The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering

5 NOVEMBER 2024

ASE 367K: FLIGHT DYNAMICS

TTH 09:30-11:00
CMA 2.306

JOHN-PAUL CLARKE
Ernest Cockrell, Jr. Memorial Chair in Engineering, The University of Texas at Austin

Topics for Today

- Topic(s):
  - Landing (cont'd)
  - Continuous Decent and Approach

The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering

EXCERPTS FROM AN INTERESTING PRESENTATION ON LANDING

JOHN-PAUL CLARKE
Ernest Cockrell, Jr. Memorial Chair in Engineering, The University of Texas at Austin

Aircraft Landing Operations on Contaminated Runways

Nihad E. Daidzic, Ph.D., Sc.D., ATP/CFII

Associate Professor of Aviation

Adjunct Associate Professor of Mechanical Engineering

WATS 2009

April 28-30, 2009, Orlando, FL, U.S.A.

World Aviation Training Conference & Tradeshow

Aircraft Landing Operations on Contaminated Runways

Misjudg & calc
overrun

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.

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

Google

Reverse thrust.

Aircraft Landing Operations on Contaminated Runways

threshold: beginning of runway

50 ft for commercial

~1000 ft

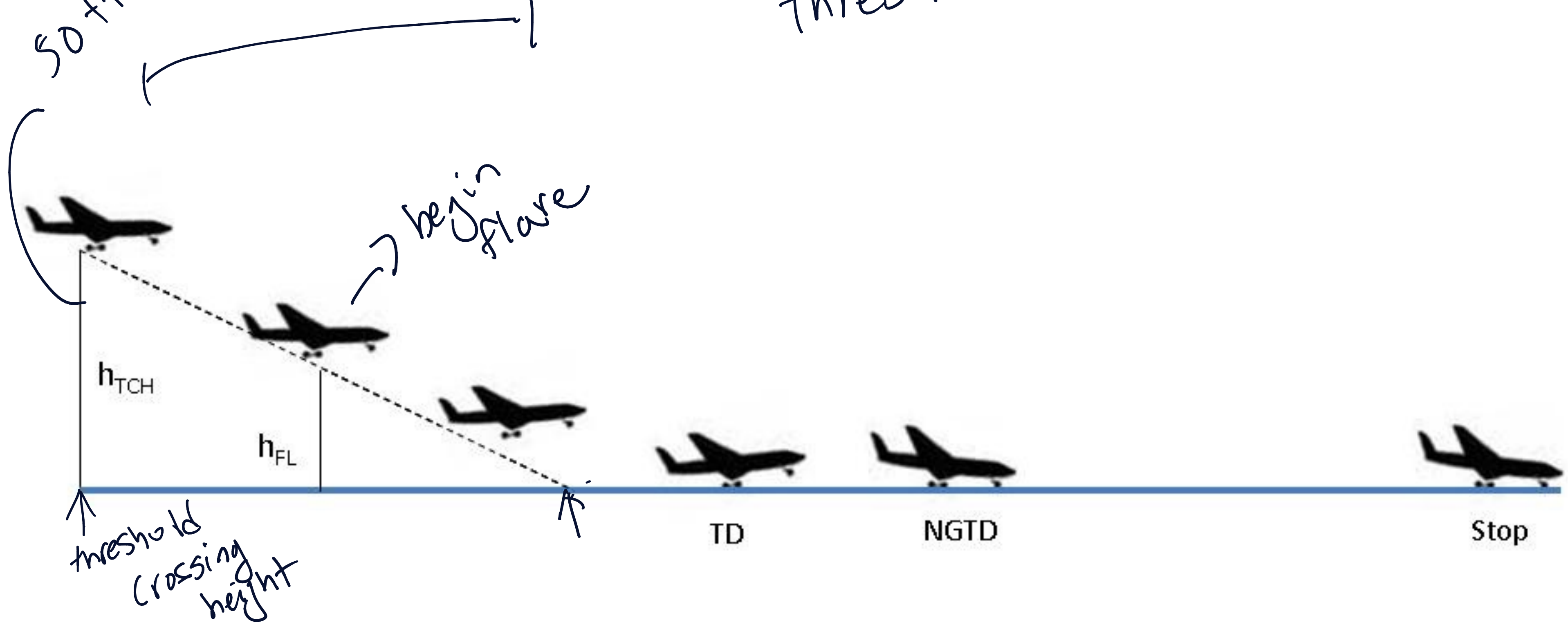


Figure 1: Schematic drawing of the landing maneuver with all important segments (not to scale).

Aircraft Landing Operations on Contaminated Runways

Heavier plane
↑ Vref landing speed

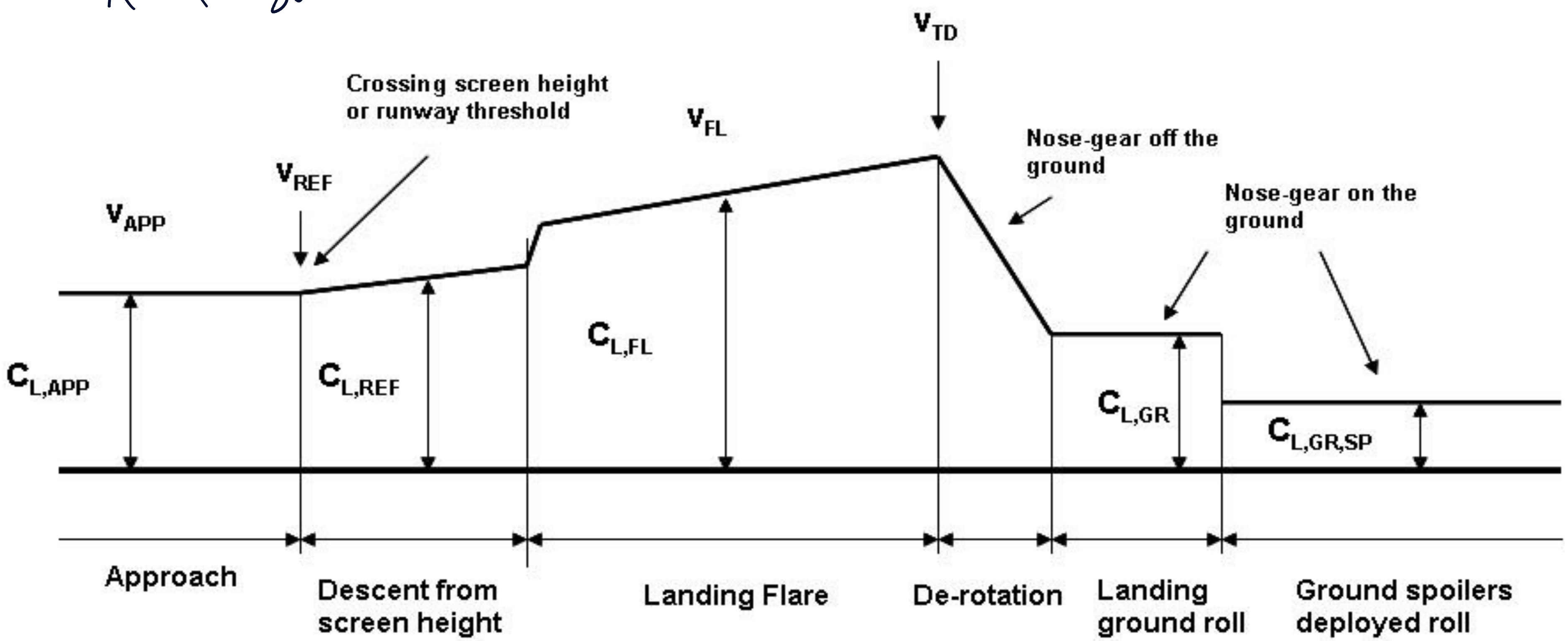


Figure 2: Variation of lift coefficient throughout the landing (not to scale).

Aircraft Landing Operations on Contaminated Runways

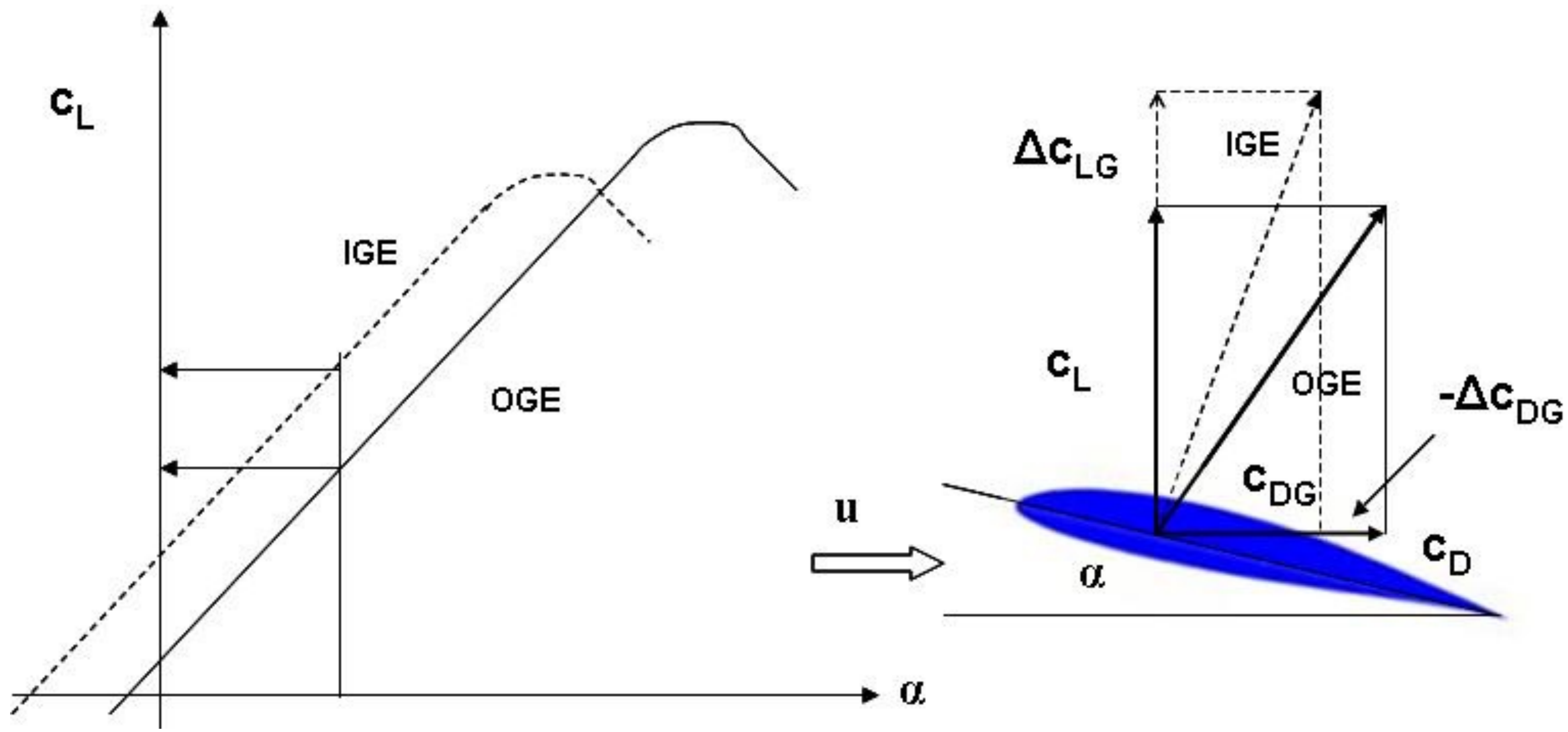


Figure 3: Variation of lift and drag coefficients due to ground effect (not to scale).

Aircraft Landing Operations on Contaminated Runways

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

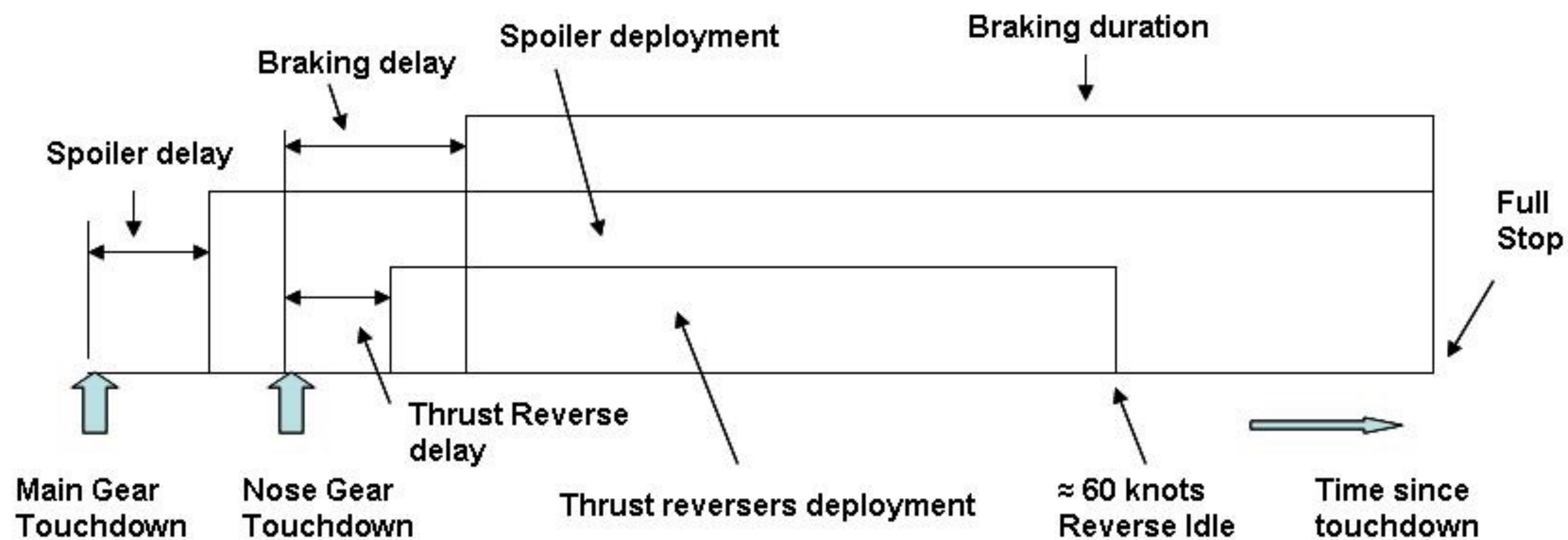


Figure 4: Schedule of ground and flight spoilers (lift-dump system), friction braking and thrust reversers' deployment and re-stowing (not to scale).

Aircraft Landing Operations on Contaminated Runways

Model of Flare

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

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

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

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

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

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

$$\dot{s} = v \pm v_w = v_{GS} \rightarrow \text{ground speed}$$

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^o 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 <u>downhill slope</u> 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). <u>Need to add about 70-100 feet for the nose gear location.</u>

Aircraft Landing Operations on Contaminated Runways

Radar/radio altimeter (E/GPWS) is only ±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

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 the are based on small linear perturbations from steady states.

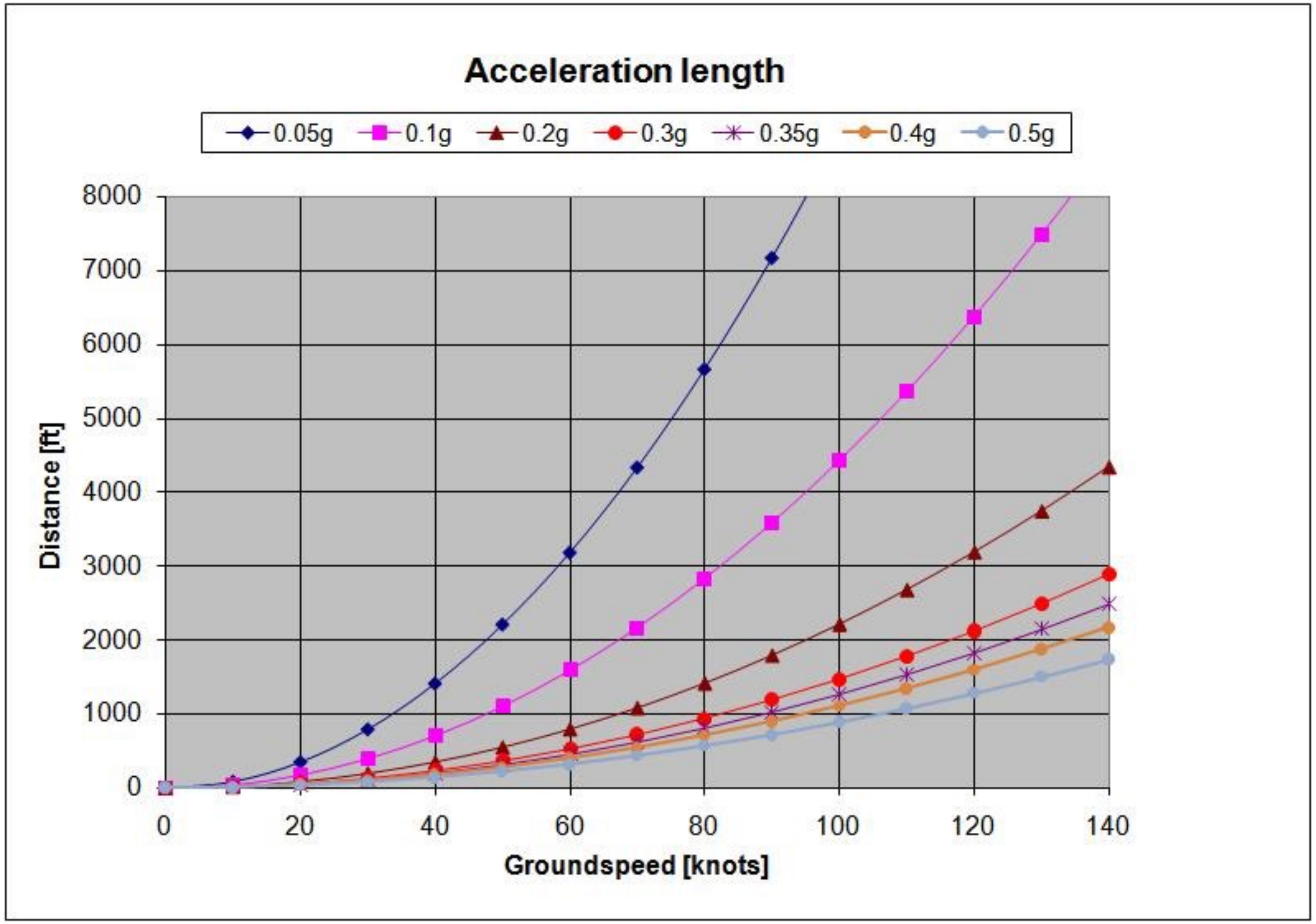
Aircraft Landing Operations on Contaminated Runways

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.

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

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:

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

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:

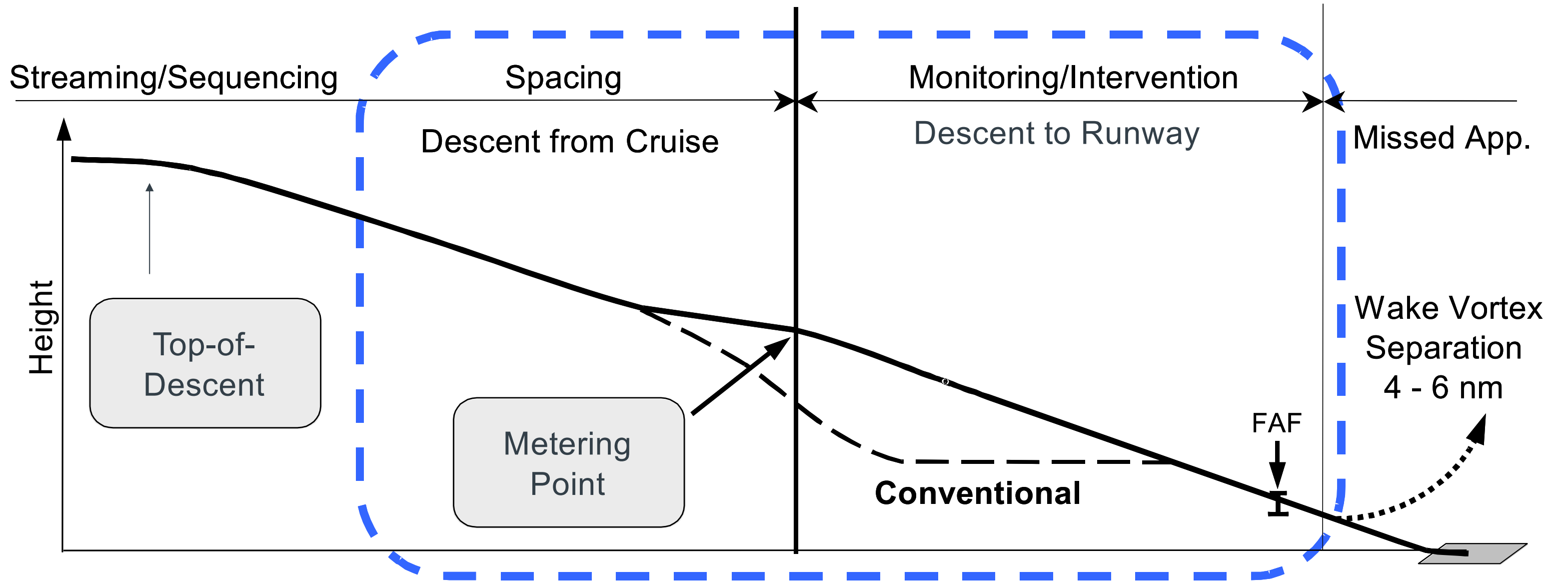
$$\frac{\Delta s}{s} \propto \left(\frac{\Delta W}{W} + \frac{2\Delta v}{v} \right)_{lin} + \left[\left(\frac{\Delta v}{v} \right)^2 \right]_{nonl}$$

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% V 5%	10%	10.25%	5000 5500 5513	13ft
W 0% V 10%	20%	21.0%	5000 6000 6050	50 ft
W 0% V 20%	40%	44.0%	5000 7000 7200	200 ft
W 0% V 30%	60%	69.0%	5000 8000 8450	450 ft
W 0% V 40%	80%	96%	5000 9000 9800	800 ft

Environmental Considerations in Descent and Approach

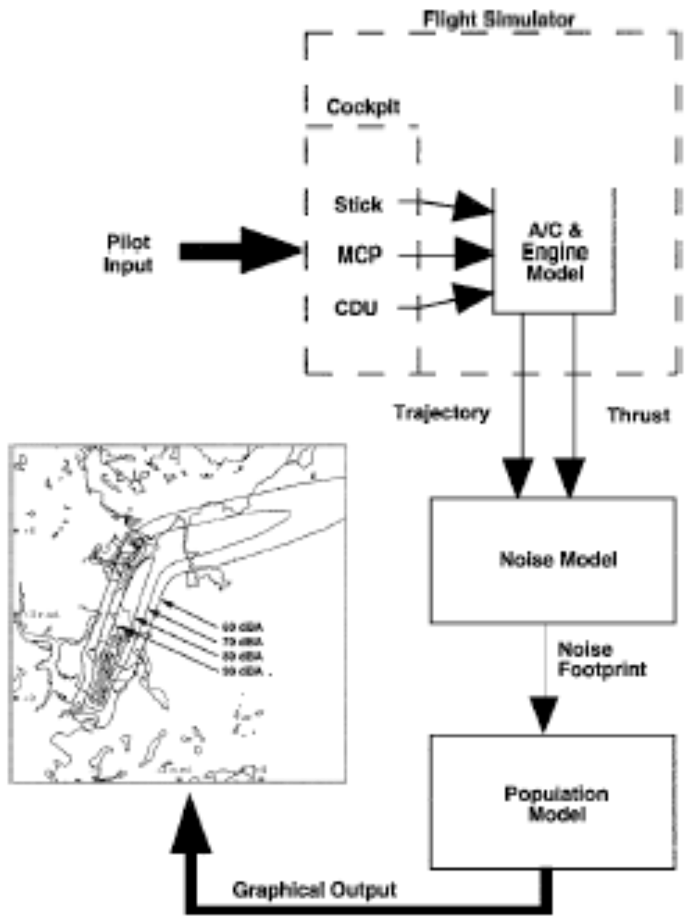
Optimized Descent

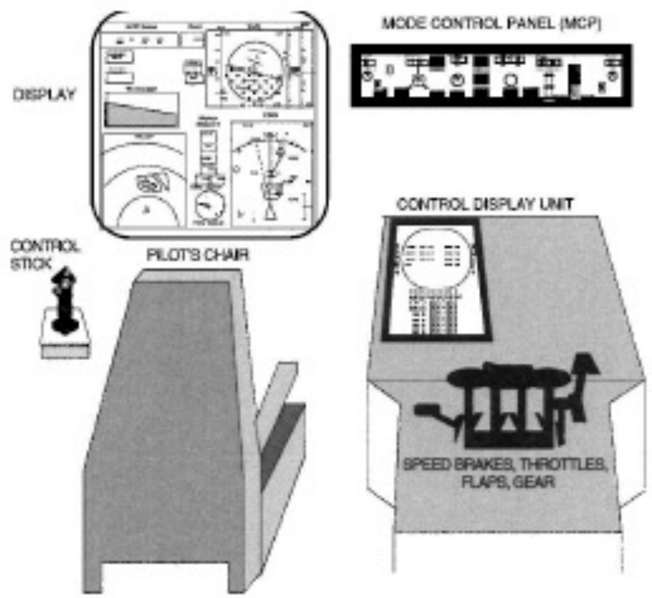


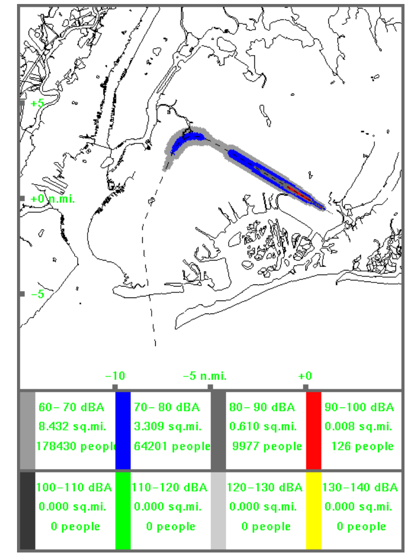
- Desired sequence and spacing achieved during initial descent from cruise altitude (top-of-descent) to metering point
- No vectoring during descent to runway i.e. after metering point
- Location of metering point dependent on traffic conditions

From concept and initial validation…

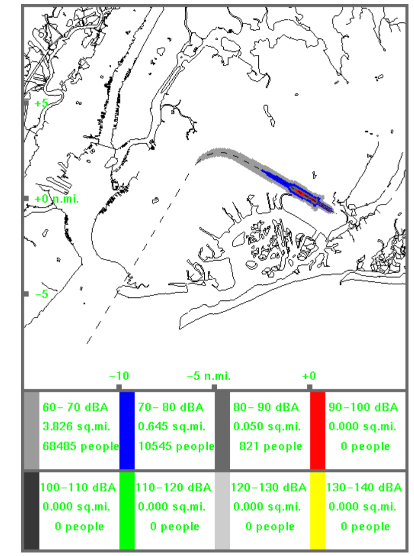
- NOISIM



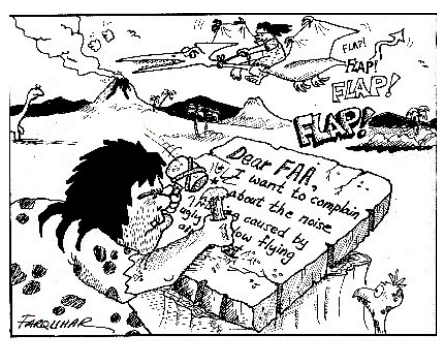




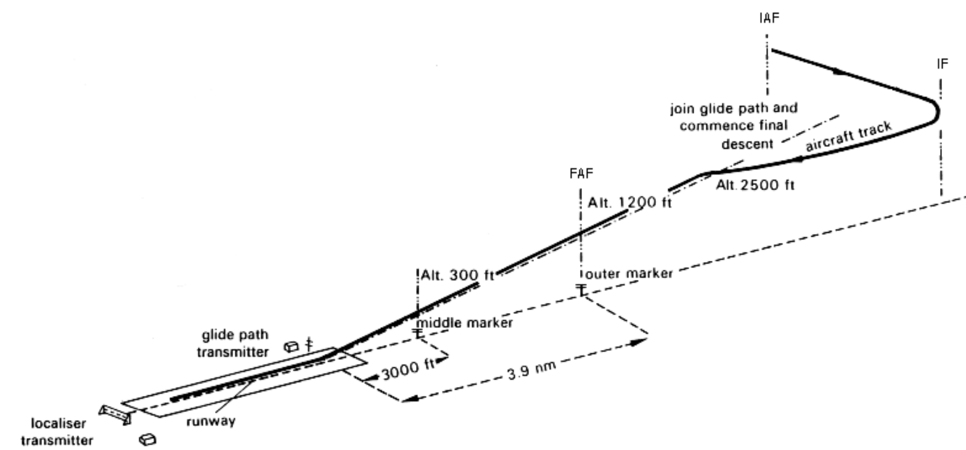
Existing ILS Approach



3° Decelerating Approach



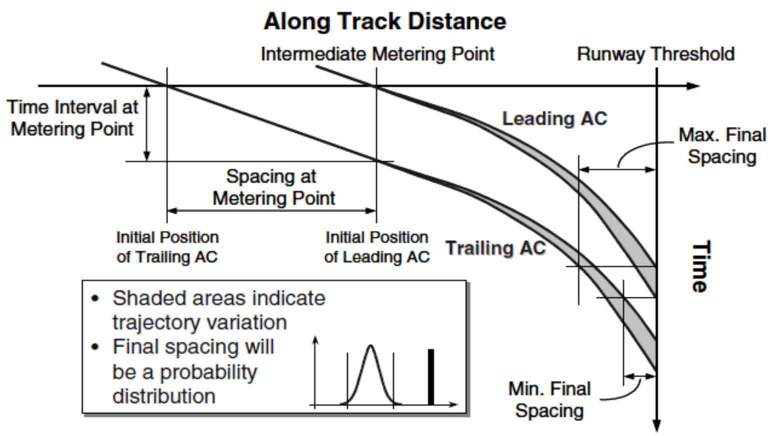
"THE FIRST RECORDED NOISE COMPLAINT WAS RECENTLY DISCOVERED IN A CAVE NEAR ST.LOUIS"

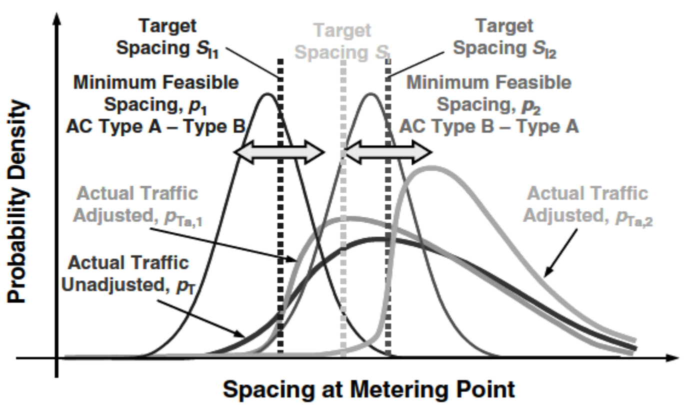


Source: Clarke and **Hansman** (1997)

To rigorous prototype and field trials…

- TASAT

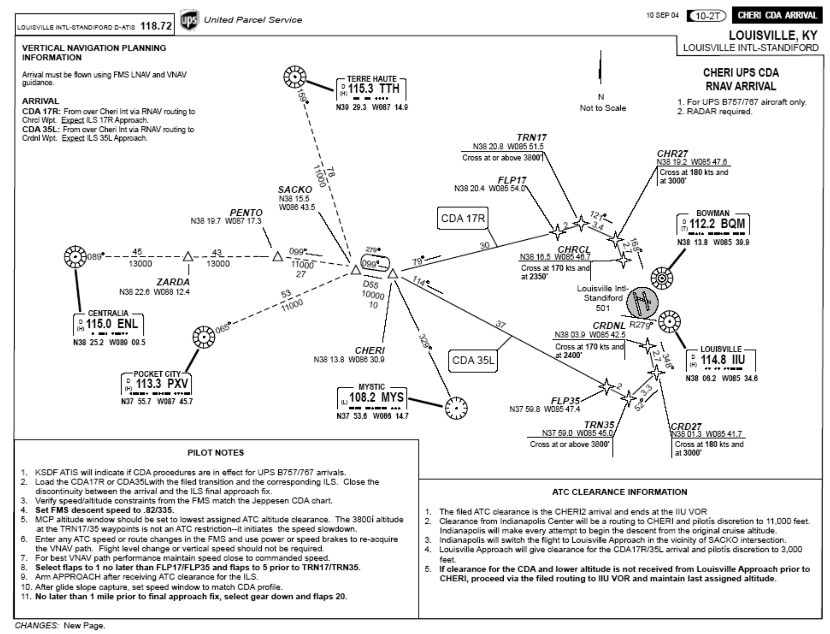


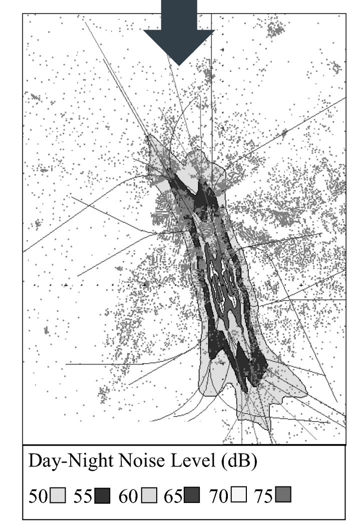


$$P_{Ta} = \sum_i P_i P_{Ta,i} = \sum_i P_i \int_0^\infty \left(\int_0^s p_i \, \mathrm{d}x \right) p_{Ta,i} \, \mathrm{d}s$$

Source: Ren and Clarke (2004)

- Flight Trials at Louisville International Airport (SDF)





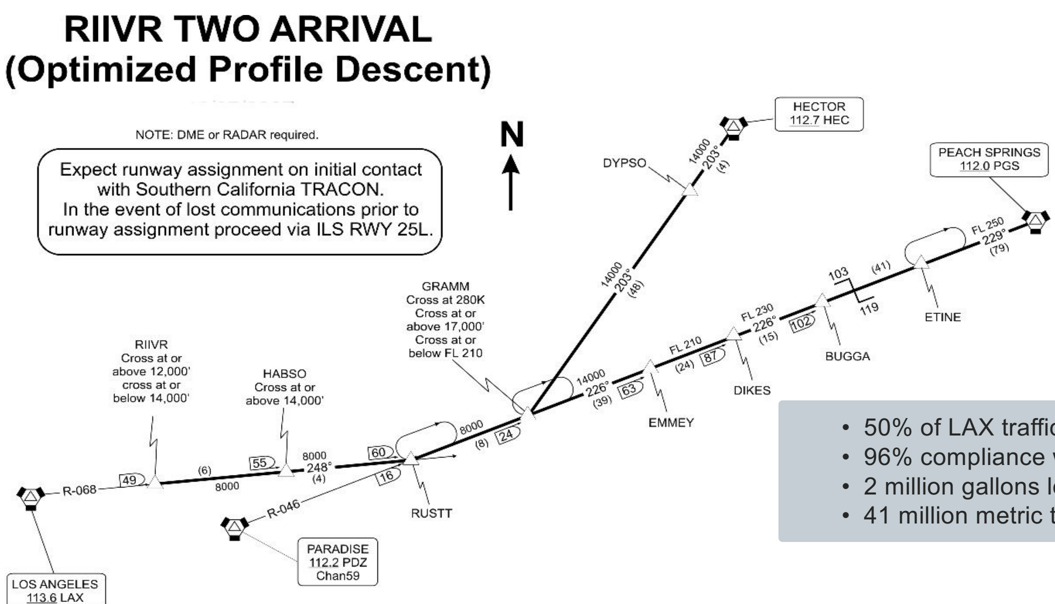
- 4 to 6 dB peak noise reduction (7.5 to 15 NM from runway)
- 30% reduction in NOx
- 500 lb. fuel burn reduction
- 100 sec. flight time reduction

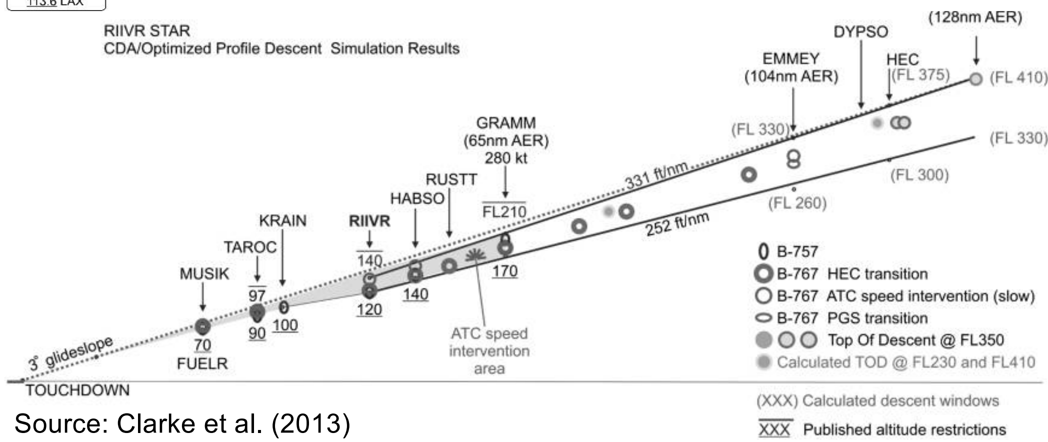
Source: Clarke et al. (2004)

CLARKE RESEARCH GROUP

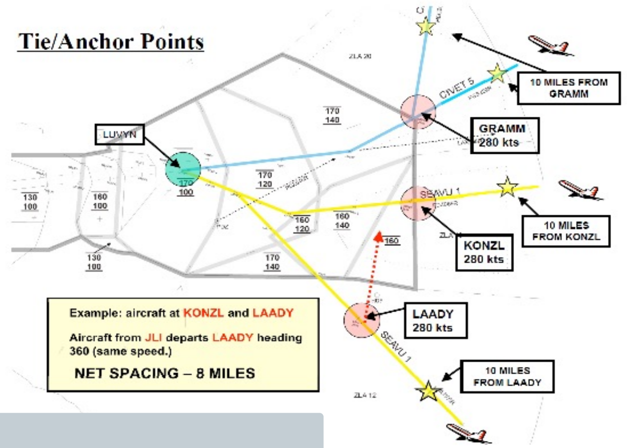
To daily operations…

- Optimized arrivals (from cruise to landing) at Los Angeles International Airport (LAX)





Source: Clarke et al. (2013)



- 50% of LAX traffic
- 96% compliance with vertical profile
- 2 million gallons less fuel consumed annually
- 41 million metric tons less CO_2 annually

Table 6 Time from Top Of Descent (TOD) to threshold (s)

		737	757	767
CIVET5	s	1375	1409	1367
RIIVR1	s	1317	1394	1308
Savings	s	58	15	59

Table 7 Percentage change in noise

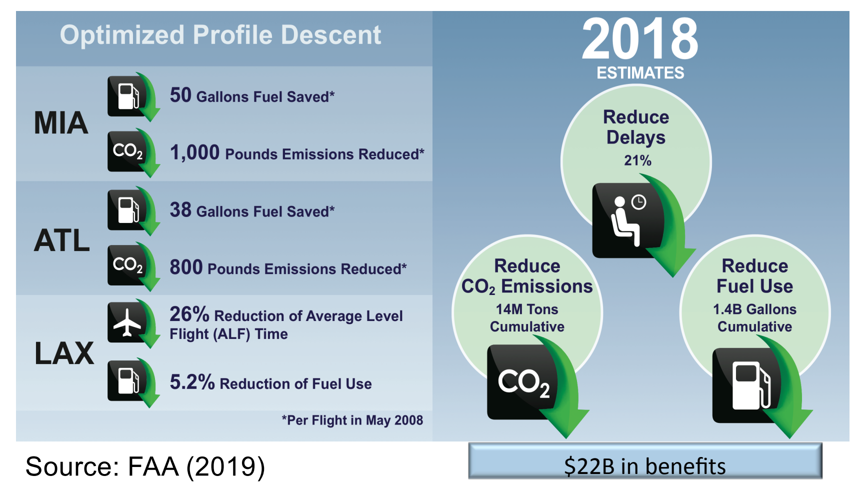
		Noise contour threshold			
		40 dB	50 dB	60 dB	70 dB
Area of noise	737 CIVET	29.8	7.4	0.5	0
	737 RIIVR	24.9	5.4	0.5	0
	% noise change	–16.4	–28	0	0
Area of noise	757 CIVET	21.7	4.8	0.4	0
	757 RIIVR	21.4	4.7	0.4	0
	% noise change	–1.0	–2.5	0	0
Area of noise	767 CIVET	38.8	9.4	0.8	0
	767 RIIVR	35.1	6.9	0.8	0
	% noise change	–9.4	–26.5	0	0

Table 5 Descent mean fuel burn

		737	757	767
CIVET5	lb	745	901	1307
RIIVR1	lb	590	834	1047
Savings	lb	155	67	260
	gal (U.S.)	23	10	39

Table 2 Example of spacing matrix at GRAMM

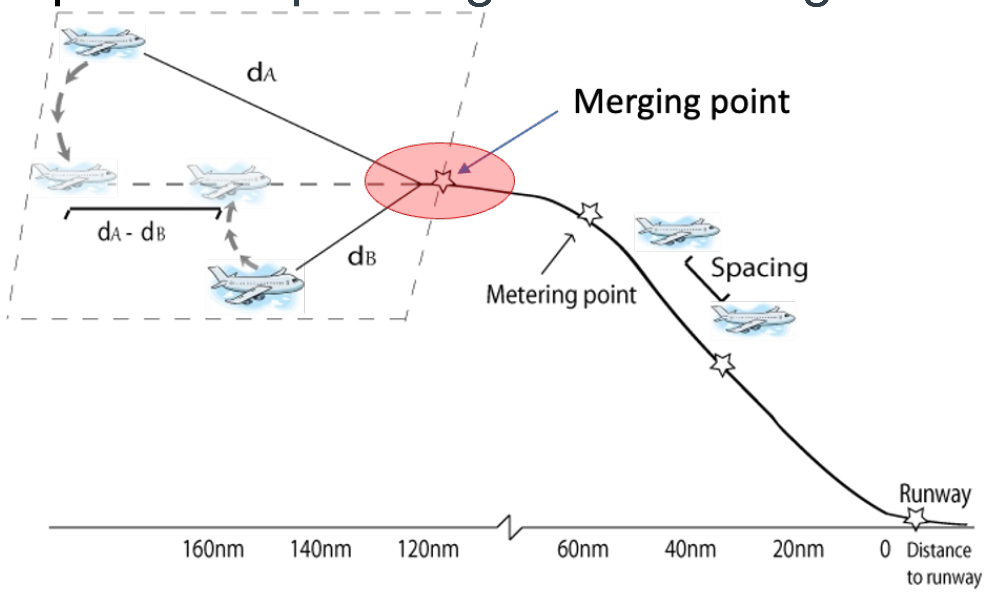
		Spacing, nm Leading aircraft		
Trailing aircraft	Intervention, %	B737	B757	B767
B733	90	7.7	11.4	14.6
B733	80	7.5	11.1	14.3
B733	70	7.3	10.9	14.1
B744	90	8.7	12.0	12.9
B744	80	8.4	11.8	12.6
B744	70	8.2	11.6	12.3

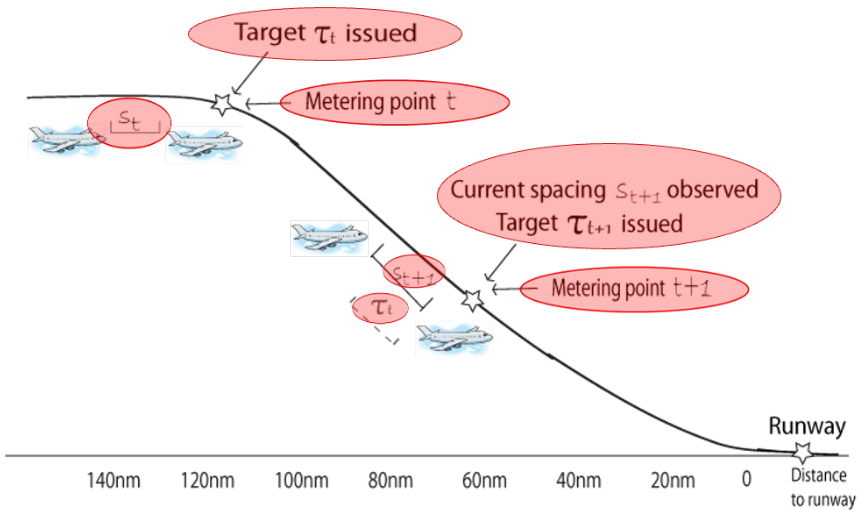


Source: FAA (2019)

And beyond!

- Optimal sequencing and metering of arrivals via stochastic dynamic programming



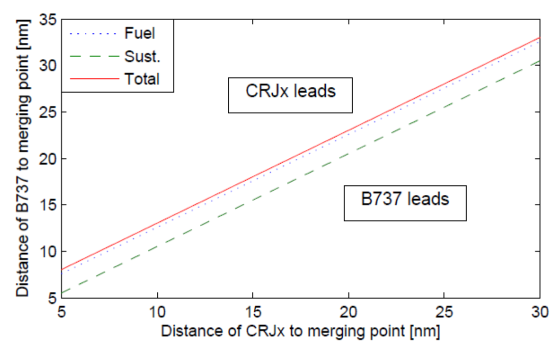


- **Sequencing Policy:** Let d_A and d_B represent the direct distance of the two aircraft (A, B) to the merging point, based on cost structure l, A should be the leading aircraft if:

$$d_A - d_B \leq \delta_{AB}^{l}$$

Where δ_{AB}^{l} denotes the "critical (distance) difference" between A and B.

Source: Chen and Solak (2014)



- **Spacing Policy:** *An approximated optimal target spacing change $\widetilde{\Delta}_t^{l*}$ at metering point t for $t \in \{1, 2, \ldots, N-1\}$ and $l \in \{F, S, T\}$ is given as follows:*

$$\widetilde{\Delta}_t^{l*} = m_t^l s_t + n_t^l \tag{4}$$

where $m_t^l = -\alpha_t^l / \Psi_t^l$, and

$$n_t^l = -\frac{2\Phi_t^l + \beta_t^l \Psi_{t+1}^l - \lambda_N^l \left(\prod_{t'=t+1}^{N-1} \lambda_{t'}^l p_{t'} \right) \left(\sum_{t'=t+1}^{N-1} \left[\beta_{t'}^l / \lambda_{t'}^l \prod_{t''=t'+1}^{N-1} p_{t''} \right] \right)}{2\Psi_t^l}$$

If $\widetilde{\Delta}_t^{l*} \leq \underline{\Delta}_t$, then the optimal spacing change is $\underline{\Delta}_t$. Similarly, if $\widetilde{\Delta}_t^{l*} \geq \overline{\Delta}_t$, then the optimal spacing change is $\overline{\Delta}_t$.

Implementable in Excel!

douglas uses reverse thrust in flight

The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering