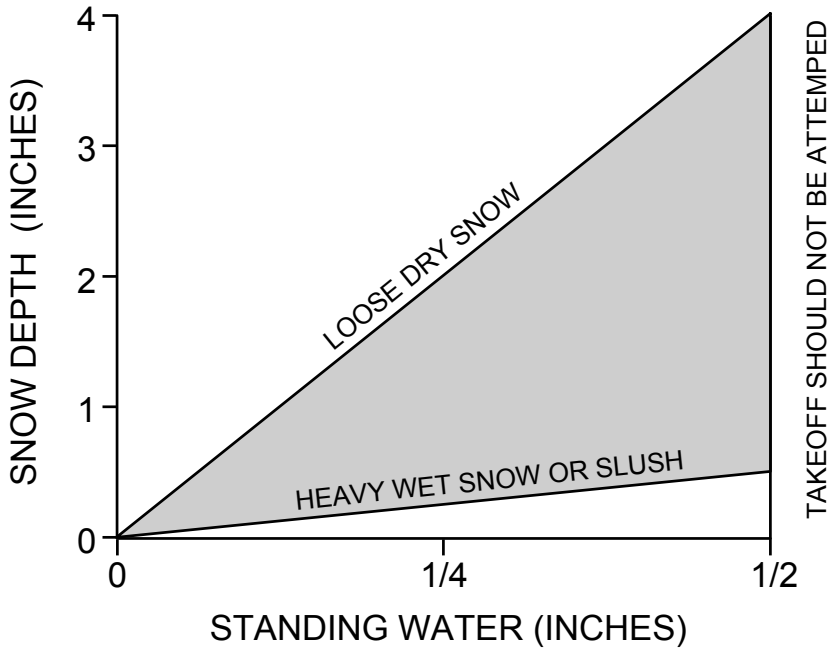
Landing on Slippery Runways

- Touchdown 1,000 ft(1200 for 747) from approach end of runway
- Maximum manual braking
- Reverse thrust
- Data provided for normal or non-normal landing configurations



Snow Equivalencies

As Taken From Draft AC 91-6B



Note: On JAR certified airplanes dry snow takeoff performance is provided as advisory data in the JAR AFM and the operational takeoff program BTM (777, 737 NG)

Crosswind Guidelines

- **Boeing publishes takeoff and landing crosswind guidelines in the *Flight Crew Training Manuals***
  - **Derived from analysis and piloted simulations**
  - **Based on steady winds**
  - **Function of runway condition - dry, wet, standing water/slush, snow - no melting, ice - no melting**
  - **Accounts for asymmetric reverse thrust**
  - **Provides guidance on technique (side slip, crab)**