Surviving the Improbable
Upset Prevention and Recovery in Flight Control

Dr Ir Thomas Lombaerts

Santa Clara University

Santa Clara University, January 23, 2019

Outline

- Introduction
- Upset Prevention:
  - Safe Flight Envelope Estimation
  - Safe Flight Envelope Protection:

    Concept Demonstration
- Upset Recovery: Stall Recovery Guidance

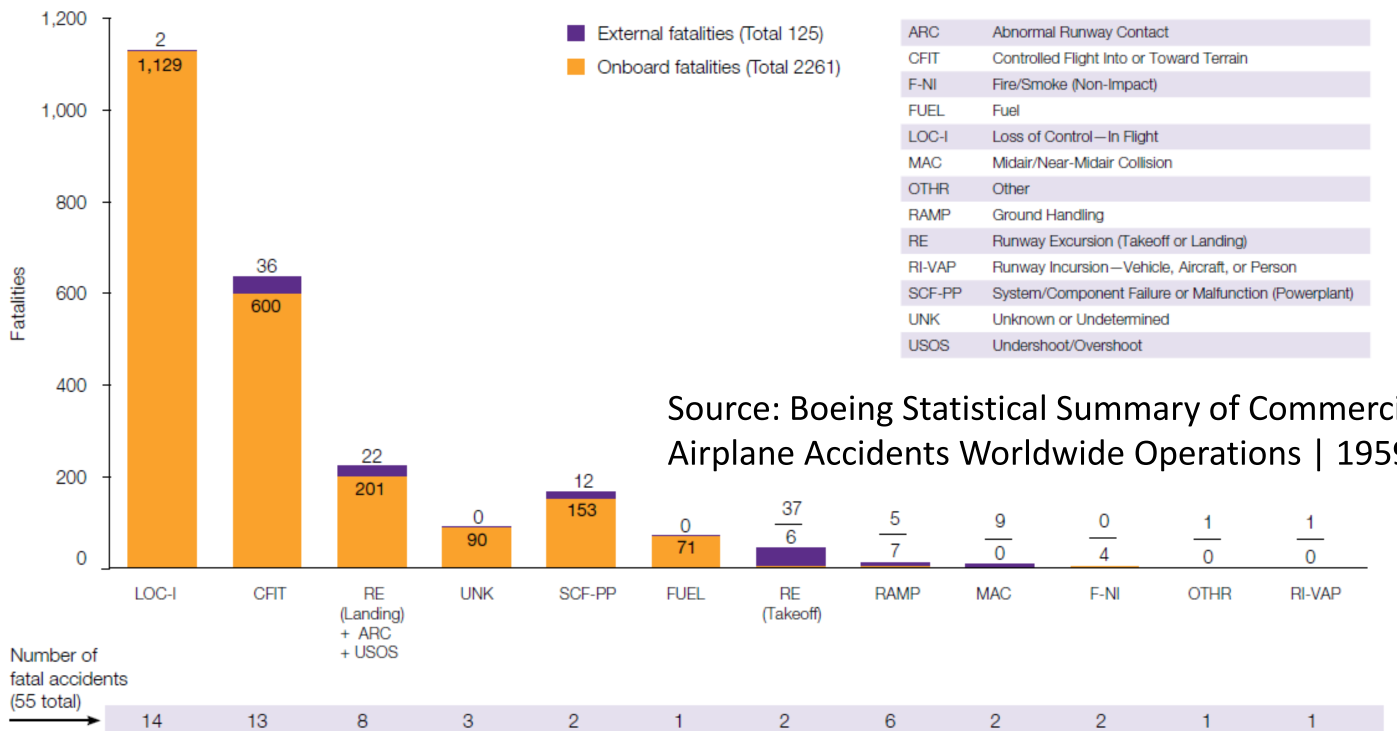
Introduction: Who am I?

History:
- 1998 – 2004: Aerospace Engineering, Delft University of Technology, NL
- 2004 – 2010: lecturer and PhD researcher in Delft
  - 2009: visiting scientist at DLR in Germany during 4 months
- 2010 – 2016: scientific researcher at DLR in Germany
  - 2012 – 2014: Visiting Marie Curie Fellow at NASA Ames
- 2016 – today: senior aerospace research engineer at NASA Ames

Interests:
- Aircraft state estimation and Kalman filtering
- Aerodynamic model identification: structure selection and parameter identification, fault detection
- Adaptive control and nonlinear dynamic inversion, Pseudo Control Hedging
- Control Allocation
- Handling qualities and pilot workload analysis

Introduction

- Loss of control in flight (LOC-I) remains the most frequent primary cause of accidents
- 40% of all accidents is LOC-I related and this category involves most fatalities
- Increasing trend over the last decades



Source: Boeing Statistical Summary of Commercial Jet Airplane Accidents Worldwide Operations | 1959 – 2017

Upset Prevention and Recovery

order of priorities

Research subtopics, based on CAST directives on safety enhancements:

1. **Upset prevention**
   – Adaptive safe flight envelope estimation
   – Adaptive envelope protection
2. **Upset recovery**
   1. Stall recovery guidance
   2. Unusual attitude recovery

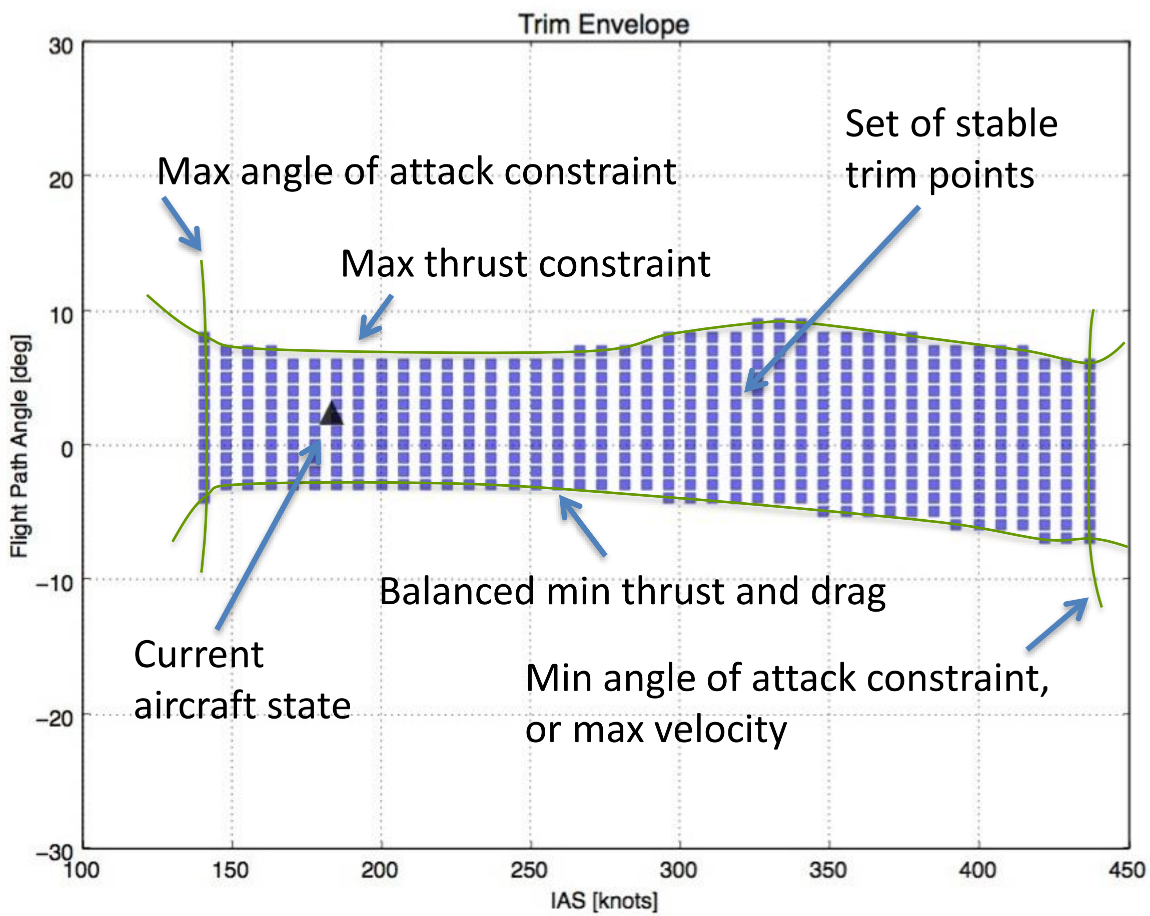
Upset recovery training aspect

Estimation of the envelope boundaries trim envelope

Trim envelope: all the sets of stable equilibrium conditions (V,γ) within the input limits.

Aircraft variables:
- Airspeed V
- Flight path angle γ

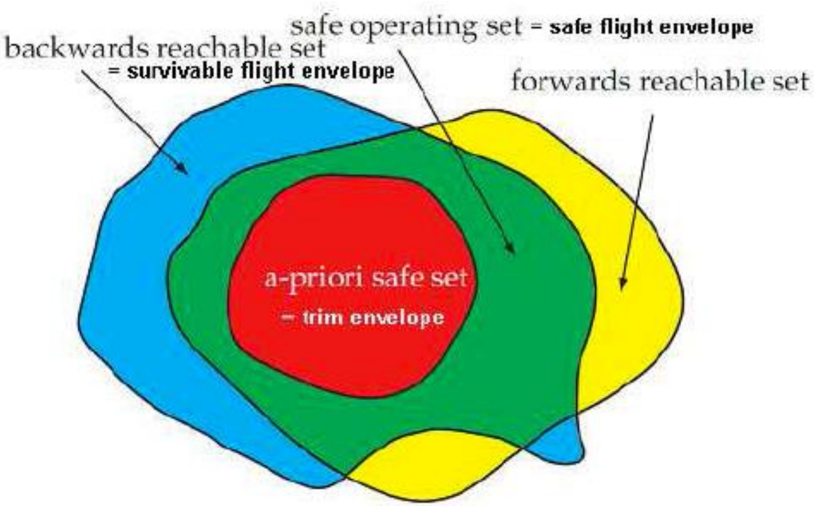
Inputs:
- Angle of attack α
- Thrust T

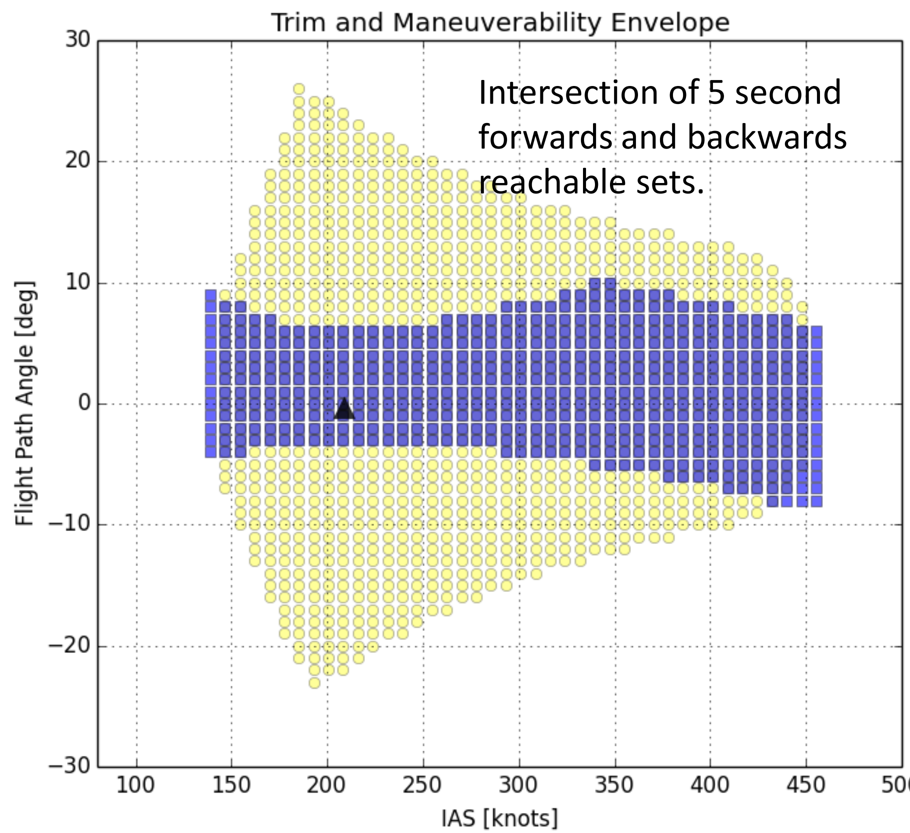


ACT Simulation Model at 15000 feet.

Estimation of the envelope boundaries maneuvering envelope

Safe maneuverability envelope is defined as intersection between forward and backward reachable sets

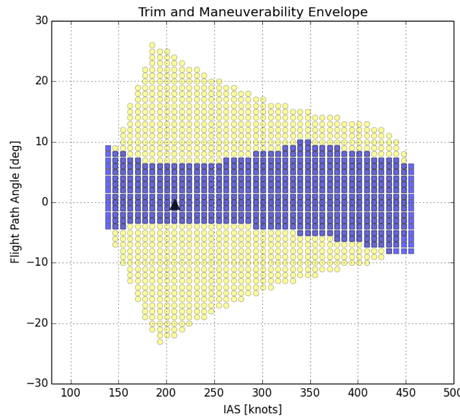




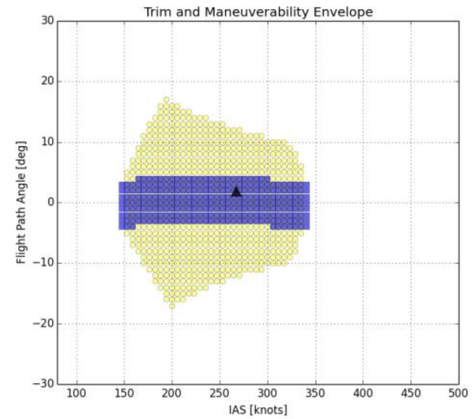
Based on ACT Simulation Model at 15000 ft.

Estimation of the envelope boundaries trim and maneuvering envelope variation

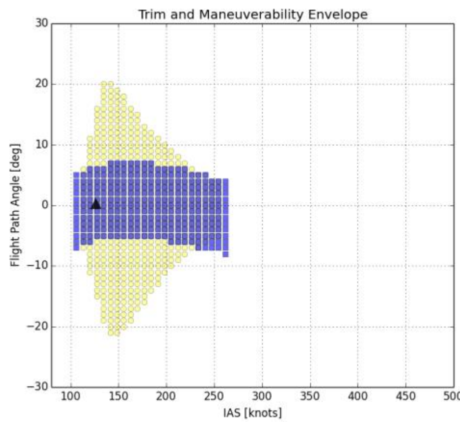
Nominal at 15000 ft.



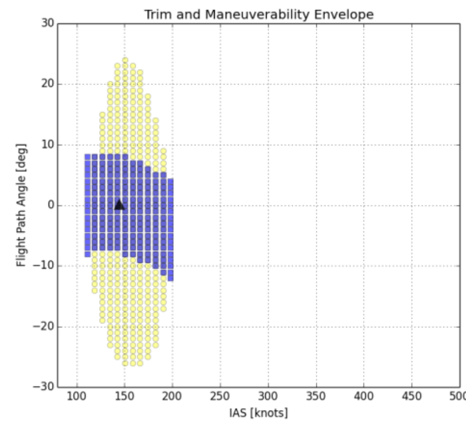
Nominal at 30000 ft.



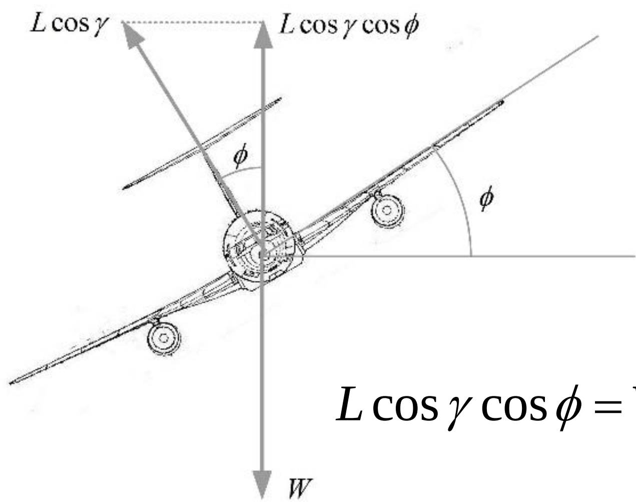
Full Flaps at 15000 ft.



Full Flaps, Gear, Spoilers at 13000 ft.

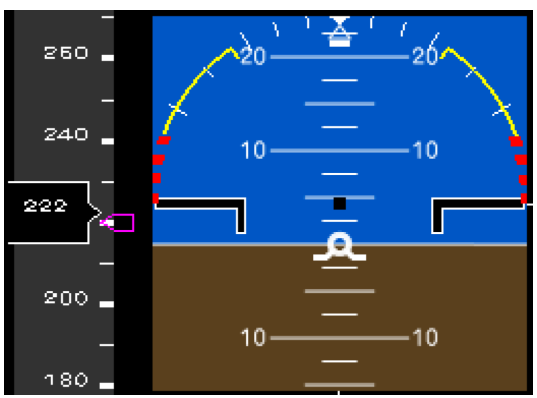


Estimation of the envelope boundaries maximum roll angle

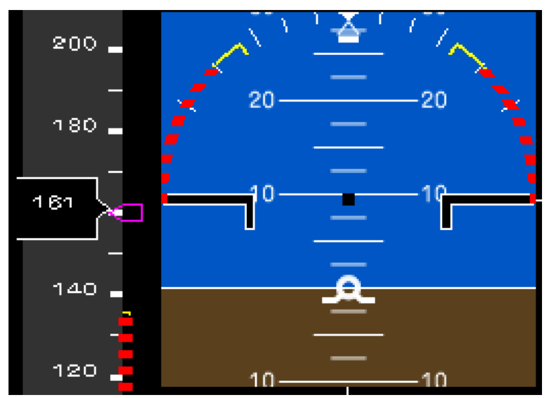


$$L\cos\gamma\cos\phi = W$$

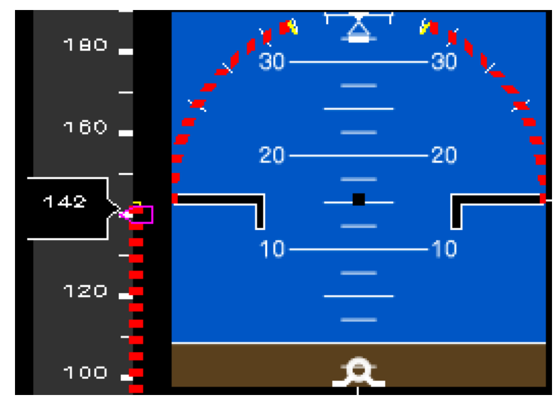
maximum achievable roll angle at current airspeed and flight path angle before stall occurs



V_{IAS} = 222 kts, $\phi_{max} > 60°$

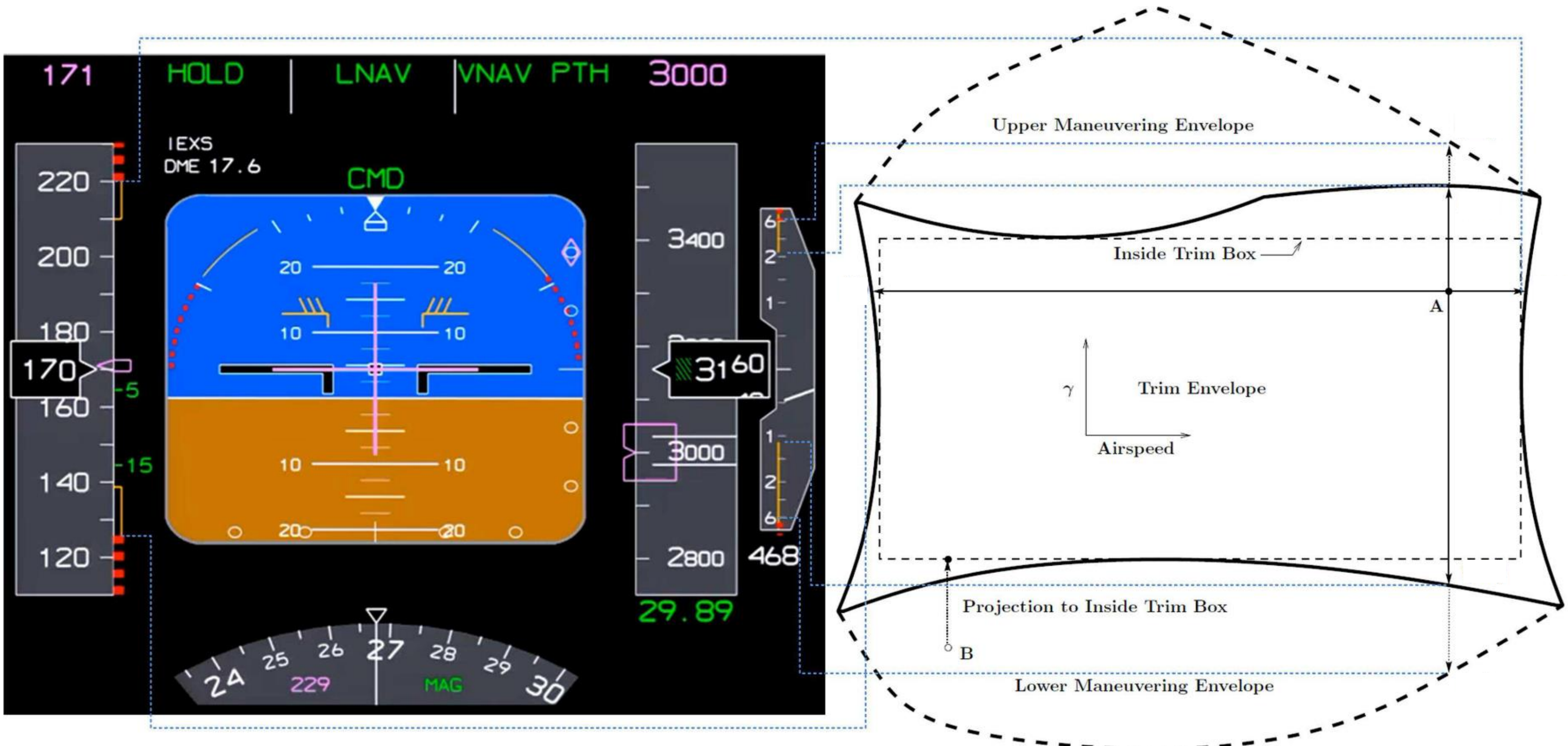


V_{IAS} = 161 kts, $\phi_{max} = 45°$



V_{IAS} = 142 kts, $\phi_{max} = 20°$

Additional information provided to the pilot over the cockpit displays



Primary Flight Display (PFD)

Experiment overview: Advanced Concepts Flight Simulator

- Objective

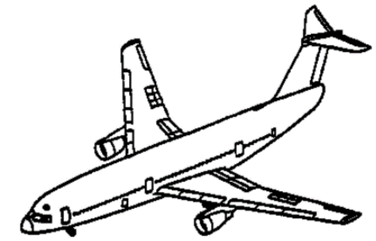
  Explore how crews manage their energy state, both with and without new technology

- Overview
  - 10 commercial flight crews
  - 4 descent and landing scenarios in Memphis airspace
  - Workload assessment, questionnaires

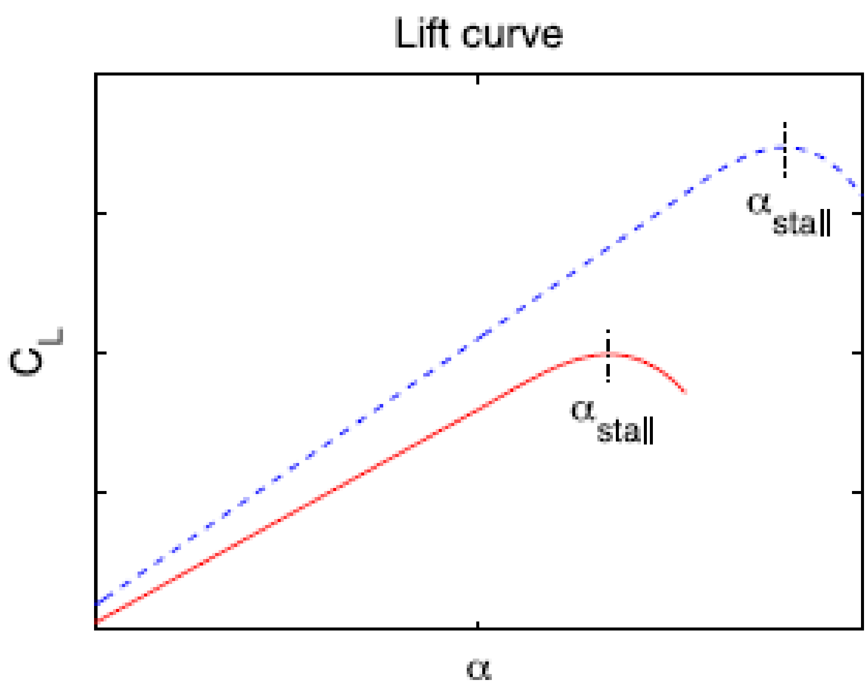
- New technology:
  - **Maneuver envelope limits displayed on the primary flight display (PFD)**
  - Others (not discussed here)

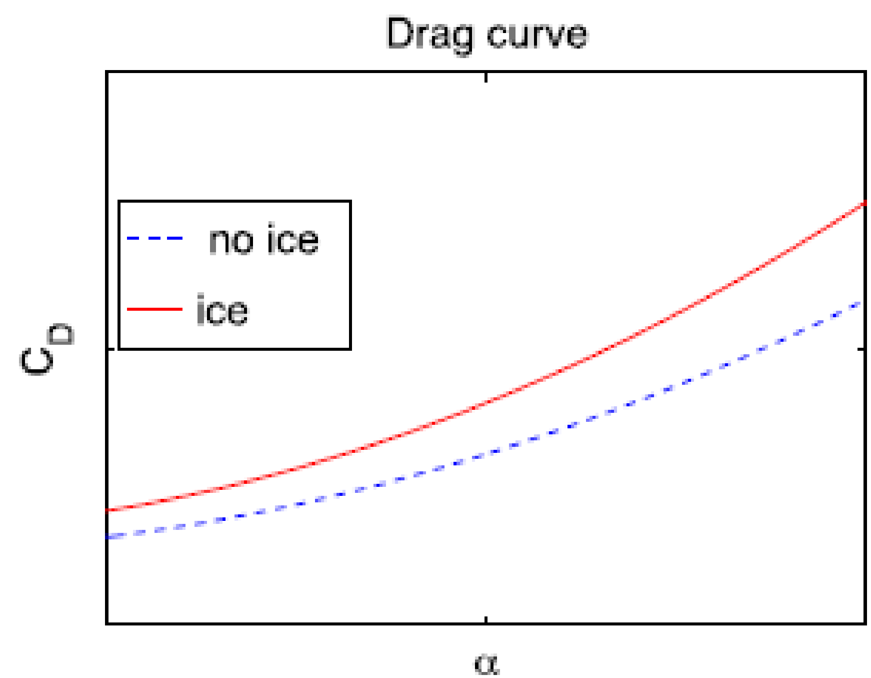
Advanced Concepts Flight Simulator (ACFS)

Experiment overview: Icing scenario



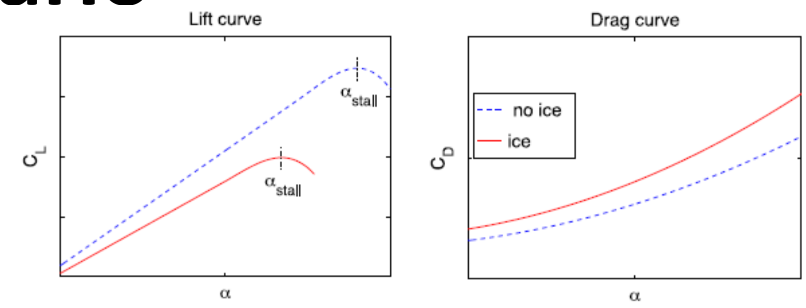
- Aircraft is initialized in an icing condition:
  modified flight dynamics: less lift, more drag, α_{stall} smaller

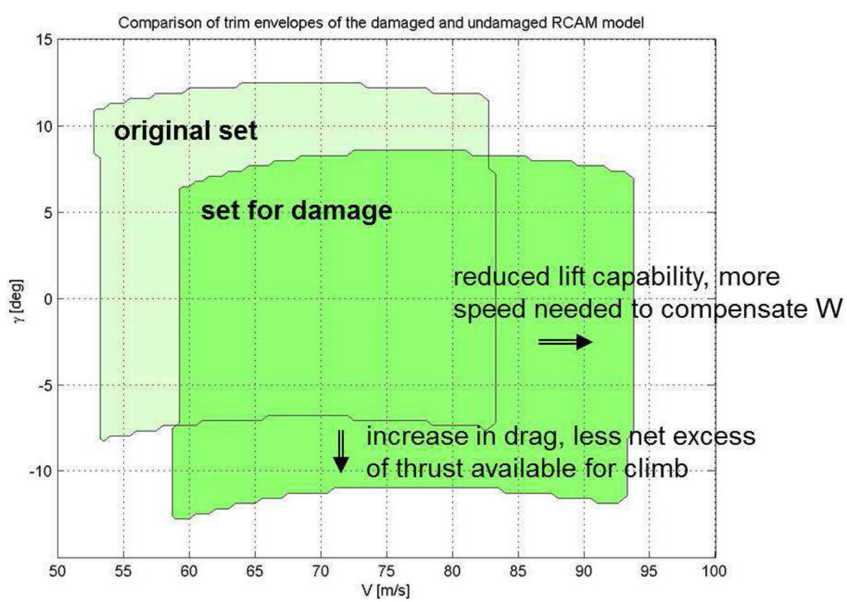




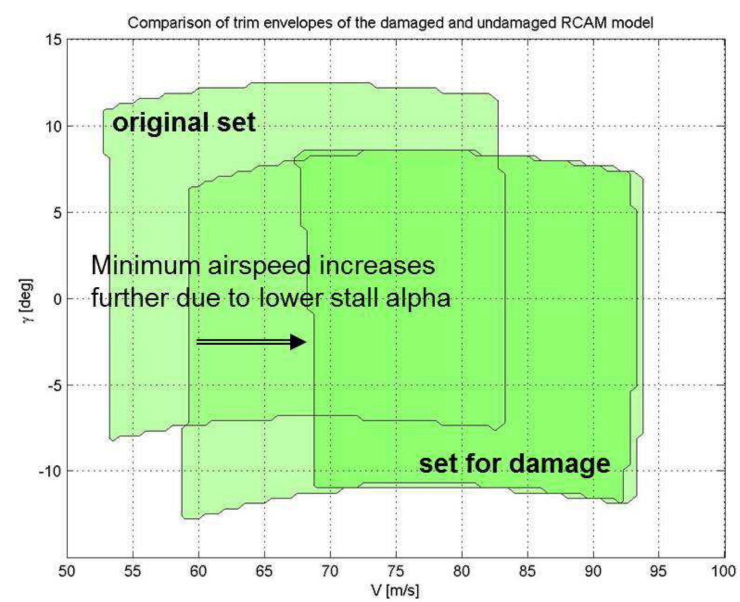
Results
Icing scenario

Impact of icing on the safe flight envelope



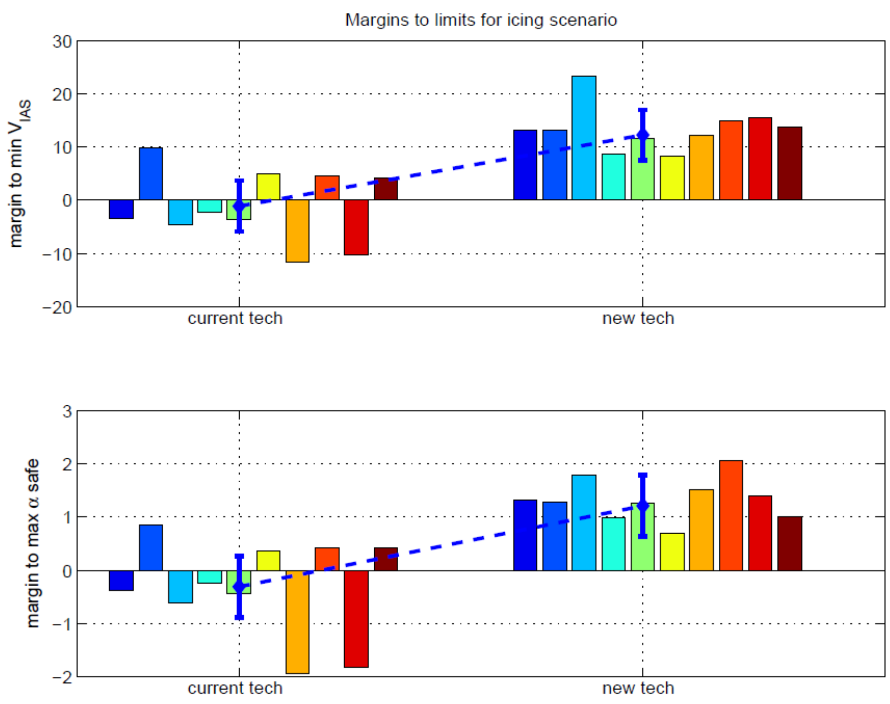


icing effect

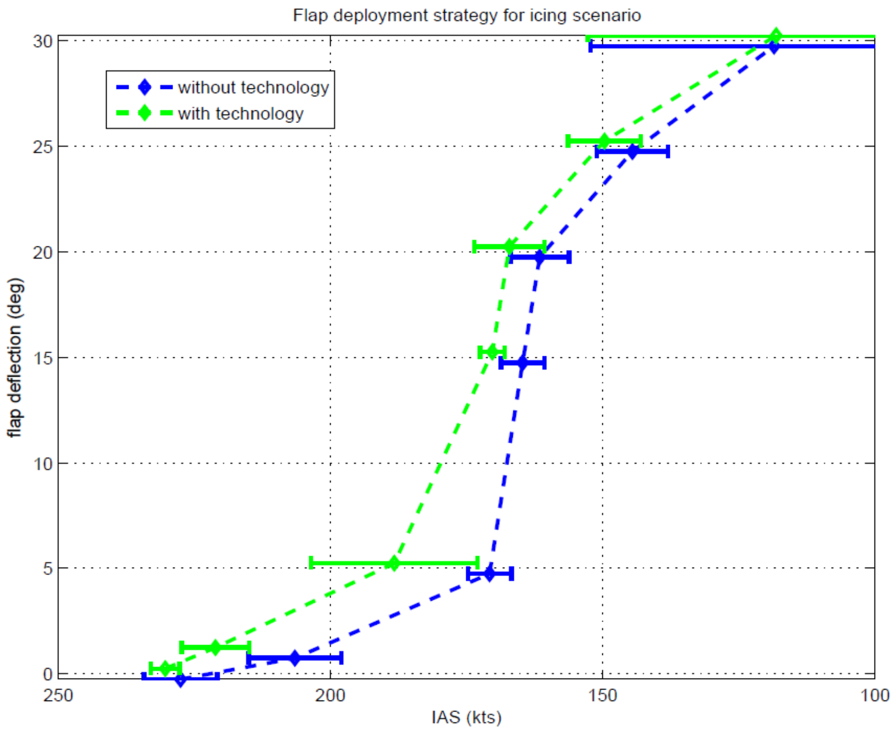


icing effect and reduced α_{stall}

Results
Icing scenario



margins for all crews



flap deployment strategy

Implementation of the protections in the closed loop architecture

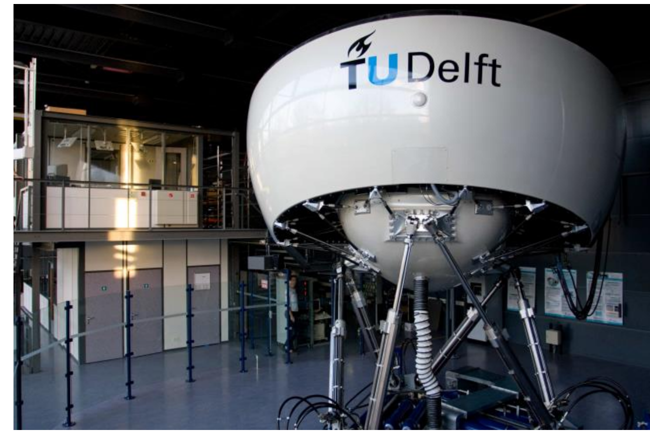
Protections are implemented in:

- Flight control laws
- Cockpit displays
- Haptic feedback

Envelope boundary	Protection in controller	Displayed in PFD	Haptic feedback
max roll	X	X	X
max α	X		X
min airspeed	via max α	X	via max α
max load factor	X		X
min/max flight path angle		X	

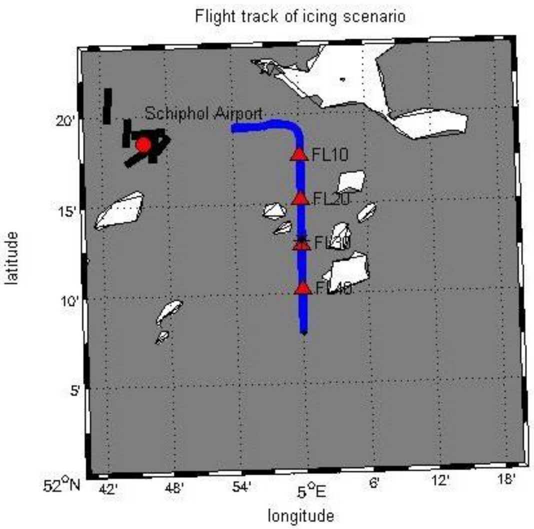
Experiment method:
Simona Research Simulator

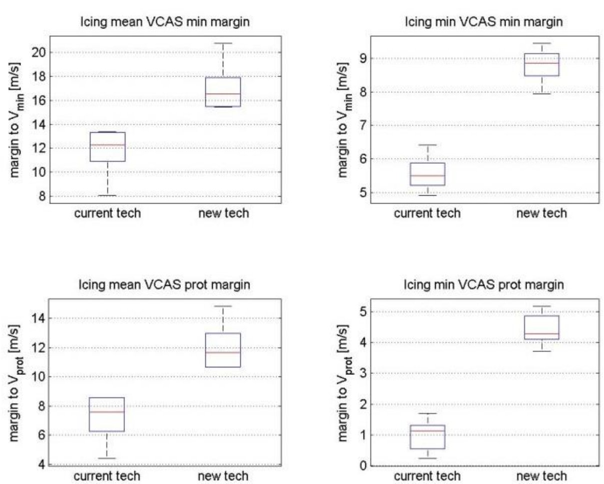
- Research hypotheses
  - Will envelope protection prevent loss of control and reduce workload?
  - Will modified PFD improve situational awareness about flying capabilities?
  - Will haptic feedback improve situational awareness about protective action?
- Overview
  - 7 commercial pilots
  - Icing scenario in approach near Amsterdam Schiphol Airport
  - Workload assessment and questionnaires
- New technologies
  - Adaptive envelope protection in flight control laws
  - Extended primary flight display
  - Haptic feedback on stick

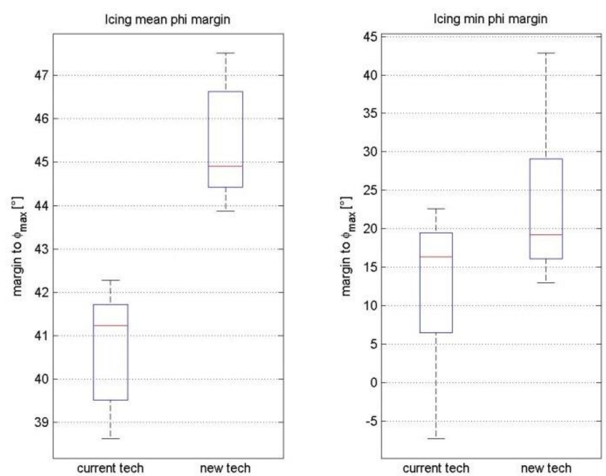


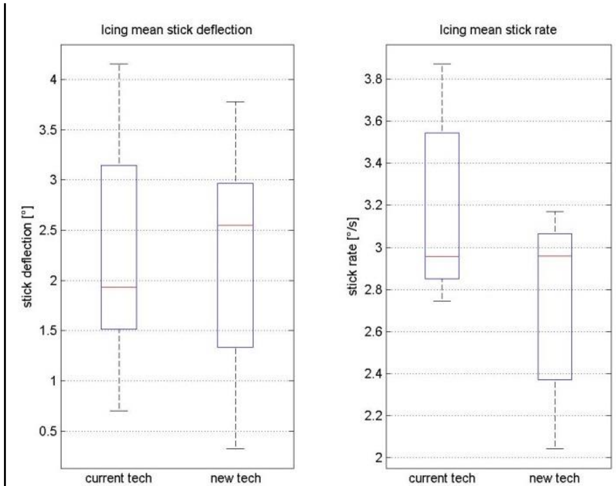
Results: icing scenario

- Gradual ice accretion on the wings, starts around FL30
- Wind gusts make effect on envelope less obvious
- Speed and bank angle margins improve with new tech
- No increase in workload

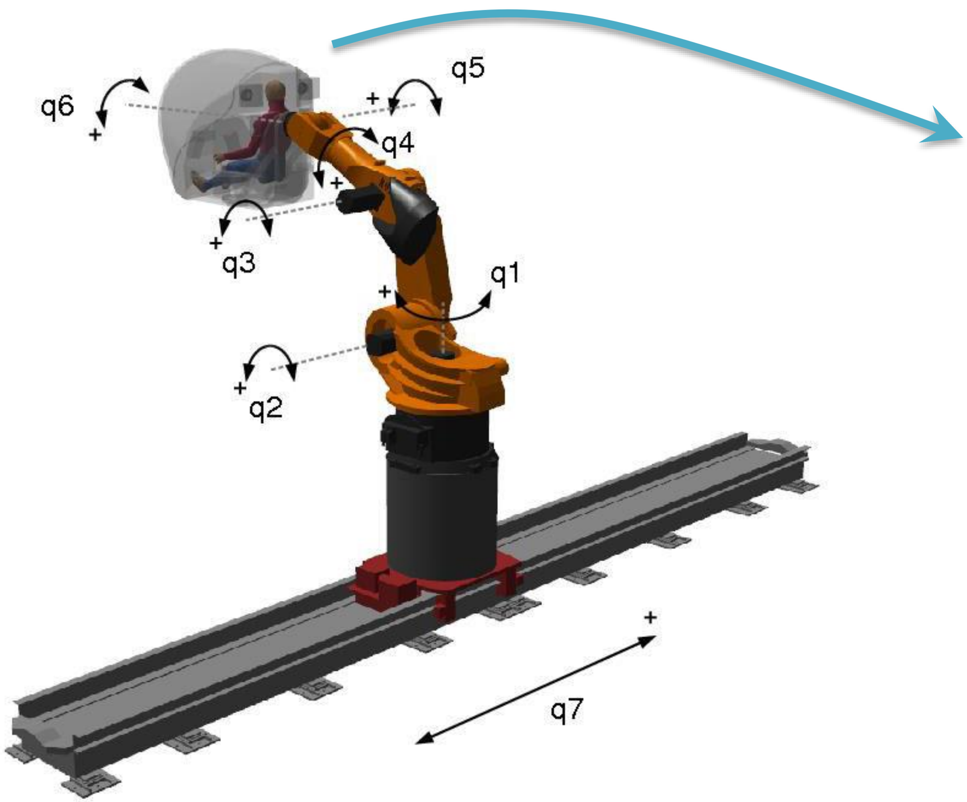




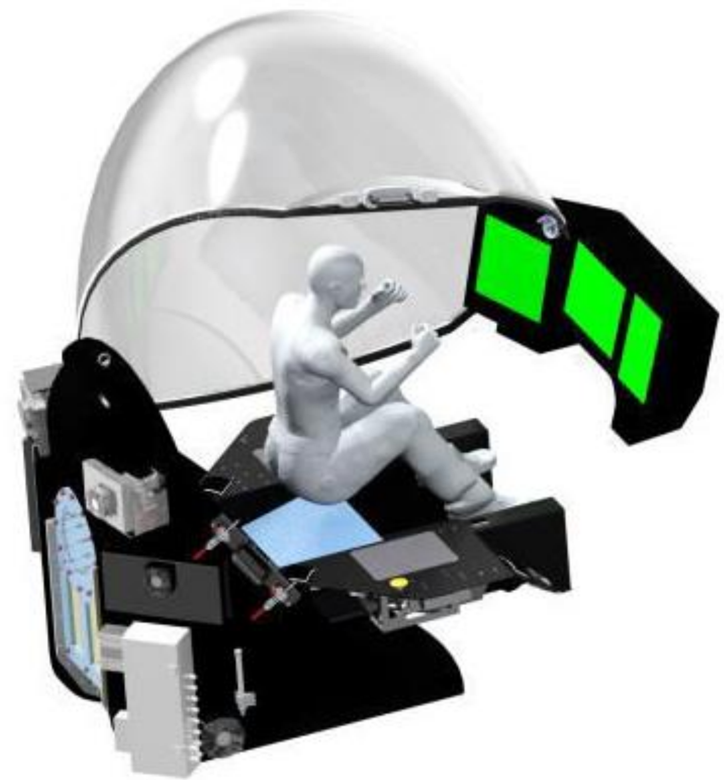




Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen

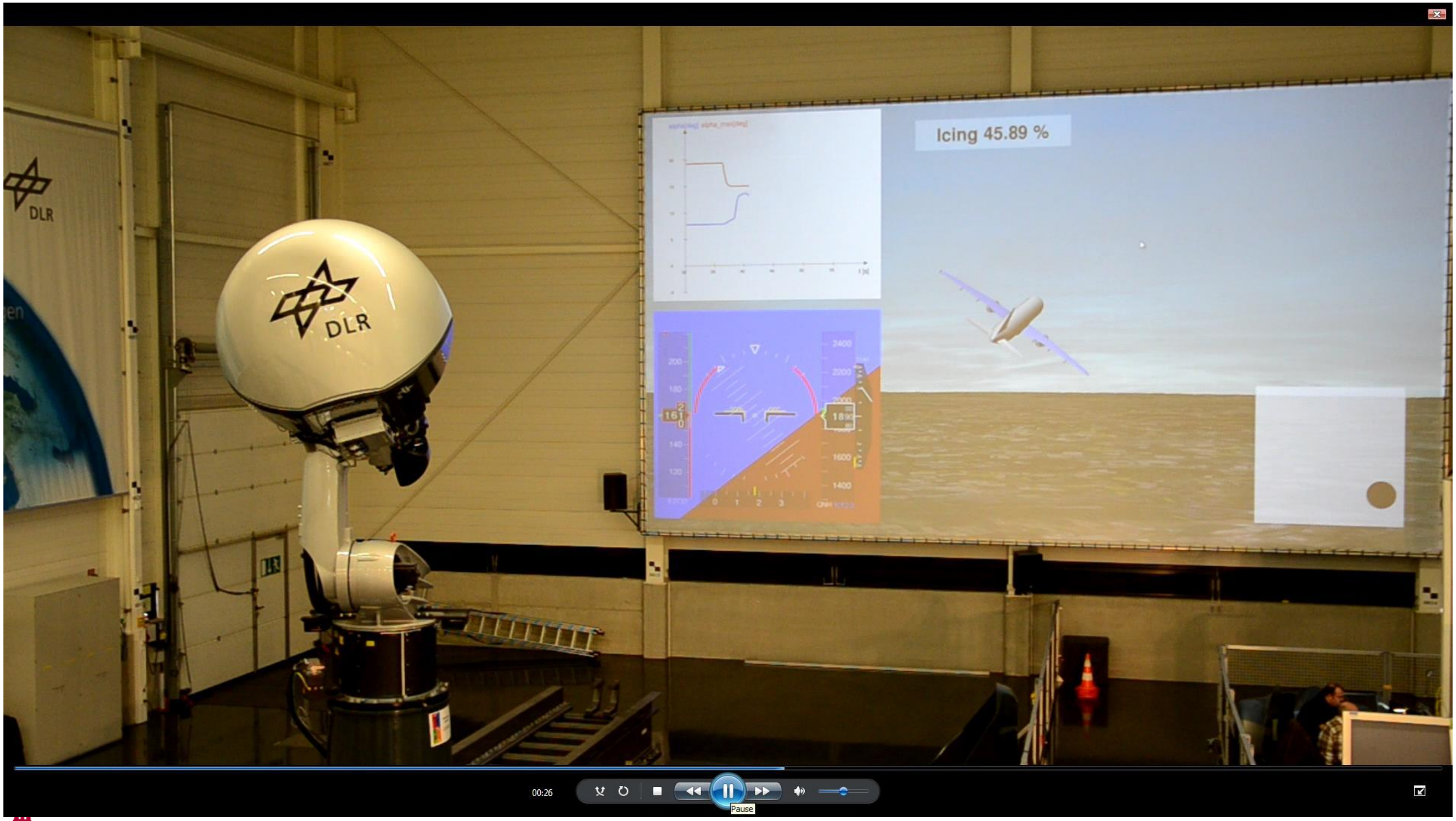


DLR Robotic Motion Simulator: overview



Simulator cab of
Robotic Motion Simulator

Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen



Conclusions of upset prevention

- Adaptive safe flight envelope estimation and protection algorithms were designed and evaluated by several airline pilots in various simulators

- Safe envelope bounds estimated in real time taking into account malfunctions and upsets, used for three kinds of protections:
  - Extended Primary Flight Display → Experiments in ACFS
  - Hard protections in the flight control laws
  - Haptic feedback on sidestick

  (all three) → Experiments in Simona

- Significant performance changes detected in icing scenario

- Observations with new technology:

ACFS experiments:

pilots adapted strategy based on information

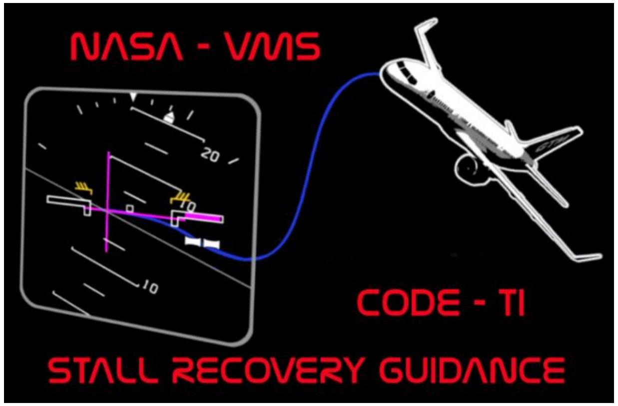
Icing scenario:

- higher V_{min}
- flap deployment for higher speeds

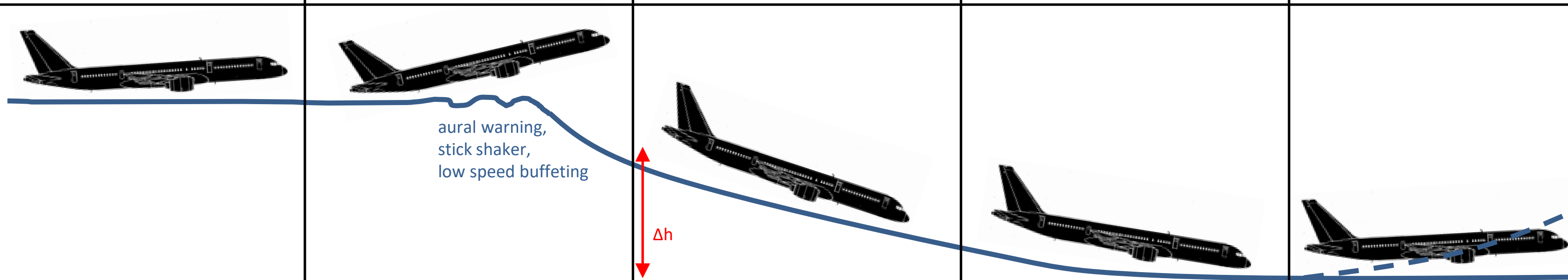
Simona experiments:

- larger safety margins to envelope boundaries prevent loss of control in off-nominal conditions,
- reduced workload (objective and subjective ratings),
- improved situational awareness (subjective ratings).

Stall Recovery Guidance



Sequence of events for stall recovery



onset to stall	stall occurrence	stall recovery		
		accelerating dive	pitch up	out of stall
Decreasing airspeed, increasing angle of attack	Speed below stall speed, alpha exceeds stall value	Trade altitude for speed, potential → kinetic energy	Transition to level flight, avoiding secondary stalls or overstressing structure	Establish level flight or climb
FAA stall recovery template:	1. Disconnect autopilot and autothrottle/ autothrust	2. Nose down until stall indications eliminated, 3. Bank wings level, 4. Apply thrust as needed 5. Retract speed brakes and spoilers	6. Return to the desired flightpath	

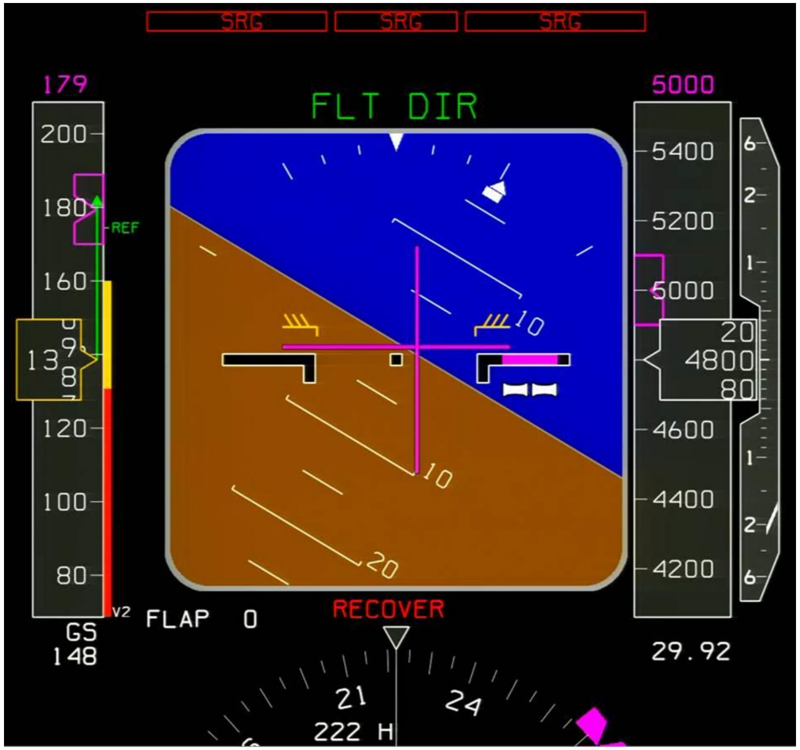
Upset recovery: stall recovery guidance

Strategy: exchange potential energy (altitude) for kinetic energy (speed), taking into account energy dissipation (drag) and energy inflow (thrust)

Constraints:

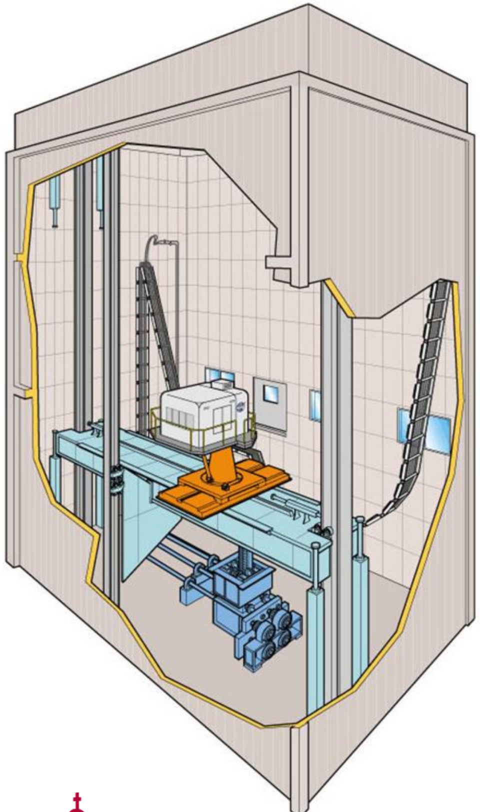
- Secondary stalls (α)
- Structural loads (n_z)
- Pitching moment (T_{max})

Pilot guidance through flight director (θ_c) and throttle tape (T_c) in PFD



Evaluated in 3 different simulators

Vertical Motion Simulator
at NASA Ames

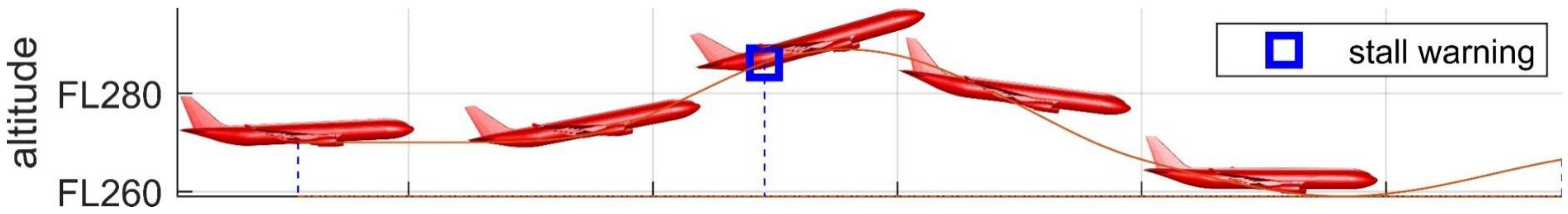


Research Flight Deck
at NASA Langley

Level D A330 simulator
at FAA

Experiment results

Traffic avoiding maneuver in cruise phase:



Performance improvements with guidance:

- Fewer and less severe secondary stalls
- Less total altitude loss during recovery
- No violations of maximum/minimum load factor limits
- On average shorter time to recover
- Better buffer to overspeed limit

Conclusions and remarks

- Overall, stall recovery guidance algorithms evaluated in 3 simulators
  - NASA Ames
  - NASA Langley
  - FAA.
- 2 dissimilar aircraft configurations
- 65 participating flight crews:
  - 40 at NASA Ames (of which 10 test pilots)
  - 13 at NASA Langley (Boeing pilots)
  - 12 at FAA (Airbus pilots)
- Different scenarios: cockpit display malfunctions, autothrottle failure, sensor faults, windshear, traffic avoiding maneuvers in all phases of flight.
- Satisfactory performance, well received by pilots.

Thank you for your attention

This work would not have been possible without:

Stefan Schuet, Diana Acosta, John Kaneshige, Kim Shish, Vahram Stepanyan
Gertjan Looye, Andreas Seefried, Miguel Neves, Tobias Bellmann,
Joost Ellerbroek, Mitchell Rodriguez y Martin