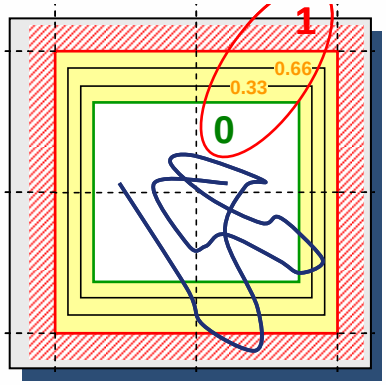
FMRA

Fachgebiet Flugmechanik, Flugregelung und Aeroelastizität



Berlin Institute of Technology

WAKE VORTEX SEVERITY CRITERIA FOR TAKEOFF AND DEPARTURE

S. Amelsberg – 2 June 2010

WakeNet3 - Europe Specific Workshop: Models and Methods for WVE Simulations

Introduction

- **Motivation**

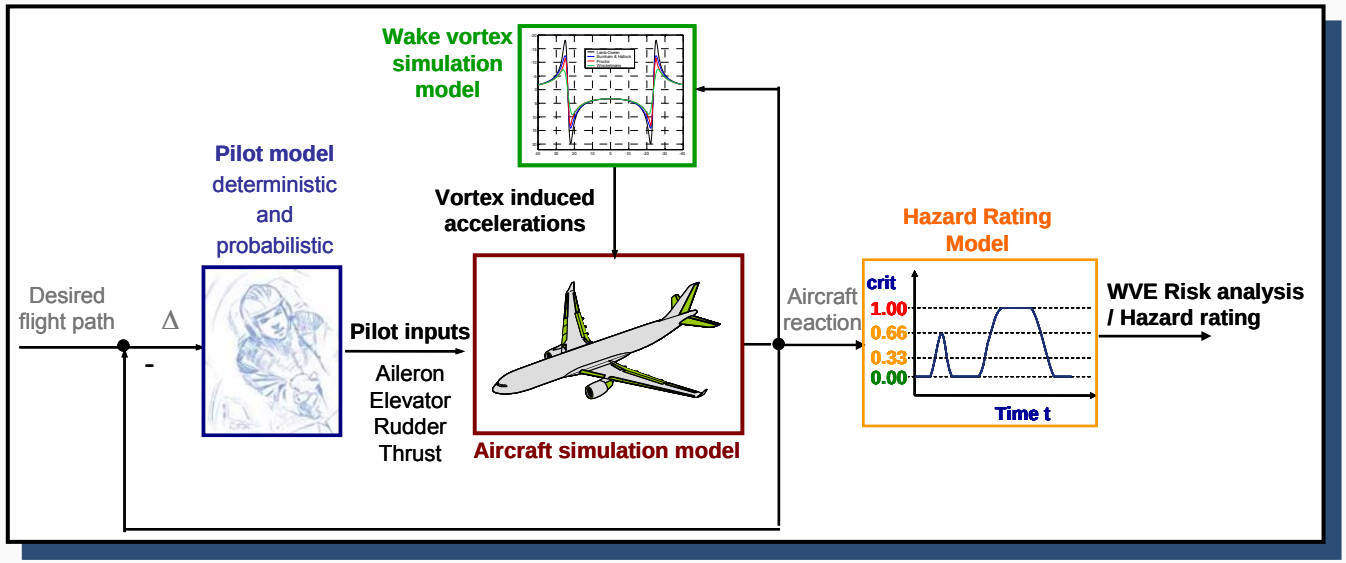
  Risk analysis→ Monte Carlo Simulation

  Application: Wake Vortex Encounter (WVE)

  → Models needed:
  - Aircraft
  - Vortex model (Evolution, Interaction)
  - Pilot behaviour
  - **Hazard rating**

- **Objective**
  - o Identify severity criteria → objective a/c state parameters
  - o Assess effect of WVE on pilot work load and flight safety
  - o Applicable for MCS
  - o Verify with human pilot hazard rating

Elements of MCS



Content

- Development process
- Structure of severity metrics
  - Parameters for severity envelopes
  - Limits of severity envelopes
- Verification
- Conclusion

Identification Process and Application

FCOM (Flight Crew Operational Manual)

Normal / special procedure

Previous projects

S-Wake

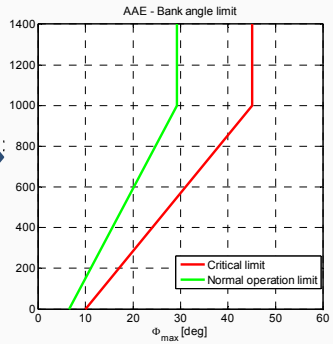
WEHA

Paper

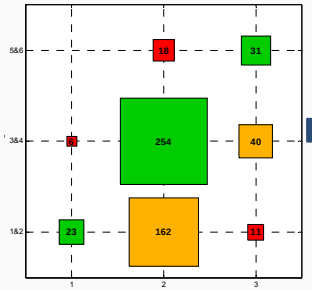
J. Wilborn, Boeing

A. Reinke, Airbus

Parameter choice
Define limits of envelopes



Test evaluation
(Time histories & Questionnaires)



Severity criteria model

SC

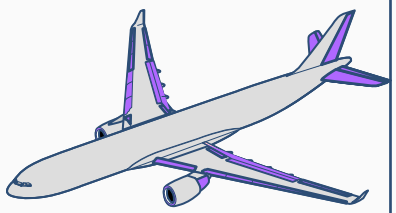
Normal / special procedure

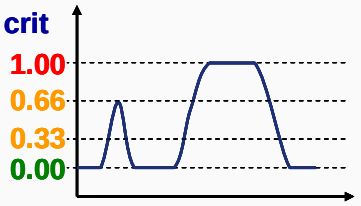
SC

Wake Vortex

Control inputs

Monte Carlo Simulation





WVE Risk analysis / Hazard rating

Evaluation of Simulator Data

- Investigate the effect of a WVE on pilot work load and safety
  - o A330 Full-Flight Simulator, Berlin
  - o A320 THOR Simulator Hamburg
- Pilots experienced with different kind of encounters (magnitude, character)
- 576 WVE were flown by 15 pilots in the A320 simulator
- 691 encounters in the A330 by 11 pilots with different flight experience

Scenery	Frankfurt/Main airport (EDDF)
Runway	25R – 249°
SID	TOBAK2F
Crew	Pilot + Co pilot (Engineer)
Visibility	CAVOK
Wind QNH	190° / 10kt 1013.5hPa

	A320 (Airbus)
A/C type	A320-200
A/C GW	66000 kg
CG	25% MAC
Thrust setting	Flex 42
V_{Rot}	137 kts (Flaps 2)
V_2	142 kts (Flaps 2)

Evaluation of Simulator Data

- After each encounter a questionnaire has to be filled

Wake Vortex Encounter Investigations

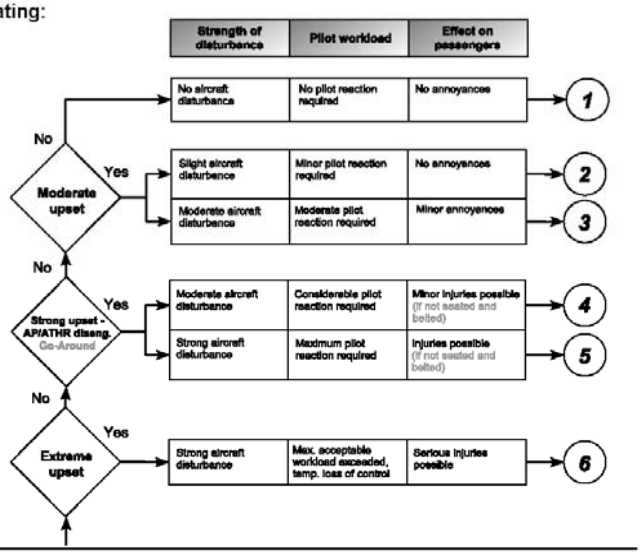
Pilot Briefing Information

Pilot : Date : [FCE] [FXE]

Run No. : ..... Case No.: ..... [M] [AP]

1a. Encounter Type: [P] [R] [Y]

1b. Hazard Rating:



2a. Which action was taken: AP Man. Diseng. | AP Aut. Diseng. | ATHR Diseng. | GA _____

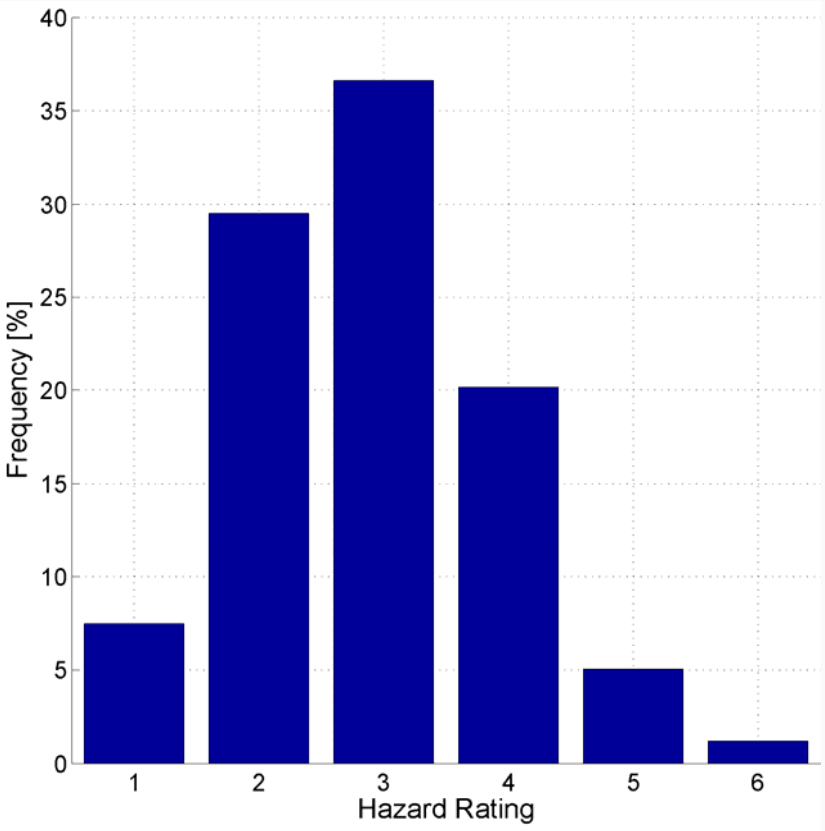
2b. What triggered the decision: P | R | Y | Sys. _____

3. Max. Alert level: No Alert | Caution | Avoid

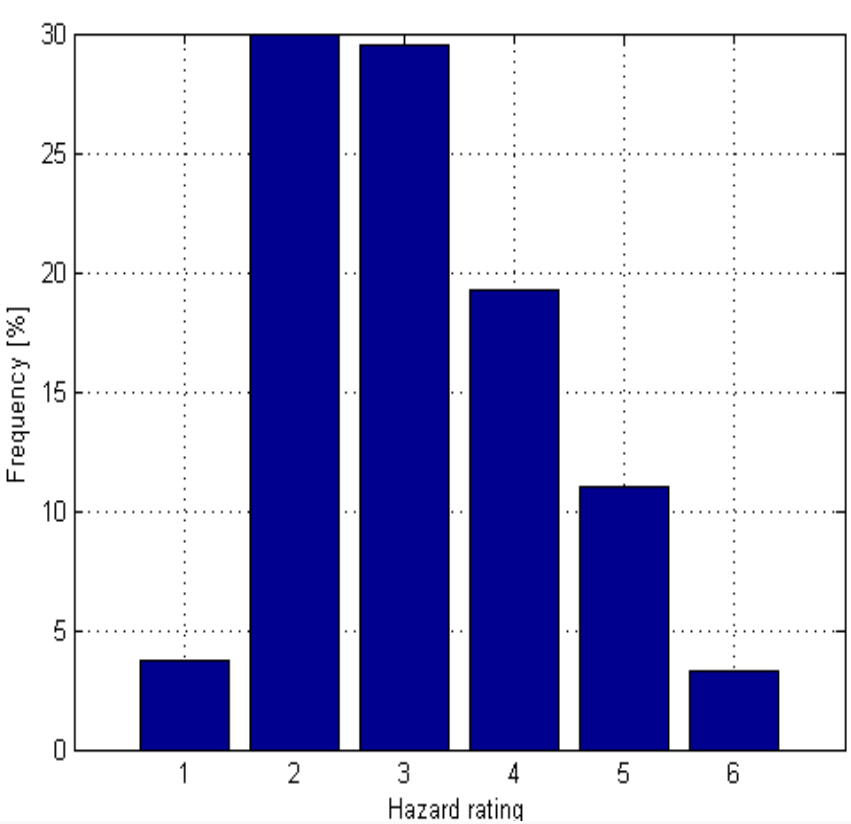
Remarks: (e.g. how was AP/ATHR disengaged?)

Evaluation of Simulator Data

- Pilot judge the impact of the wake vortex encounter and the resulting aircraft response on a scale between 1 and 6. This value is called the *Hazard Rating*.



A320 overall distribution of Hazard Ratings (576 encounters in total)



A330 overall distribution of Hazard Ratings (691 encounters in total)

Identification of Severity Criteria

Requirement

- SC for WVE shall be an objective measure
- Take into account all relevant a/c parameters
- Applicable to different flight phases and different aircraft types (minor adaptations)
- Easy to integrate into a simulation environment
- Applicable on fast-time simulations

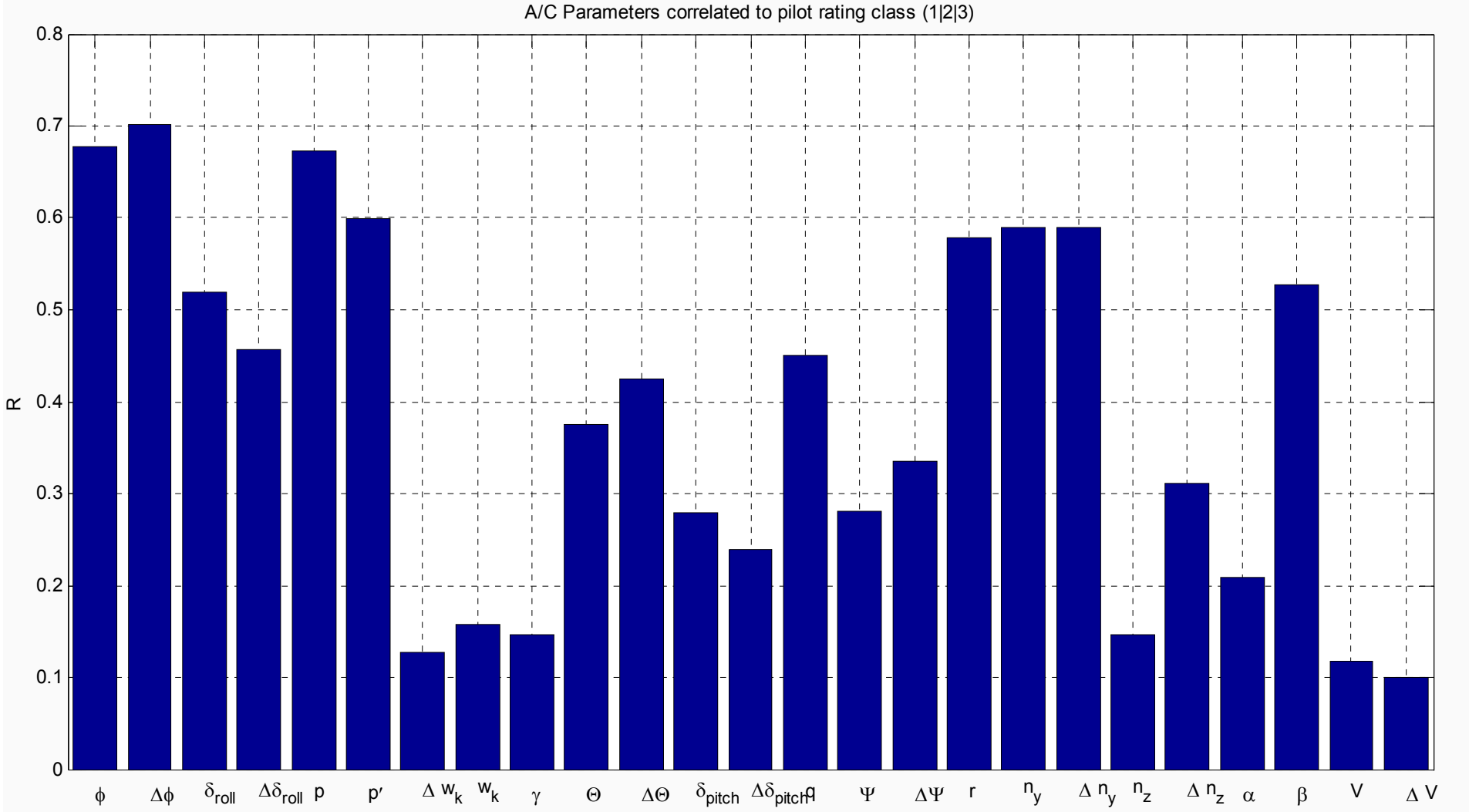
The severity criteria were derived by:

- The limits for severity metrics based on handbook data published e.g. in
  - Flight Crew Operating Manual (FCOM),
  - airline standards for passenger transport,
  - and evaluations of simulator tests.

- Engineering judgement
- Parameter correlation between a/c state parameter and pilot ratings

Evaluation of Simulator Data

- Correlations between aircraft upset parameters and hazard ratings



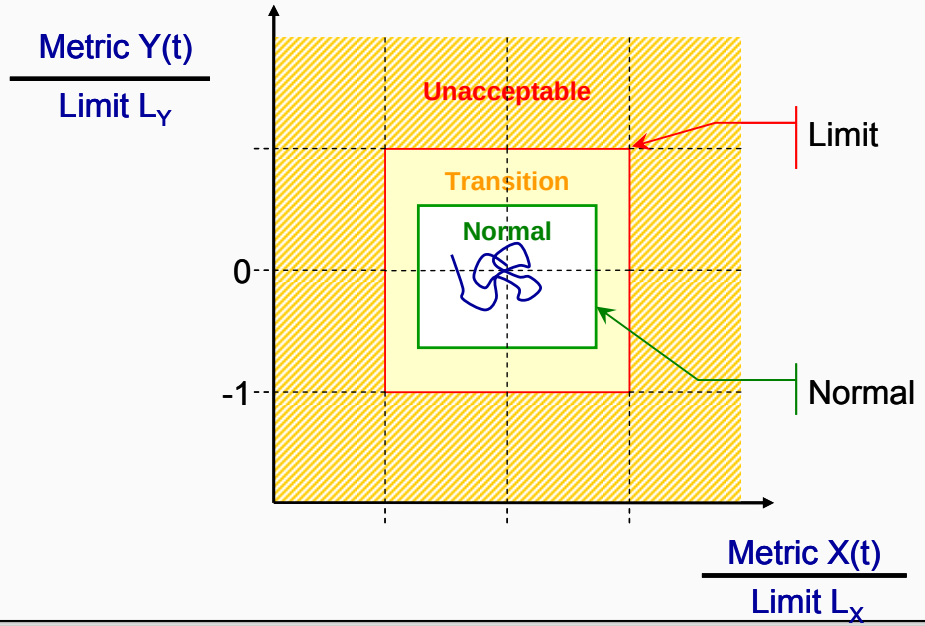
Hazard Metric and Envelopes

- The hazards are described by the following objective metrics
- 2 metrics that are related to a specific hazard type are combined in one envelope

Hazard	Metric	Envelopes
Unusual aircraft attitude	Bank angle Φ Pitch angle θ	**Aircraft Attitude Envelope (AAE)**
Loss of aircraft attitude control	Uncommanded roll δ_{roll} Uncommanded pitch δ_{pitch}	**Attitude Control Envelope (ACE)**
Exceedance of normal aerodynamic envelope	Angle of attack α Sideslip angle β	**Air Flow Envelope (AFE)**
Large accelerations within the cabin an flight deck	Vertical load factor n_z Horizontal load factor n_y	**Cabin Acceleration Envelope (CAE)**

General Hazard Metric

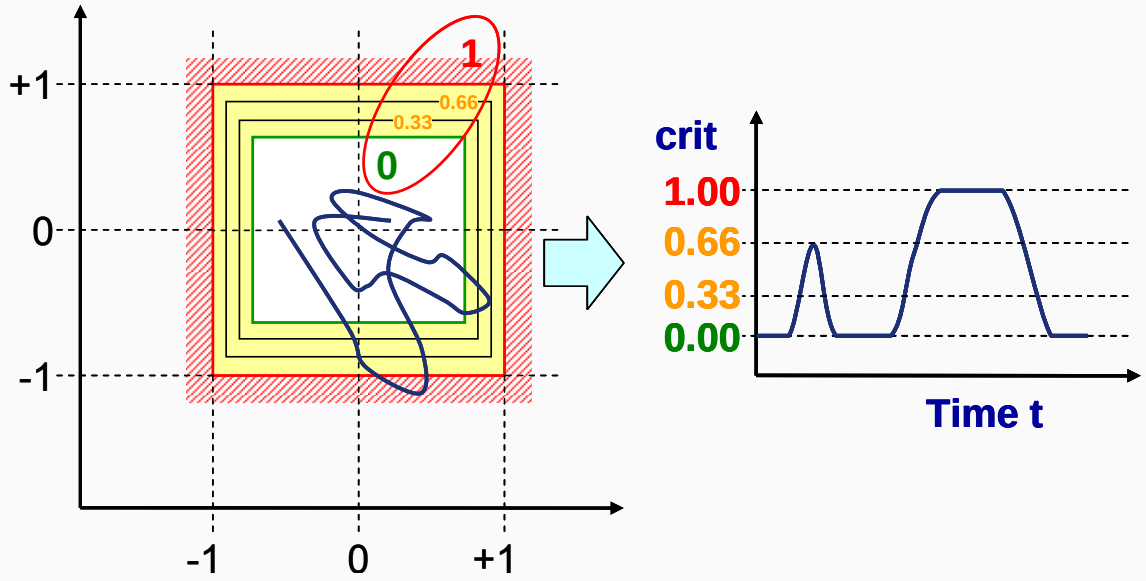
- Each envelope combines the two metrics, the most relevant for a specific hazard
- The metrics are normalized by specific limits
- The outer (red) envelope represents the boundary to a region which is considered "Unacceptable“→ Hazard
- The inner (green) envelope represents the area of "Normal" operation
- Both envelopes can depend e.g. on height, aircraft type and/or configuration
- Transition region, characterized operation outside usual boundaries, but not yet exceeding the limit.



General Hazard Metric

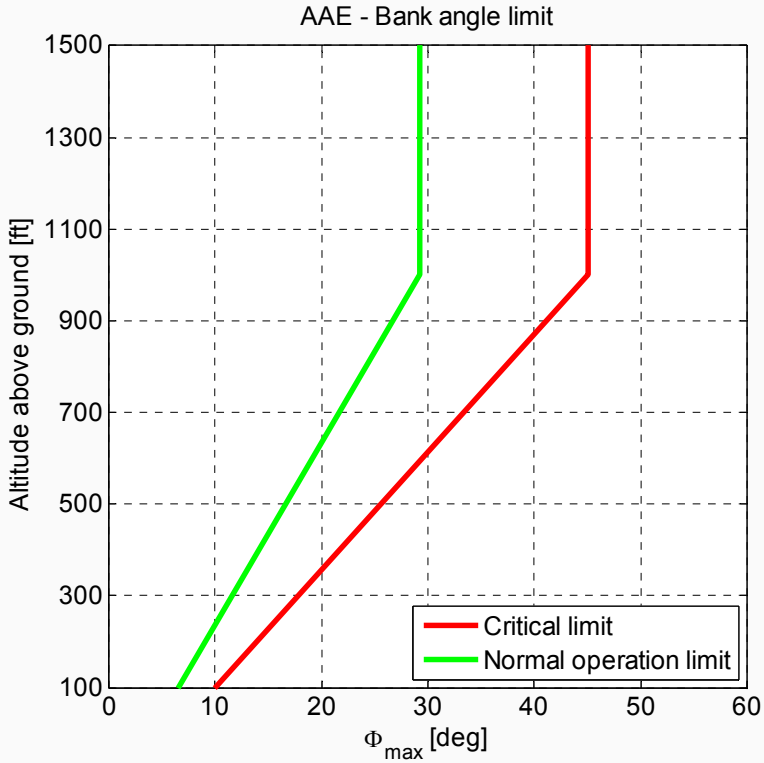
Three states of the severity criterion:

- If within the normal envelope
  criterion = 0.0
- If within the transition region:
  0.0 < criterion < 1.0
- If outside limit envelope:
  criterion = 1



Aircraft Attitude Envelope (AAE)

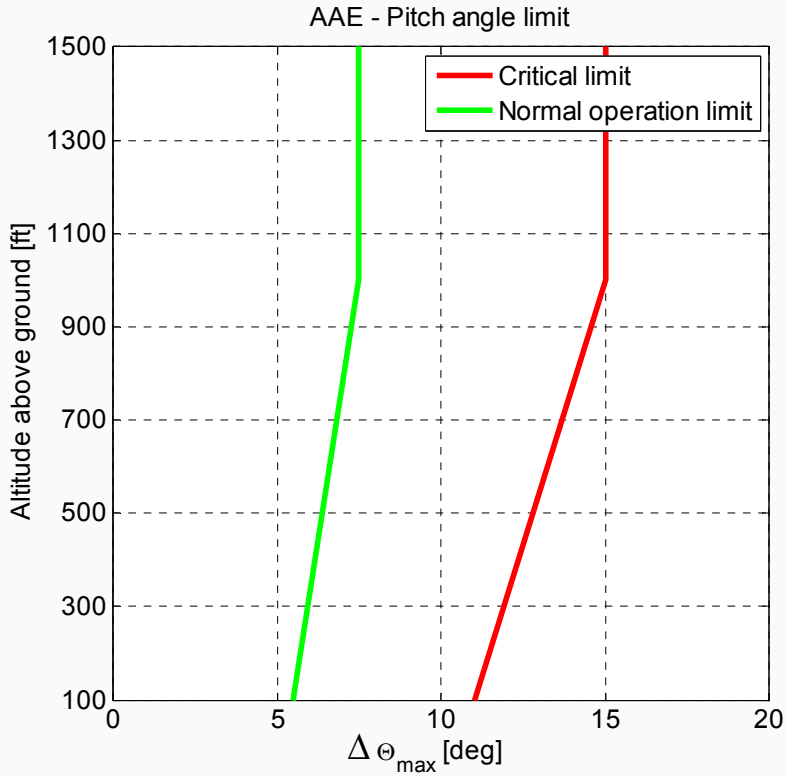
- **Bank angle limits:**
  - Symmetric
  - Limits Consistent with
    - AP disconnect ($|\Phi| = 45°$)
    - Airbus flight control philosophy (stick-free sustained $\Phi = \pm 33°$)
    - Ground clearance (9.1°-15° depending on actual pitch angle)
  - Comparable to NASA 707/720 VFR bank over height WV hazard criterion



- **Above 1,000 ft AGL:**
  - Normal operation if $|\Phi| < 33°$
  - Upset if $|\Phi| > 45°$
- **Below 1,000 ft AGL:**
  - Linear variation of limits
- **After rotation (above 100 ft AGL):**
  - Normal operation if $|\Phi| < 7.5°$
  - Upset if $|\Phi| > 15°$

Aircraft Attitude Envelope (AAE)

- **Pitch angle limits:**
  - Symmetric about reference
  - Reference is f (A/C type, GW, V_{Ref} and Config), changes in take-off (Θ_{ref} =15° , H>100 ft AGL)
  - Consistent with
    - Airbus flight control philosophy (pitch attitude protection, Θ> 30°)
    - PFD ranges up to 22.5°



- **Above 1,000 ft AGL:**
  - Normal operation if $|\Delta\Theta| < 7.5°$
  - Upset if $|\Delta\Theta| > 15°$
- **Below 1,000 ft AGL:**
  - Linear variation of limits
- **After rotation (above 100 ft AGL):**
  - Normal operation if $|\Delta\Theta| < 5.5°$
  - Upset if $|\Delta\Theta| > 11°$

Cabin Acceleration Envelope (CAE)

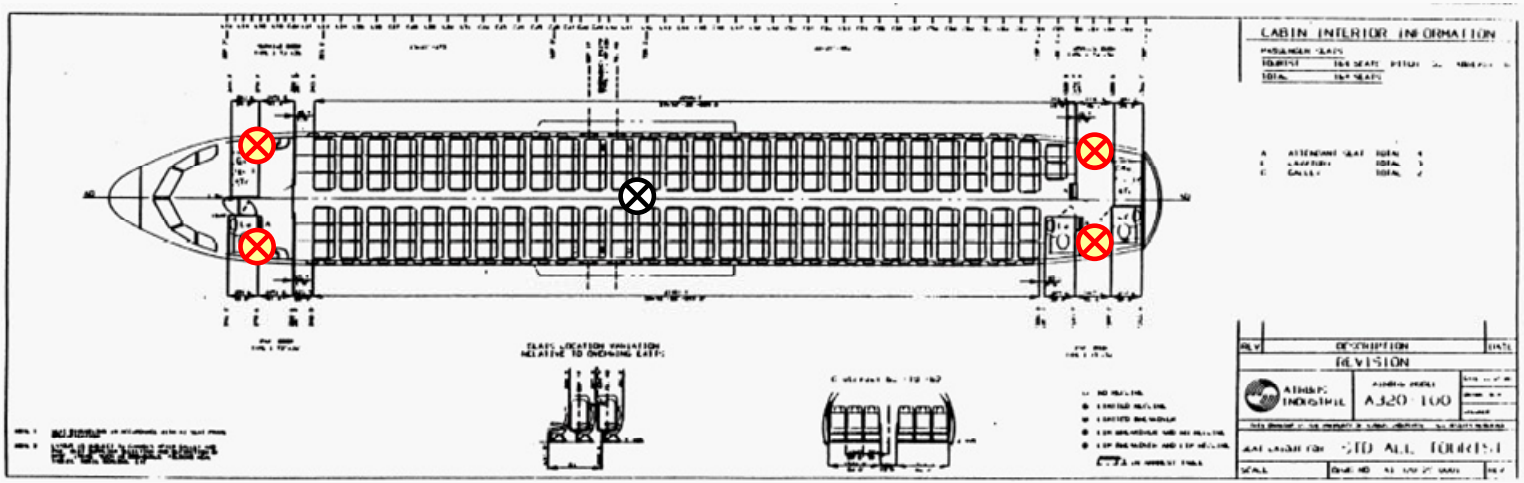
- **Cabin acceleration limits** are evaluated at the four most susceptible locations
  - Front of cabin, left and right
  - Rear of cabin, left and right
- Limits derived from
  - allowed load factors → aircraft operational documentation
  - typical accelerations encountered during flight in moderate to high atmospheric turbulence

Lateral cabin acceleration upset limit:

- ±0.5g
- Normal operation: set to ±0.3g

Vertical cabin acceleration upset limit:

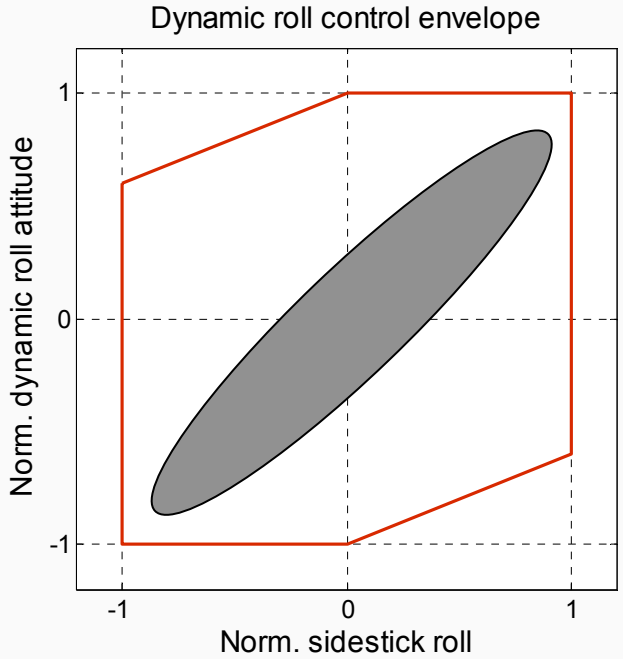
- 2.0g upper limit, 0.0g lower limit
- Normal operation: set to 1.5g



Attitude Control Envelope (ACE)

- **The Attitude Control Envelope** consists of two sub-envelopes:
  - Dynamic Roll Control Envelope (DRCE)
  - Dynamic Pitch Control Envelope (DPCE) (next slide)

- **DRCE limits**
  - The DRCE limits of this envelope reflects whether the trend in ϕ' is consistent with the roll control command
  - The constant limit of 70° above 1000ft based on the max. allowed bank angle of 67° (FCOM) + max. commanded roll rate of 15°/s multiplied with 0.2 seconds.



$$DRCE\ \Phi' = \Phi + p \times 0.2s$$

- **Above 1,000 ft AGL:**
  - Normal operation if $|\Phi'| < 60°$
  - Upset if $|\Phi'| > 70°$

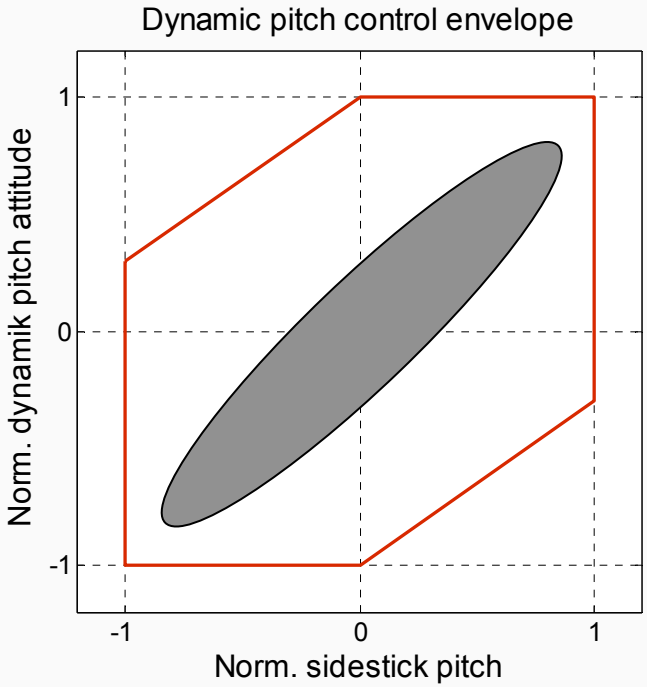
- **Below 1,000 ft AGL:**
  - Linear variation of limits

- **After rotation (above 100 ft AGL):**
  - Normal operation if $|\Phi'| < 30°$
  - Upset if $|\Phi'| > 35°$

Attitude Control Envelope (ACE)

DPCE limits

The DPCE limits of this envelope reflects whether the trend in θ' is consistent with the pitch control command

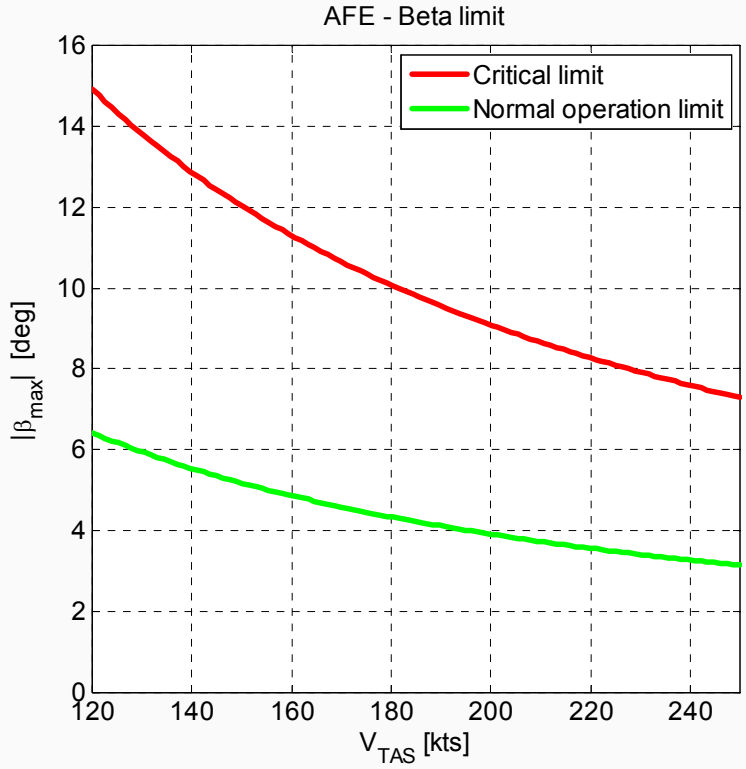


DPCE $\rightarrow \theta' = \theta + q \times 0.2s$

- **Above 1,000 ft AGL:**
  - o Normal operation if $|\theta'| < 15°$
  - o Upset if $|\theta'| > 30°$
- **Below 1,000 ft AGL:**
  - o Linear variation of limits
- **After rotation (above 100 ft AGL):**
  - o Normal operation if $|\theta'| < 7.5°$
  - o Upset if $|\theta'| > 15°$

Air Flow Envelope (AFE)

- **AoA upset limit:**
  - The angle of attack metric is calculated as a difference to a reference angle of attack: $\alpha_{max}=\alpha-\alpha_{ref}$; $\alpha_{ref}=6°$
  - Alpha stall warning as upper limit = f (A/C type, GW, Config)= 14°
  - Alpha0 as lower limit = f (A/C type, Config)
  - Normal operation: set to 75%



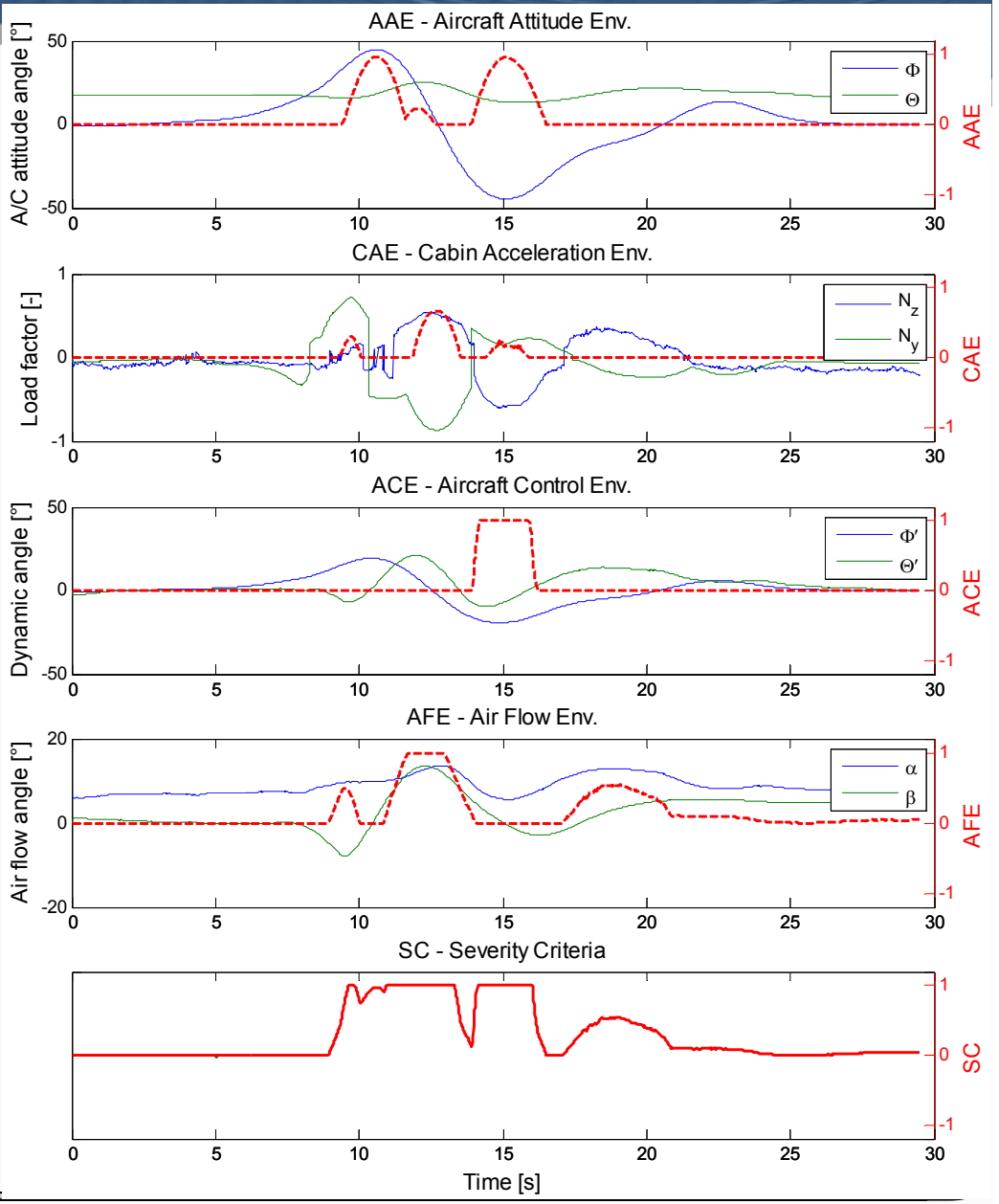
- **Angle of sideslip upset limit:**
  - Derived from maximum allowed crosswind for takeoff = f (V_{Ref})
  - Normal operation: set to 50%

Severity Criterion

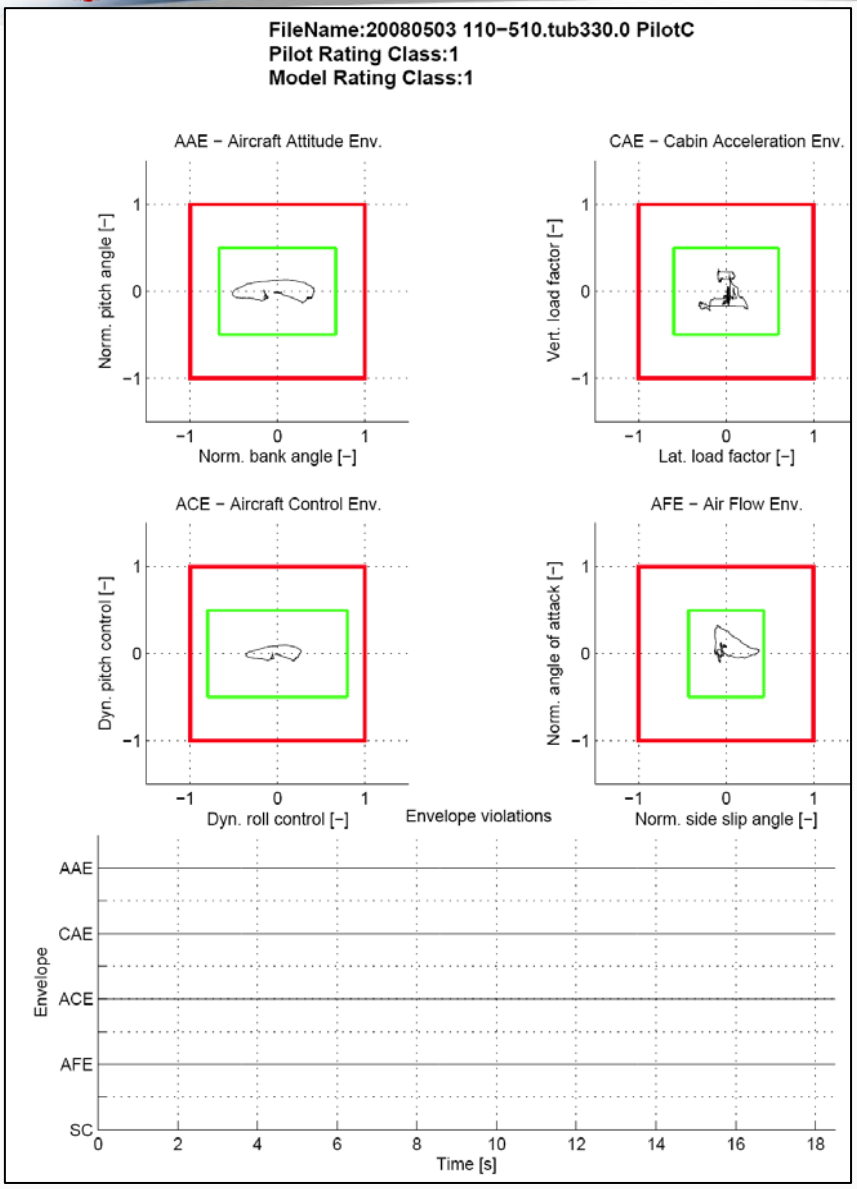
- A situation is identified as unacceptable if
  - a single limit envelope is violated
    - *OR*
  - several normal envelopes are violated

- Mathematically the severity criterion is the sum of envelope criteria

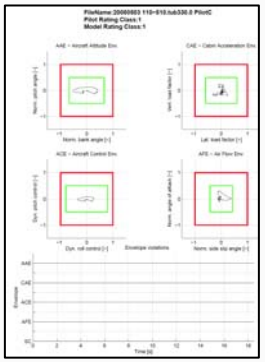
$$SC(t) = \min[\,1,\ AAE(t) + ACE(t) + AFE(t) + CAE(t)\,]$$



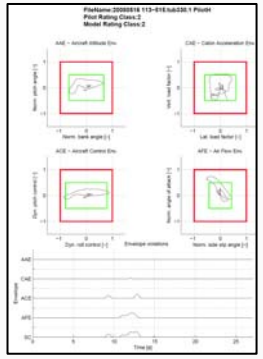
Example of Severity Class



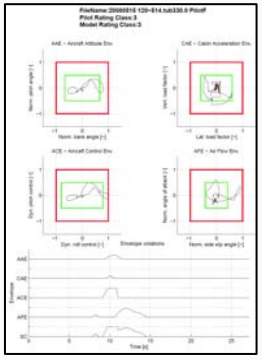
Example for Severity Class 1



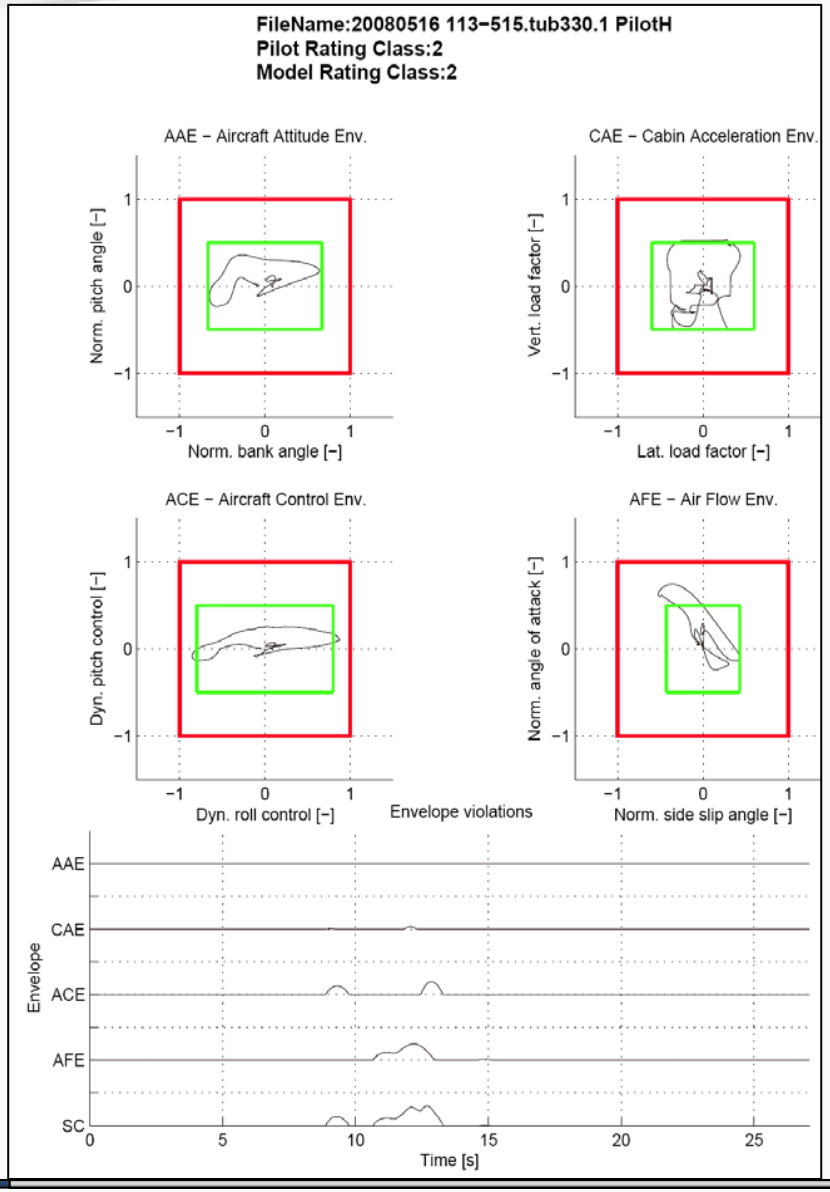
Example for Severity Class 2

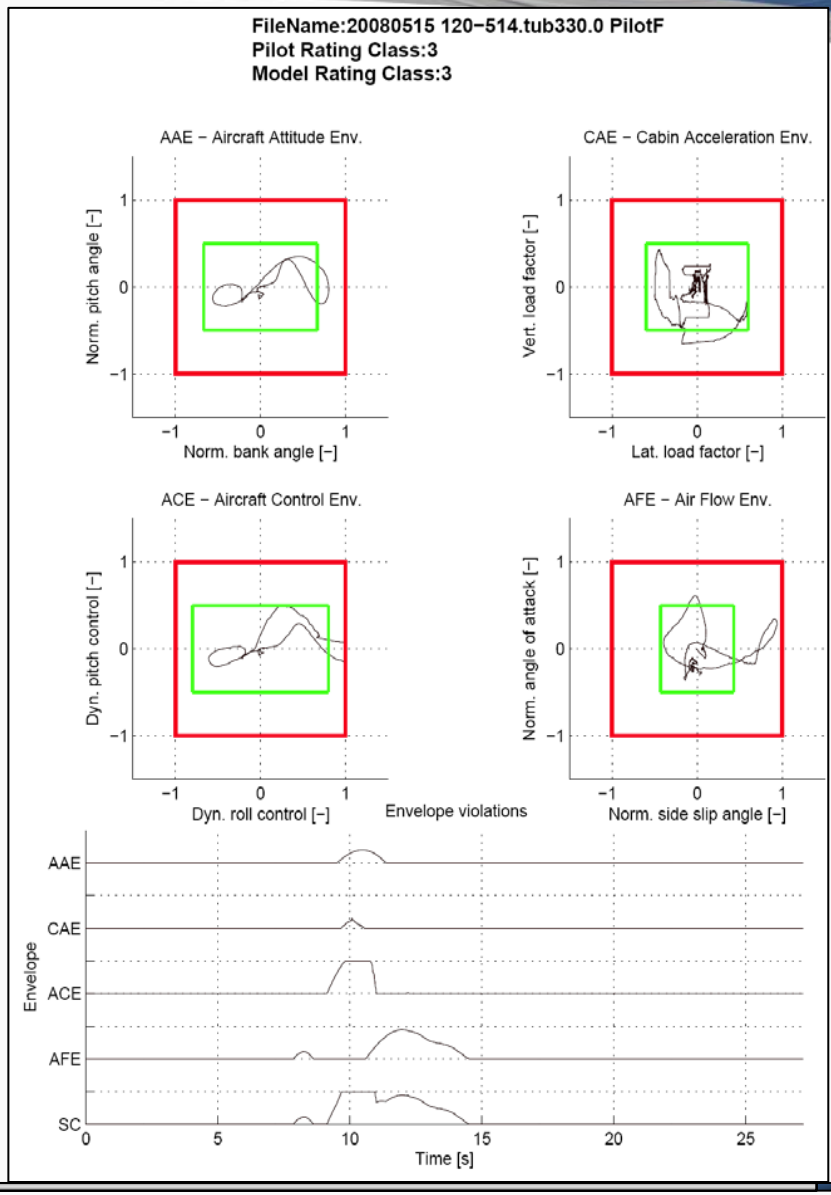


Example for Severity Class 3



Example of Severity Class





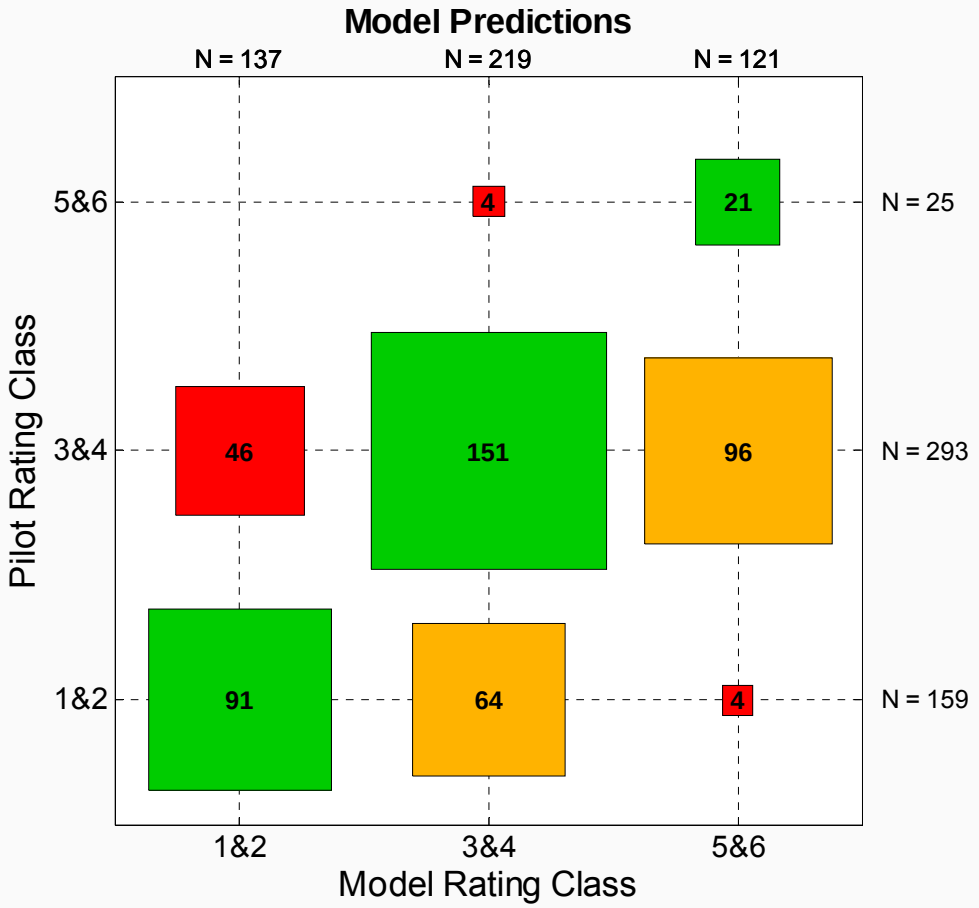
Verification of Severity Criterion

- Comparison between human pilots rating and the model prediction for hazard of wake vortex encounters

Severity categories related to pilot ratings

Category	Pilot Rating	Severity Criterion
1	1-2	SC=0
2	3-4	0 < SC < 1
3	5-6	SC = 1

- Correct prediction: 55.14%
- Conservative Prediction: 33.54%
- False Prediction: 11.32%



Conclusion

- A severity criterion has been developed based on a multi-parameter approach
- Verified with pilot hazard ratings
- The criterion was applied for takeoff within the CREDOS project on A320 and A330
- It can be easily adapted to other flight phases, as well as to other aircraft types
  - Most parameters needed to adapt the criterion to a specific aircraft can be taken from readily available handbook data.
  - Remaining parameters can be determined with the developed methodology
- The prediction performance of this criterion with respect to the simulator data is satisfying

Recommendations

- Refining the boundary definition for normal operations
- Verification of the presented hazard metrics for other flight phases or encounter types
  - The verification in CREDOS was covers only takeoff (low-speed range) and roll dominated encounters
- Consider variable reference parameters for alpha, theta, etc. for different flight phases (Ground law, …)
- Validation by flight recorder data (expensive, long term)

Thanks for your attention!

Questions?