



# Aircraft Landing Operations on Contaminated Runways



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 **World Aviation Training**  
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# Aircraft Landing Operations on Contaminated Runways

## MOTIVATION

- Almost half of the aviation accidents/incidents can be attributed to approach and landing phase. There is one overrun of a transport category airplane per month worldwide.
- Usually not many fatalities and therefore often not considered too critical.
- Landings on contaminated runways still cause persistent overruns despite all the industry efforts. It requires precise touchdown, good braking and crew effort when fatigue is at the highest. (BTW, how do you simulate fatigue in FSim or FTD?)

# Aircraft Landing Operations on Contaminated Runways

## MOTIVATION

- Landing flare lasts 3-5 seconds (normally). Difficult to teach! Impossible to perform with any consistency. After 10,000+ landings (in airplanes and gliders) I wanted to understand the physics of landing and landing flare better.
- Pilot may not know the real runway surface conditions until too late!
- Conventional “landing” controls (elevator for pitching movement) not best suited for the task.
- The future hypersonic HSCT will have big problem with landings.

# Aircraft Landing Operations on Contaminated Runways

- Nihad E. Daidzic and Juna Shrestha (2008) "*Airplane Landing Performance on Contaminated Runways in Adverse Conditions*", *Journal of Aircraft*, Vol. 45, No. 6, pp. 2131-2144.
- Nihad E. Daidzic and Thomas L. Peterson (2008) "*When go-around is impossible - defining the point of no return*", *Professional Pilot*, December 2008, pp. 110-113.

# Aircraft Landing Operations on Contaminated Runways

## Runway Overrun During Landing

Shuttle America, Inc. (Doing Business as Delta Connection Flight 6448)

Embraer ERJ-170, N862RW

Cleveland, Ohio, February 18, 2007



# Aircraft Landing Operations on Contaminated Runways

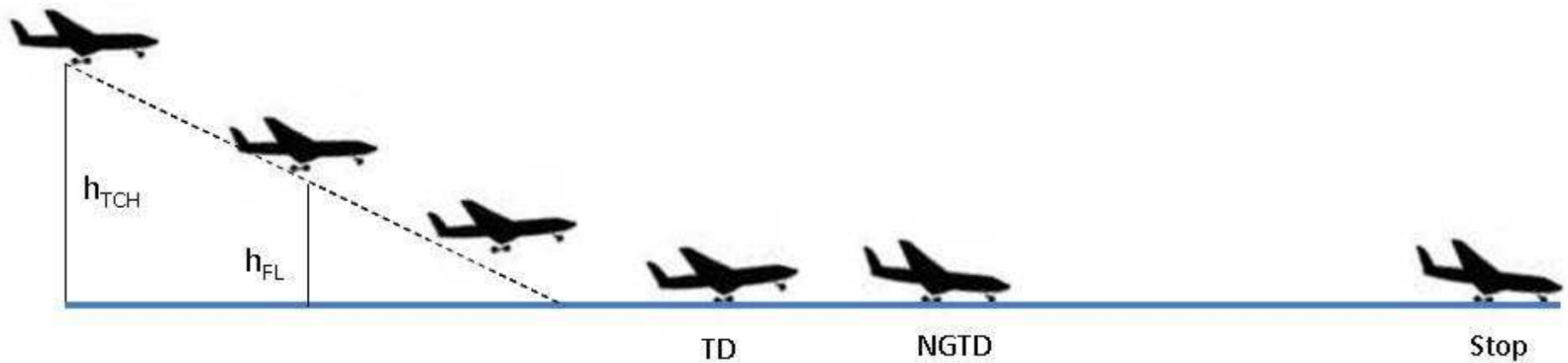


Figure 1: Schematic drawing of the landing maneuver with all important segments (not to scale).

# Aircraft Landing Operations on Contaminated Runways

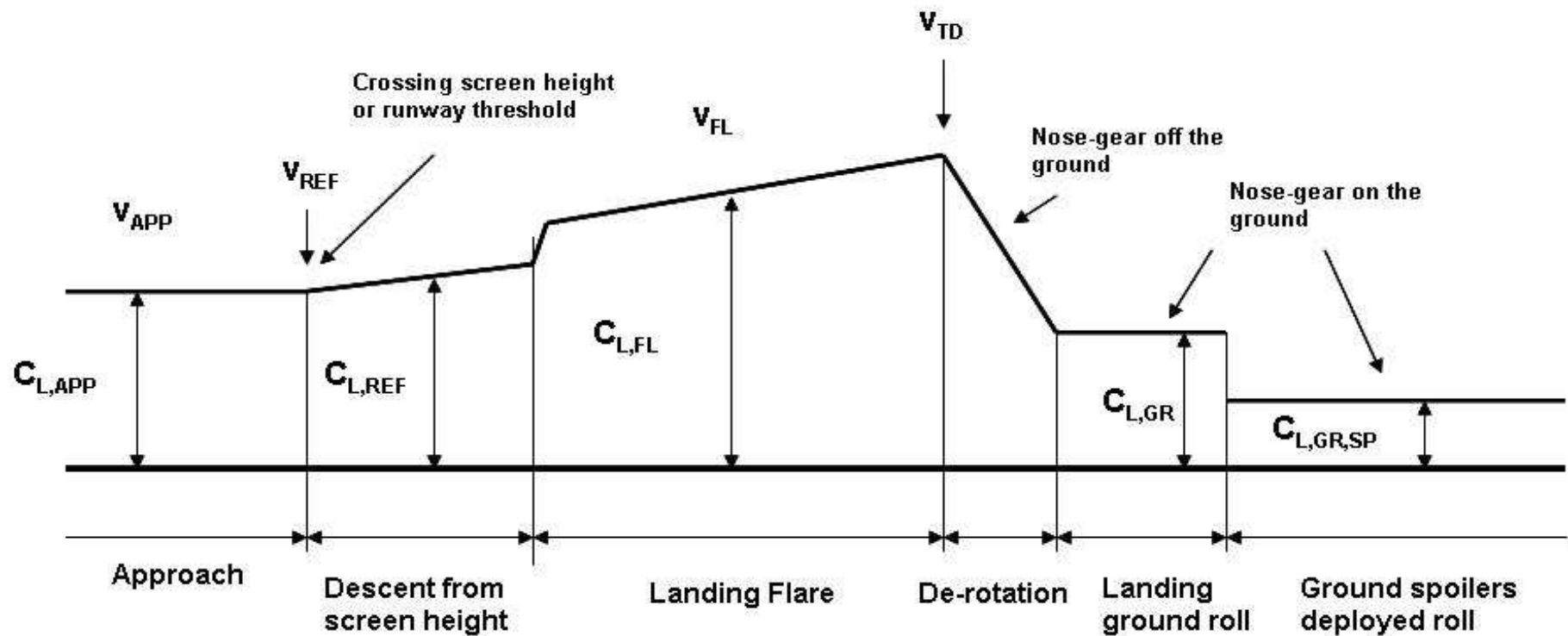


Figure 2: Variation of lift coefficient throughout the landing (not to scale).

# Aircraft Landing Operations on Contaminated Runways

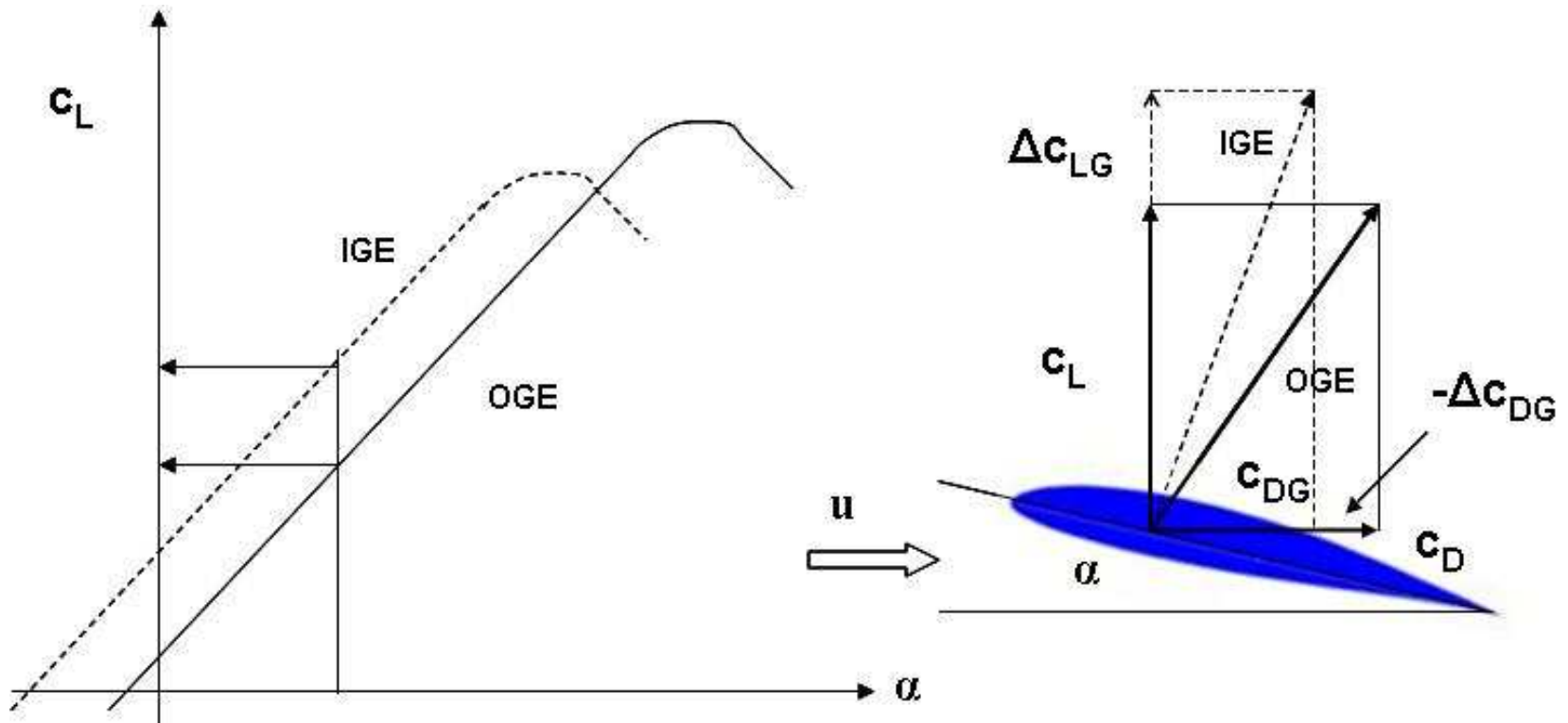


Figure 3: Variation of lift and drag coefficients due to ground effect (not to scale).

# Aircraft Landing Operations on Contaminated Runways



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## Problems in landing-touchdown-rollout

- Contaminated runways (ice, hydroplaning, packed snow, etc.)
- The effect of wind
- Ground Effect
- Adverse Elevator Effect (AEE)
- Judging the flare height and proper flare maneuver
- Threshold crossing altitude deviations
- Proper approach and landing airspeed deviations

# Aircraft Landing Operations on Contaminated Runways

## Various adverse landing conditions are:

- Runway contamination (hydroplaning, ice, snow, slush, etc.)
- Effect of density altitude (higher TAS and GS)
- Effect of wind (tailwind or crosswind, turbulent)
- Zero flap landing (increased KIAS, KTAS and GS)
- Anti-skid and/or brake system malfunction
- Spoiler deployment delay (mechanical, pilot technique)
- Thrust reversers deployment time delay (mechanical, pilot technique)
- Effect of being high over threshold (piloting technique)
- Effect of being fast over threshold and at touchdown (pilot technique)
- Bouncing and ballooning with floating (pilot technique)
- Skid development

# Aircraft Landing Operations on Contaminated Runways

Typical runway surface conditions are:

- Dry asphalt/concrete
- Wet asphalt/concrete (grooved and non-grooved surface)
- Slush asphalt/concrete
- Fresh, loose, or packed snow on asphalt/concrete
- Thin ice on asphalt/concrete

# Aircraft Landing Operations on Contaminated Runways

## Landing Distance Calculator

We developed landing distance calculator that takes into effect the aircraft aerodynamics and performance as well as various runway contaminations, density altitude, and wind effect.

Realistic pilot operations and the time-delayed deployment of deceleration devices is simulated.

# Aircraft Landing Operations on Contaminated Runways

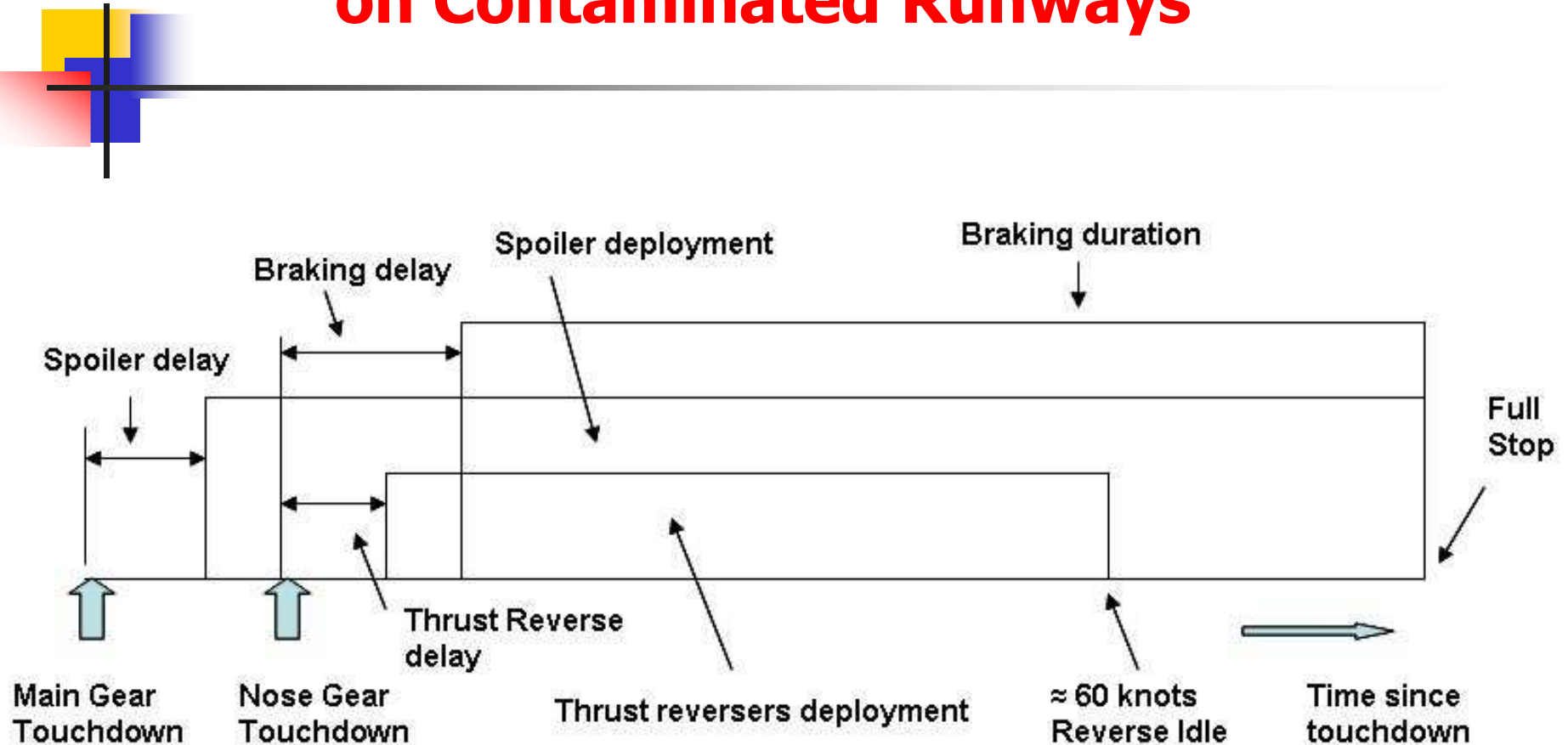
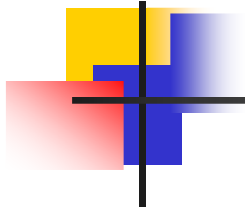


Figure 4: Schedule of ground and flight spoilers (lift-dump system), friction braking and thrust reversers' deployment and re-stowing (not to scale).

# Aircraft Landing Operations on Contaminated Runways



## Model of Flare

$$\ddot{\theta} = \frac{1}{I_{yy}} \cdot (\mathcal{M}_{tail} - \mathcal{M}_{wing} - \mathcal{M}_{pitchdamp} - \dots)$$

$$\ddot{h} = \frac{g}{W} \cdot (L_{wing} - L_{tail})$$

$$\dot{x} = v \cdot \cos \gamma \quad v = \sqrt{\dot{x}^2 + \dot{h}^2}$$

$$\dot{v} = g \cdot \left\{ \left[ \frac{T(h)}{W} \right]_{FL} \cos(\alpha + \delta) - \left[ \frac{D_G(h)}{W} \right] - \sin \gamma \right\} \approx g \cdot \left\{ \left[ \frac{T(h)}{W} \right]_{FL} - \left[ \frac{D_G(h)}{W} \right] - \sin \gamma \right\}$$

$$\dot{\gamma} = \frac{g}{v} \cdot \left\{ \left[ \frac{T(h)}{W} \right]_{FL} \sin(\alpha + \delta) + n - \cos \gamma \right\} \approx \frac{g}{v} \cdot (n - \cos \gamma)$$

$$\dot{\alpha} = \dot{\theta} - \dot{\gamma}$$

$$\dot{s} = v \pm v_w = v_{GS}$$

# Aircraft Landing Operations on Contaminated Runways

Landing Weight LW [lb]	Density Altitude DA [ft]	DLDR Boeing [ft]	DLDR Simulation [ft]	Difference	
				[ft]	[%]
144,000	SL	5380	5432	+52	+0.97
	4000	5890	5795	-95	-1.61
140,000	SL	5230	5291	+61	+1.17
	4000	5710	5658	-51	-0.89
135,000	SL	5025	5120	+95	+1.86
	4000	5510	5442	-68	-1.23
130,000	SL	4820	4902	+82	+2.90
	4000	5310	5254	-56	-1.05

**Table 1: Comparison of DLDR between the original Boeing 737-800 (no winglets) landing data and the simulation results for different weights and density altitudes. Maximum effort anti-skid braking and auto-spoiler operation were simulated. Thrust reversing was not used and the aircraft crossed threshold at reference airspeed.**

# Aircraft Landing Operations on Contaminated Runways

## Boeing 737-800 at MLW of 144,000 lb. (Simulations)

- Reference speed plus 5 knots:  $v_{REF}$  is 142 KIAS
- Full landing flaps and slats
- 3° glidepath angle
- Density altitude 4,000 feet
- Maximum braking anti-skid effort
- Full reverse thrust (40% of max fwd thrust)
- HW 10 knots
- Gear TCH of 40 feet
- Flare height of 24 feet
- Load factor in flare constant at  $n=1.1g$  (pitch rate 0.81 deg/s).
- No float, three seconds to lower the nose gear
- Zero seconds in spoiler delay, three seconds in reverse thrust delay, and five seconds delay in maximum braking effort after the nose gear touchdown.
- Idle reverse was commanded at 60 KIAS
- Average RWY downhill slope was 1%, and 7,000 ft long runway was used.

# Aircraft Landing Operations on Contaminated Runways

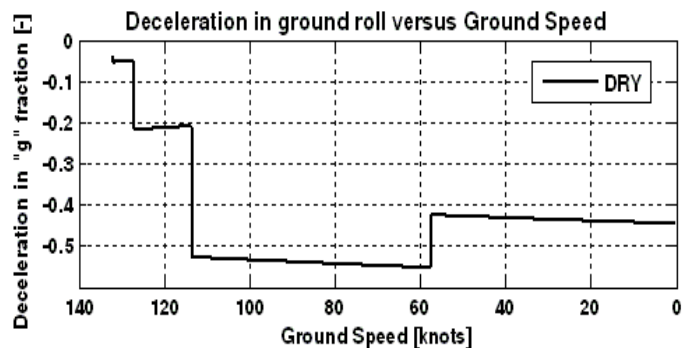
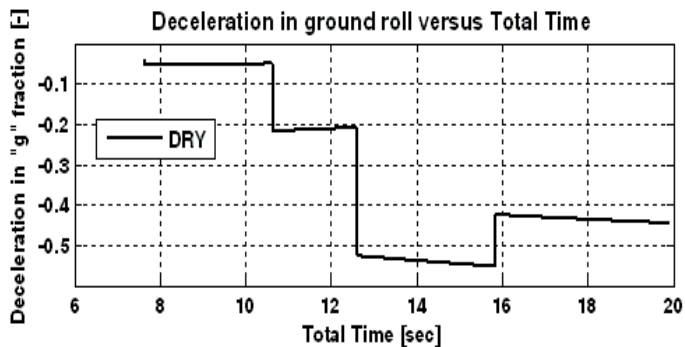
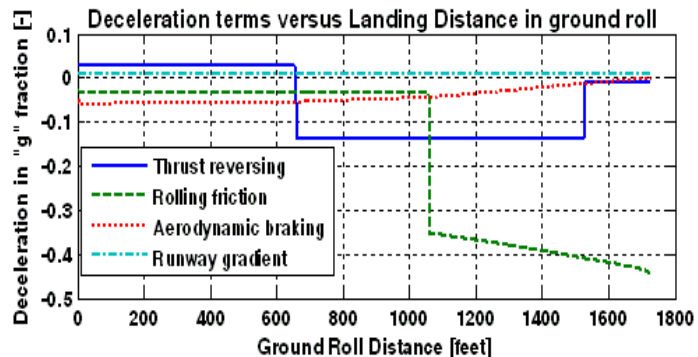
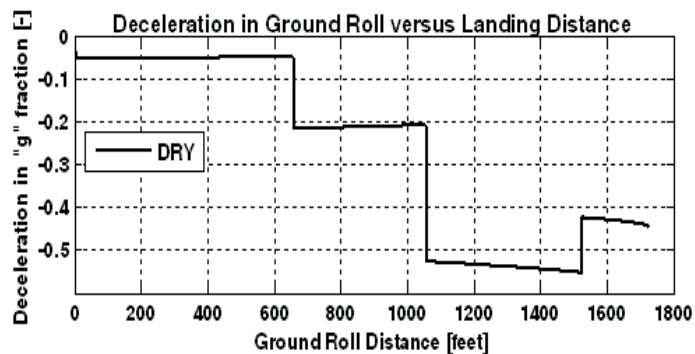
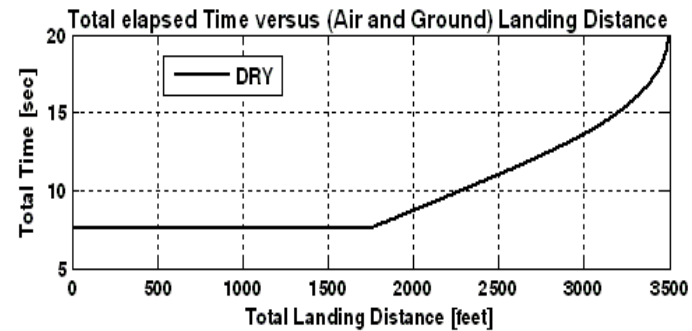
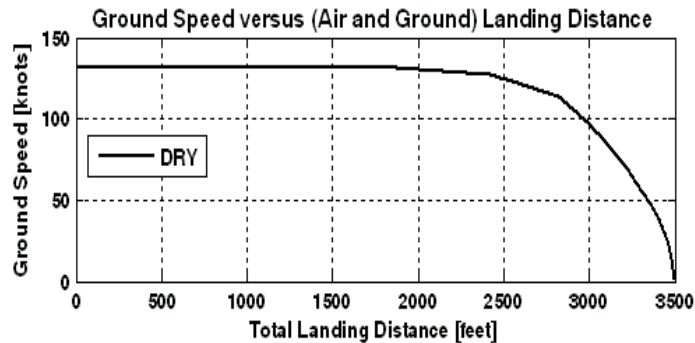
- In all instances, the air distance to main gear touchdown is 1115 ft.
- Time elapsed from TCH to touchdown is 4.64 seconds.
- Main gear touchdown occurred at 138 knots and the nose gear touched down 3 seconds later at the GS of 132 knots, during which the airplane consumed additional 653 feet of runway (1768 ft total until NGDN).
- The ROD at touchdown was firm and safe 96 fpm (1.6 fps) and the total distance (air plus ground) to stop was 3496 feet for dry runway.
- The FAA required landing distance (from Boeing references) is 5890 feet for dry and 6774 for wet-factored runway. These are zero-wind values! Using the FAA mandated 50% of headwind distance correction (Title 14 CFR 25) would result in shorter DLDR and WLDR. The LDA of 7,000 feet should be then quite satisfactory in both cases.

# Aircraft Landing Operations on Contaminated Runways

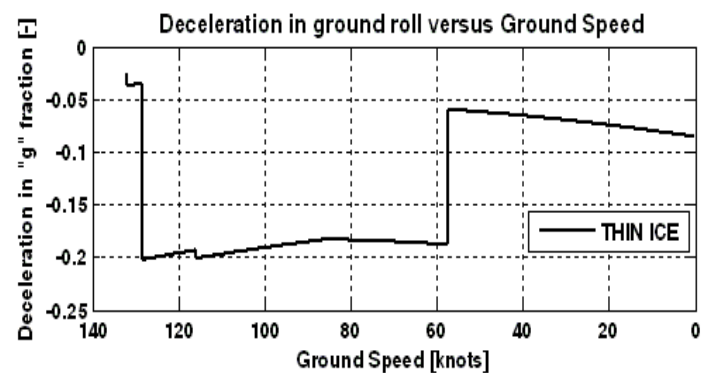
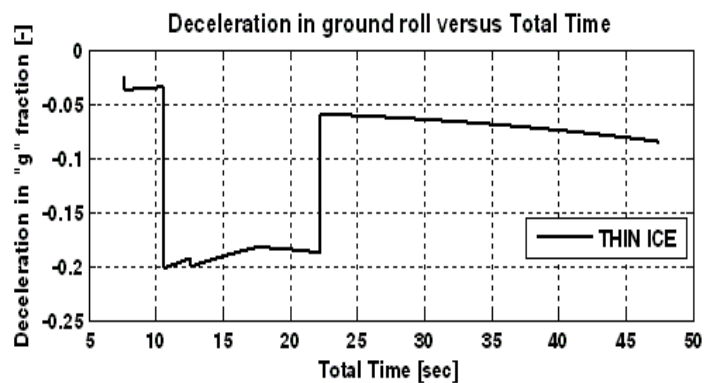
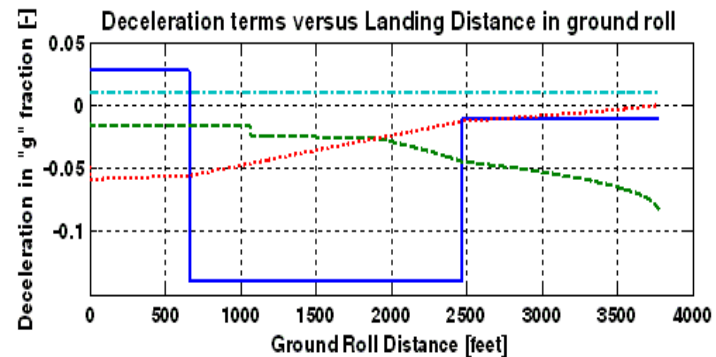
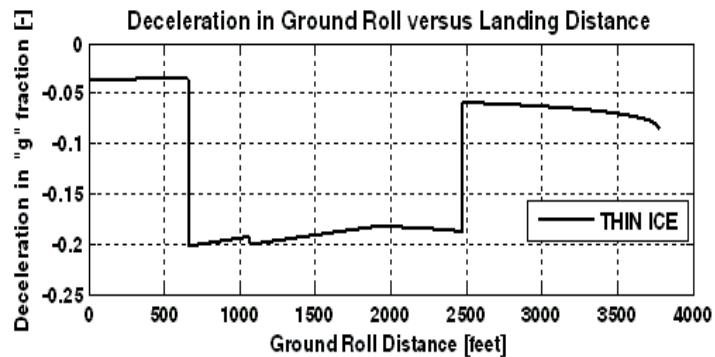
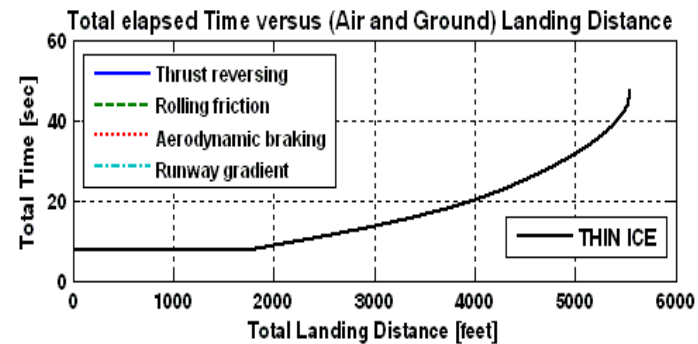
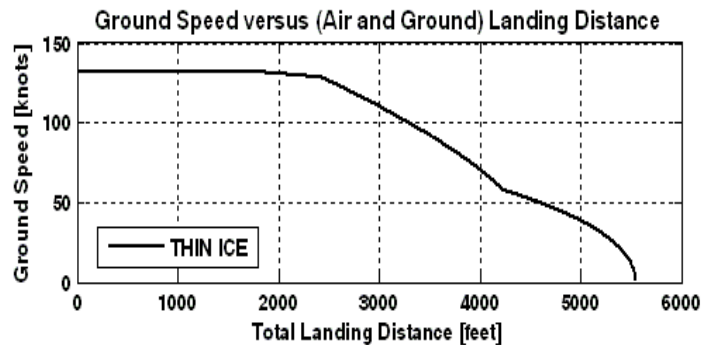
Runway LDA=7000 ft	Dry	Wet grooved	Wet non- grooved	Flooded non- grooved	Slush	Dry loose snow (0.5- 3 inch)	Packed snow	Thin Ice
Total landing distance [ft] ±100 ft	3496	3543	4177	4473	3896	4671	4377	5549
Percent increase distance	0	1.33	19.5	27.9	11.4	33.6	25.2	58.7
Time [sec] ±0.67 sec	19.9	20.7	25.4	30.0	23.4	36.8	29.0	47.5

**Table 2: Landing distances (main gear distance), percentage distance increase, and time to stop, over dry runway from TCH to full stop for a Boeing 737- 800 at MLW, and conditions given above. Maximum effort braking and thrust reversing until 60 KIAS is assumed (after that idle reverse). Need to add about 70-100 feet for the nose gear location.**

# Aircraft Landing Operations on Contaminated Runways



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# Aircraft Landing Operations on Contaminated Runways

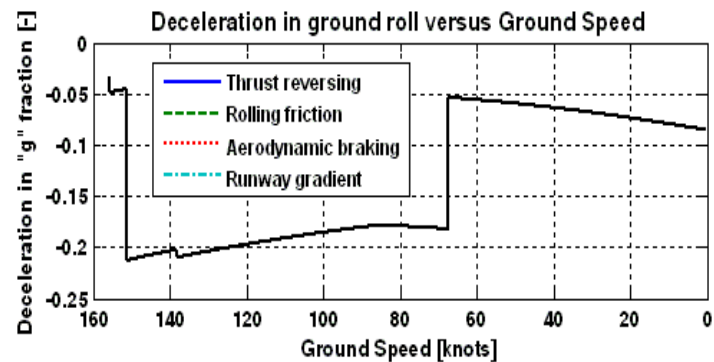
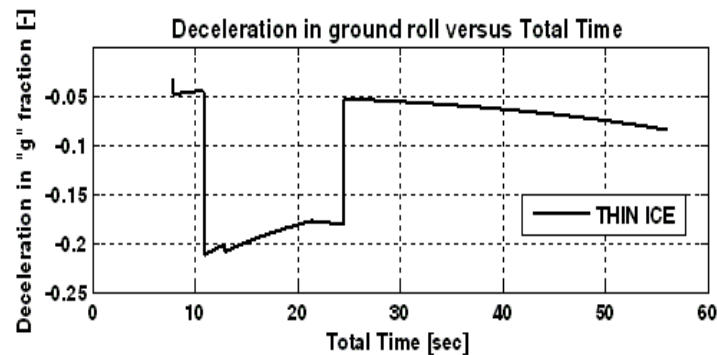
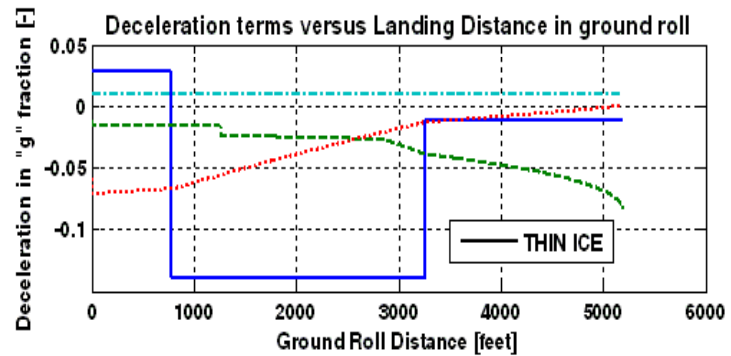
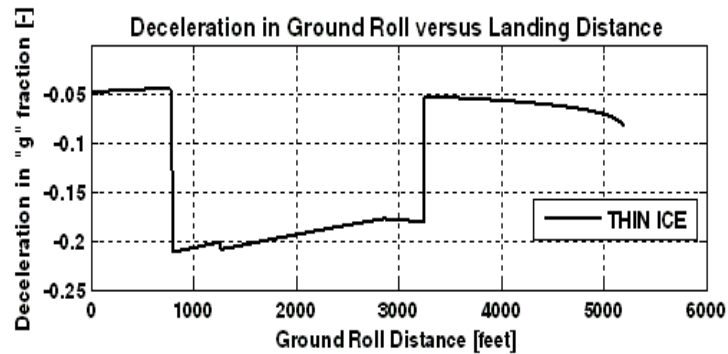
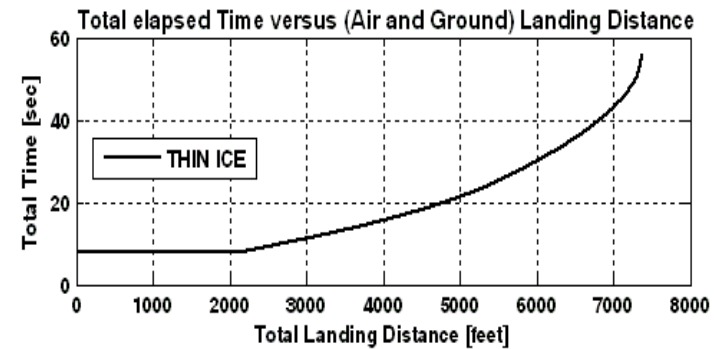
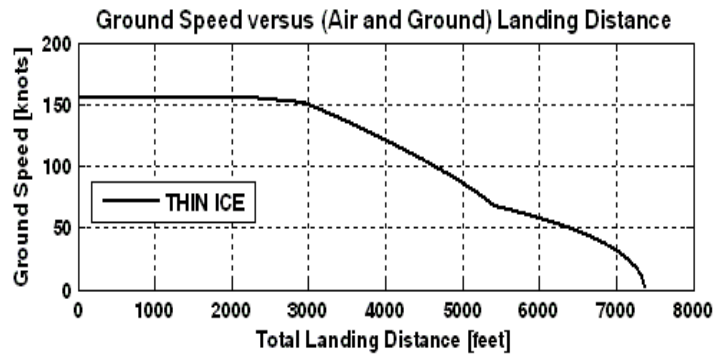
FAA's/JAA's additional 15% "wet-runway" DLDR correction is not always sufficient (simulation example)

- B737-800 at 144,000 lb
- 50 foot TCH
- Reference speed + 20 KIAS (max allowable "wind correction")
- No HW or TW
- Optimal flare height for  $n=1.1g$  was 33 ft.
- Air distance was 1400 feet (4.93 seconds elapsed from TCH)
- Boeing WLDR - 6774 ft.

So how did we do?

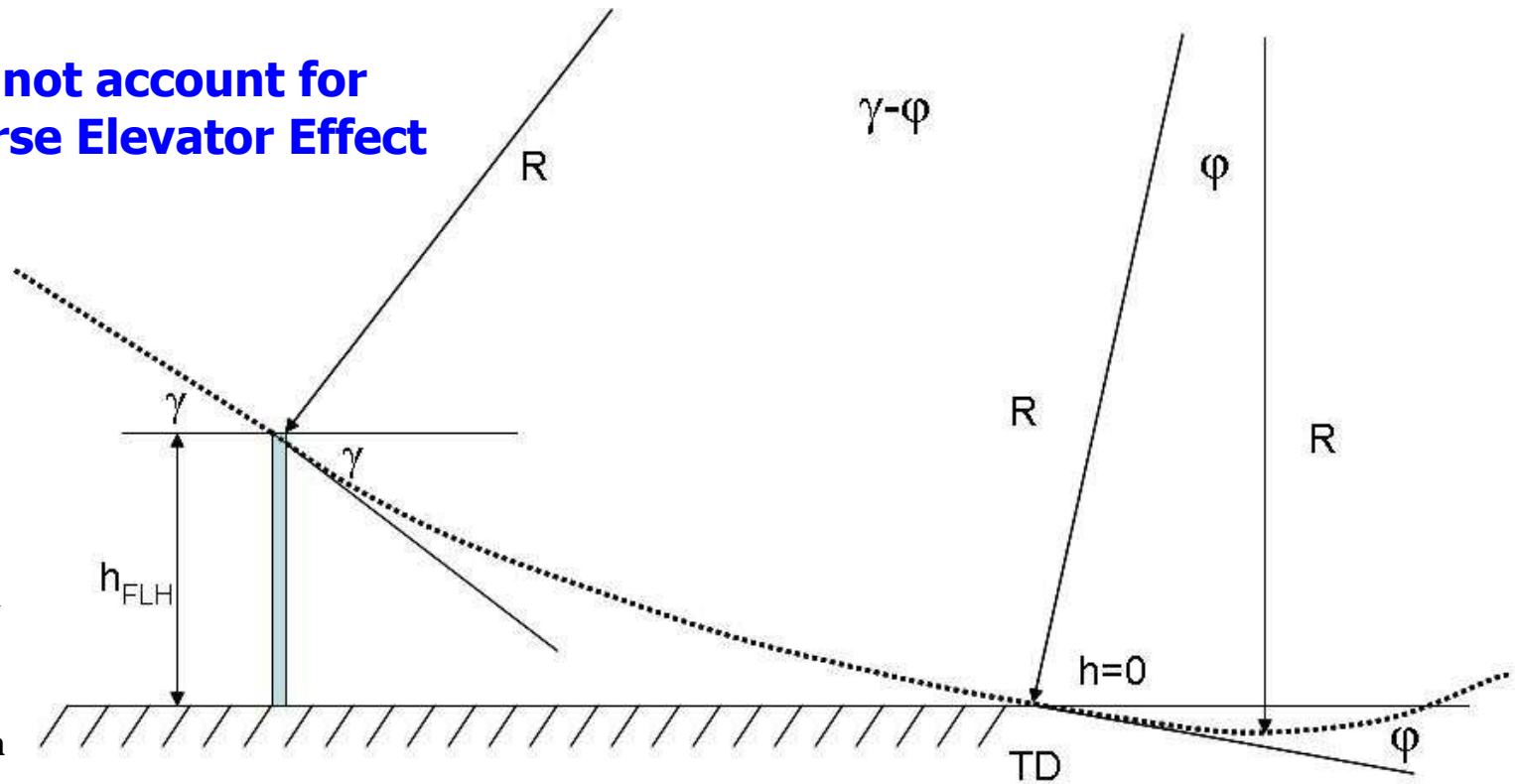
- B737 skidded off the runway end 43 s after TCH at GS of 32 knots. Actual landing distance was 7,369 ft (only LDA=7,000 ft available and 6,774 ft was required) in 56 seconds.

# Aircraft Landing Operations on Contaminated Runways



# Aircraft Landing Operations on Contaminated Runways

Does not account for Adverse Elevator Effect



The optimum flare height (in feet), for  $\gamma = 3$  deg. approach angle, constant normal flight load in flare of  $n_{FL}=1.1$ , and ROD at touchdown not exceeding 1 fps (60 fpm), is:

$$h_{FL}^* = \frac{v_{FL}^2 \cdot \zeta_{FL}^2}{2g(n_{FL} - 1)} \cdot (\gamma_{APP}^2 - \phi_{TD}^2) \approx \frac{v_{FLGS}^2 \cdot \gamma_{APP}^2}{6.5} \approx \frac{(dh/dt)_{APP}^2}{6.5}$$

# Aircraft Landing Operations on Contaminated Runways

ROD <sub>app</sub> [fpm] ([fps]) Touchdown @ <u>60 fpm</u>	Main gear flare height for sustained n=1.1 (pitch rate of 0.8 deg/s)
1000 (16.67 fps)	42.58 ft (13.0 m)
900 (15.00 fps)	34.46 ft (10.5 m)
800 (13.33 fps)	27.20 ft (11.5 m)
700 (11.67 fps)	20.79 ft (6.34 m)
600 (10.00 fps)	15.23 ft (4.64 m)
500 (8.33 fps)	10.53 ft (3.21 m)

$$h_{FL}^* = \frac{ROD_{app}^2 - ROD_{TD}^2}{2 \cdot g \cdot \Delta n_{FL}} \approx \frac{ROD_{app}^2 - ROD_{TD}^2}{6.5} \quad [ft]$$

# Aircraft Landing Operations on Contaminated Runways

ROD <sub>app</sub> [fpm] Touchdown @ <u>120 fpm</u>	Main gear flare height for sustained $n=1.1$ (pitch rate of 0.8 deg/s)
1000	42.12 ft (42.73)
900	34.00 ft (34.62)
800	26.74 ft (27.35)
700	20.32 ft (20.94)
600	14.77 ft (15.38)
500	10.07 ft (10.68)

Only 0.62 feet less than for 0 fpm TCHDN (in parenthesis) and 0.46 ft (5.6 inch or 14.2 cm) less than 60 fpm TCHDN!

**How do you judge this?**

# Aircraft Landing Operations on Contaminated Runways

Touchdown ROD [fpm] ROD <sub>app</sub> [fpm] = 600 fpm (10 fps or 3.05 m/s)	Main gear flare height for sustained $n=1.1$ (pitch rate of 0.8 deg/s) Flare delay time [ms]
0 (greaser)	15.38 ft (0)
100	<b>14.96 ft (42 ms)</b>
200	13.68 ft (130 ms)
300	<b>11.53 ft (343 ms)</b>
400	8.55 ft (641 ms)
500	4.7 ft (1030 ms)
600	0 ft (1469 ms)

Misjudge your flare height by 3.43 ft (reaction delay by 300 ms) and you will get hard landing!

**(TCHDN at 300 fpm instead of 100 fpm)!**

# Aircraft Landing Operations on Contaminated Runways

Radar/radio altimeter (E/GPWS) is only  $\pm 2$  feet accurate (at best) with the instrument scale resolution of 5 feet, and the altitude callouts are 50, 40, 30, (20), and 10 feet.

Pilot does not have the altitude/height resolution to judge the right moment to flare. Flare is done by “feel”.

**So a lot depends on luck!**

# Aircraft Landing Operations on Contaminated Runways

Small changes in ROD cause “large” changes in flare height:

$$\frac{\Delta h_{FL}}{h_{FL}} = \frac{2 \cdot \Delta ROD_{APP}}{ROD_{APP}} \quad [-]$$

$$ROD_{APP} = 600 \text{ fpm (10fps)} \quad \Delta ROD_{APP} = \pm 60 \text{ fpm (1 fps)}$$

$$\frac{\Delta ROD_{APP}}{ROD_{APP}} = \pm 0.1 \text{ (10\%)}$$

$$\frac{\Delta h_{FL}}{h_{FL}} = 0.2 \text{ (20\%)} \quad h_{FL} = 30 \text{ ft} \quad \Delta h_{FL} = \pm 6 \text{ ft}$$

# Aircraft Landing Operations on Contaminated Runways

Horizontal Dispersion on touchdowns is caused by human inability to judge vertical distances accurately (Pinsker). At 40 feet pilot height above landing gear (B747) the error of 15% is  $\pm 6$  feet (uncertainty: 34 ft to 46 ft).

$$\Delta s_{HD} = \frac{v_{app}}{ROD_{TDN}} \cdot \epsilon \cdot H \quad [ft] \quad \epsilon = 0.1 - 0.15$$

$$\Delta s_{HD} = \frac{230}{2} \cdot 0.15 \cdot 40 = \pm 690 ft \quad ROD_{TDN} = 120 fpm$$

# Aircraft Landing Operations on Contaminated Runways

## Adverse Elevator Effect

Adverse elevator effect (AEE) or negative tail-lift can lead to hard-landings, bounce, ballooning and large dispersion of touchdown point. It can be used beneficially by pilots for more accurate and softer touchdowns if control column is pushed briefly 1-2 seconds before touchdown at 4-5 feet height (e.g., B737). It will also enable faster lowering of the nose gear and provide more than sufficient clearance of the nose gear.

# Aircraft Landing Operations on Contaminated Runways

## Adverse Elevator Effect and DLC

DLC (Direct Lift Control) is an excellent way to minimize adverse elevator effect (AEE) and provide  $\pm 0.1g$  vertical acceleration (with minimal adverse pitch changes) for better glide-path control without delays and adverse tail-lift using elevator only. Also minimizes the risk of bounce and ballooning and provides better TCHDN control (e.g., L-1011). Gliders use it ALL the time on landing.

# Aircraft Landing Operations on Contaminated Runways

## The problem with Landing rules-of-thumb

- ❑ The landing rules-of-thumb require, for e.g., to add 1% of landing roll for each weight increase of 1%.
- ❑ They also imply to add 2% to ground roll for every 1% increase of speed above appropriate.
- ❑ These rules are inappropriate for the case when we have several adverse conditions (acting simultaneously), where we can not simply add the individual contributions. Also for larger deviations from the nominal the rules-of-thumb are becoming increasingly inaccurate because they are based on small linear perturbations from steady states.

# Aircraft Landing Operations on Contaminated Runways

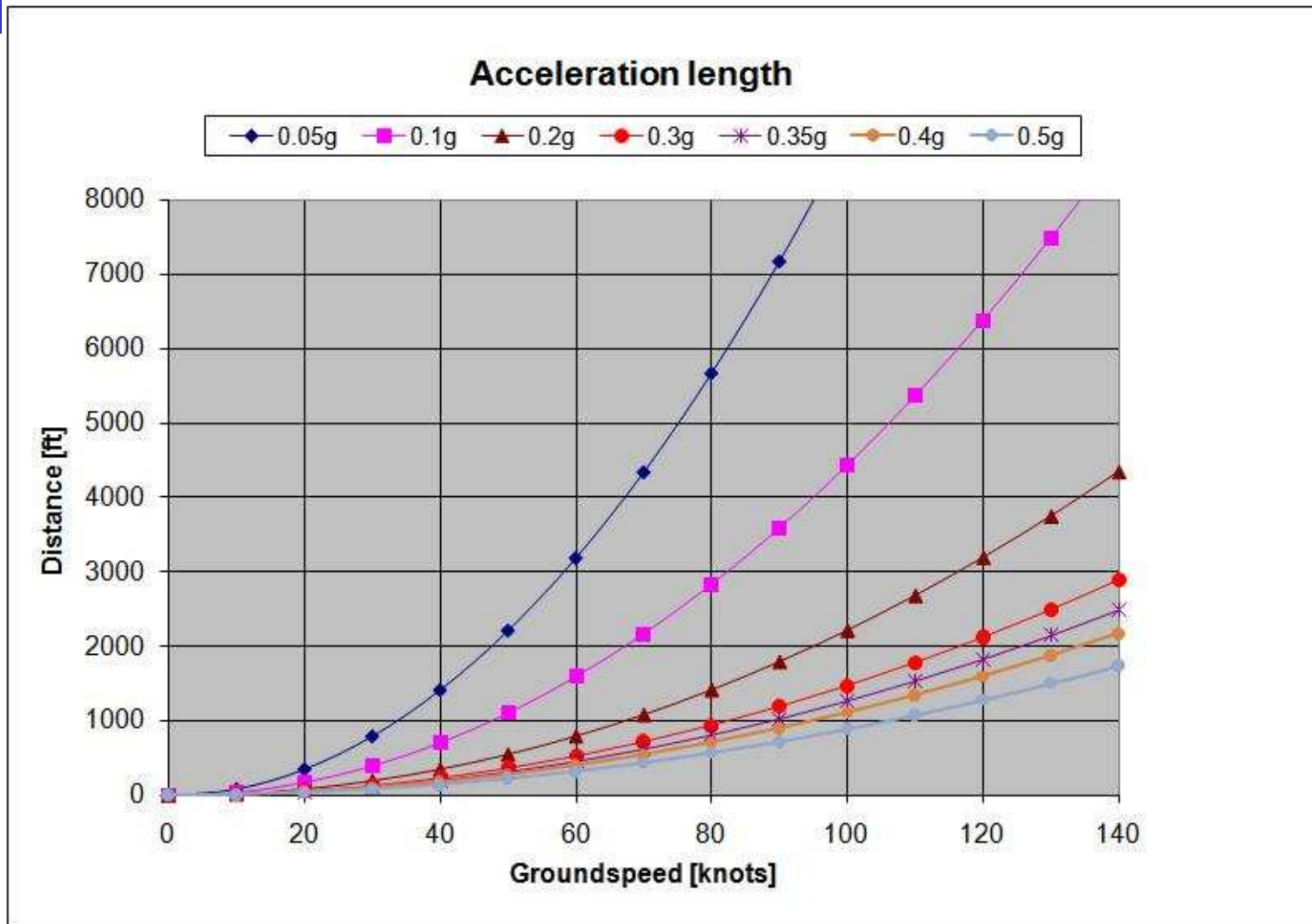
## The problem with Landing rules-of-thumb

The distance required to stop the aircraft on the ground is proportional to the kinetic energy that needs to be dissipated and is a consequence of the law of the conservation of kinetic energy. Brakes (Friction), Reverse Thrust, Upslope and Aerodynamic drag all work together to slow down the aircraft.

$$s_{ROLL} \propto \frac{m \cdot v_{TD}^2}{2} = \frac{W \cdot v_{TD}^2}{2 \cdot g}$$

$$s_{ROLL} = \frac{1}{\mu_{eff}} \frac{v_{TD}^2}{2 \cdot g}$$

# Aircraft Landing Operations on Contaminated Runways



# Aircraft Landing Operations on Contaminated Runways

## The problem with Landing rules-of-thumb

The rules-of-thumb are based on the linear analysis using small perturbations around the nominal point:

$$\frac{\Delta s}{s} \approx \left( \frac{\partial s}{\partial W} \right)_v \frac{\Delta W}{s} + \left( \frac{\partial s}{\partial v} \right)_W \frac{\Delta v}{s} = \left( \frac{\Delta W}{W} \right) + \left( \frac{2\Delta v}{v} \right)$$

This is where 1% for weight and 2% for speed correction come from.

# Aircraft Landing Operations on Contaminated Runways

## The problem with Landing rules-of-thumb

However, the nonlinear change will result in coupling terms which cannot always be neglected:

$$\frac{\Delta s}{s} \propto \frac{(W + \Delta W) \cdot (v + \Delta v)^2}{2 \cdot g}$$

$$\frac{\Delta s}{s} \propto \left( \frac{\Delta W}{W} + \frac{2\Delta v}{v} \right)_{lin} + \left[ \frac{\Delta W}{W} \cdot \frac{2\Delta v}{v} + \left( \frac{\Delta v}{v} \right)^2 + \frac{\Delta W}{W} \cdot \left( \frac{\Delta v}{v} \right)^2 \right]_{nonl}$$

# Aircraft Landing Operations on Contaminated Runways

Individual uncertainty percentage increase	Total linear increase	Total nonlinear increase	Ground roll Required from 5000 DLD [ft]	Difference between linear and nonlinear
W 5%	15%	15.76%	5000	38ft
V 5%			5750	
			5788	
W 5%	35%	38.86%	5000	193 ft
V 15%			6750	
			6943	
W 10%	50%	58.4%	5000	420 ft
V 20%			7500	
			7920	
W 20%	70%	87.5%	5000	875 ft
V 25%			8500	
			9375	
W 20%	100%	135.2%	5000	1760 ft
V 40%			10000	
			11760	

# Aircraft Landing Operations on Contaminated Runways

## The problem with Landing rules-of-thumb

If the weight uncertainty is very small (as it should be in today's modern airliners), the second-order term in speed will cause the overall uncertainty to be larger than for linear change only:

$$\frac{\Delta s}{s} \propto \left( \frac{\Delta W}{W} + \frac{2\Delta v}{v} \right)_{lin} + \left[ \left( \frac{\Delta v}{v} \right)^2 \right]_{nonl}$$

# Aircraft Landing Operations on Contaminated Runways

Individual uncertainty percentage increase	Total linear increase	Total nonlinear increase	Ground roll Required from 5000 DLD [ft]	Difference between linear and nonlinear
W 0%	10%	10.25%	5000	13ft
V 5%			5500	
			5513	
W 0%	20%	21.0%	5000	50 ft
V 10%			6000	
			6050	
W 0%	40%	44.0%	5000	200 ft
V 20%			7000	
			7200	
W 0%	60%	69.0%	5000	450 ft
V 30%			8000	
			8450	
W 0%	80%	96%	5000	800 ft
V 40%			9000	
			9800	

# Aircraft Landing Operations on Contaminated Runways

## CONCLUSIONS I

- Precise touchdown control is essential (and especially on contaminated runways) . DLC (Direct Lift Control) can significantly reduce the dispersion of touchdown points due to variation in pilot performance
- Proper configuration, airspeed and altitude control is crucial in the final approach phase.
- The ICAO/JAA/FAA, 115% of DLDR (192% of DLD) wet-runway “protection” is not always sufficient for certain types of contamination (ice, hydroplaning, etc.) even if the pilot does everything right and according to SOP (and “best” practices).
- The efficiency of reverse thrust is almost constant throughout the landing rollout.
- Adverse Elevator Effect may cause hard touchdowns (and bounce),but can be used beneficially seconds before touchdown and 3-5 feet above the runway.

# Aircraft Landing Operations on Contaminated Runways

## CONCLUSIONS II

- Judging height over the runway is more difficult and in error the larger the airplane is. Current RA/GPWS/Callouts do not have the height resolution necessary for more accurate TCHDN control.
- The flare maneuver is very sensitive and small delays and/or uncertainty in judging height of more than 1 foot can make big difference in touchdown (“greaser” vs. hard landing).
- Reporting runway contamination and estimating rolling friction coefficient reliably still doesn’t work.
- Airplane crews need better “landing calculators” to estimate the level of risk for every landing/rollout before touchdown occurs.
- Once touchdown occurs and reversers are deployed a go-around should not be attempted even if the overrun is certain.

# Aircraft Landing Operations on Contaminated Runways

## CONCLUSIONS III

- Recent NTSB recommendation to prohibit thrust reverse credit in runway required calculations on slippery surfaces makes little sense (to me). It is equivalent to requiring that only half brake efficiency is available in normal landings on dry runway. Such rules would make many runways unavailable for landing in certain adverse conditions which under controlled rules could be used.
- It is, in my opinion, better to improve pilot training for landings on contaminated runways under adverse conditions and design more reliable/faster thrust reverse systems and cockpit warnings. On slippery runways, thrust reversing is your **PRIMARY** mean of stopping and brakes will become important only at very slow speeds.
- EMAS (Engineered Material Arresting System) are expensive and cannot be always implemented.

# Aircraft Landing Operations on Contaminated Runways

## FUTURE WORK

- We want to perform large study involving pilots of various experiences and skills/ratings by using Flight Simulators of narrow- and wide-body airplanes on how to improve touchdown control, both horizontally (say, 1,200 feet  $\pm$ 200 feet) and vertically (say, 100  $\pm$  50 feet-per-minute). Nose gear should be down by 2,000 ft from runway threshold.
- The computer simulation of the flare maneuver for various aircrafts using unconventional (DLC) and conventional flight controls will reveal optimum landing techniques.
- We need money from FAA to finance the work!!! (Simulator studies)



# Aircraft Landing Operations on Contaminated Runways



**"Una volta che hai gustato il volo, camminerai sulla terra con gli occhi rivolti sempre in alto, perché là sei stato, e là agogni a tornare"**

**"Once you experience flight, you will walk on the earth with your eyes looking up to the sky, because there you have been, and there you wish to go back". (Leonardo da Vinci (1452-1519))**

**THANK YOU!**

**Questions?**