The CREDOS Project

Wake vortex encounter severity criteria for take-off and departure

D3-5

Abstract:
In subtask 3.1.6 criteria shall be identified that quantify the severity of a Wake Vortex Encounter (WVE) during takeoff and departure. This paper (D 3-5) describes the development process of suitable metrics that are able to estimate the hazard of a wake vortex encounter situation based on objective a/c state parameters. It is applicable for Monte Carlo simulation and suitable for risk assessments. The hazard estimation based on the identified criteria is verified with the hazard ratings of human pilots. This reference data were gathered during piloted simulator tests performed in subtask 3.1.5 in the CREDOS project.
Author
Swantje Amelsberg, TU Berlin

Edition history

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GLOSSARY

Symbols

\( \alpha \) \hspace{1em} \text{Angle of attack} \\
\( \beta \) \hspace{1em} \text{Angle of sideslip} \\
\( \gamma \) \hspace{1em} \text{Climb angle/flight path angle} \\
\( \delta_{\text{roll}} \) \hspace{1em} \text{Sidestick roll} \\
\( \delta_{\text{pitch}} \) \hspace{1em} \text{Sidestick pitch} \\
\( H \) \hspace{1em} \text{Altitude above ground} \\
\( \phi \) \hspace{1em} \text{Bank angle} \\
\( p \) \hspace{1em} \text{Roll rate} \\
\( p' \) \hspace{1em} \text{Roll acceleration} \\
\( \psi \) \hspace{1em} \text{Azimuth angle} \\
\( n_y \) \hspace{1em} \text{Lateral load factor} \\
\( n_z \) \hspace{1em} \text{Vertical load factor} \\
\( R \) \hspace{1em} \text{Correlation coefficient} \\
\( r \) \hspace{1em} \text{Yaw rate} \\
\( \theta \) \hspace{1em} \text{Pitch angle} \\
\( V \) \hspace{1em} \text{True air speed} \\
\( w_k \) \hspace{1em} \text{Sink rate} \\
\( \sigma \) \hspace{1em} \text{Level of relevance}

Abbreviations

A/C \hspace{1em} \text{Aircraft} \\
AD \hspace{1em} \text{Airbus Deutschland GmbH} \\
FAR \hspace{1em} \text{False Alarm Rate} \\
FCOM \hspace{1em} \text{Flight Crew Operating Manual} \\
FD \hspace{1em} \text{Flight Director} \\
HTR \hspace{1em} \text{Hit Rate} \\
ICAO \hspace{1em} \text{International Civil Aviation Organization} \\
MCS \hspace{1em} \text{Monte Carlo Simulation} \\
NN \hspace{1em} \text{Neural Networks} \\
PM \hspace{1em} \text{Pilot Model} \\
POP \hspace{1em} \text{Probability of prediction} \\
SID \hspace{1em} \text{Standard Instrument Departure Route} \\
TUB \hspace{1em} \text{Technische Universität Berlin (TU Berlin)} \\
WVE \hspace{1em} \text{Wake Vortex Encounter}
EXECUTIVE SUMMARY

To quantify the risk of a specific event the probability (frequency) and the severity must be determined.

WakeScene-D [4] (subtask 3.1.2) was developed to quantify the probability of severe wake vortex encounters for reduced wake separation minima during departure.

To judge the hazard of a wake vortex encounter under certain conditions, severity metrics are needed that indicate whether an encounter is a safety hazard or not. For this purpose, TU Berlin developed advanced criteria during the CREDOS project. The criteria were validated by using the same piloted simulator data as for the development of the pilot model [7]. They take into account several objectively measurable aircraft parameters (like e.g. load factors, air flow incidence angles or aircraft attitude), validated by the subjective judgment of the pilots, who had to rate each flown encounter with regard to the perceived safety hazard. Those criteria were implemented in VESA-D [11] and are computed for each simulated encounter. They allow the analysis of the influence of certain parameters on the wake hazard, as well as a statement on which fraction of the simulated encounters were actually hazardous. As the encounters provided by WakeScene-D are merely "potential encounters", not knowing how severe they really are for flight safety, this provides the last step in a risk assessment. It allows computing the fraction of take-offs (of the original number simulated in WakeScene-D) which surpass specified limits, and comparing this number between different scenarios.

Within CREDOS these scenarios are different separation distances between aircraft categories under different crosswind conditions. The structure of the severity criteria follows an approach initially suggested by Wilborn [8] for aircraft loss-of-control but not specifically wake vortex encounters. An extension and refinement for use as severity criterion for wake vortex encounters was originally proposed by Reinke [12]. It is based on combining parameters critical for the safety of the wake-encountering aircraft into so-called envelopes while at the same time defining limits within which these parameters must stay. For the take-off simulations in CREDOS four envelopes have been defined:

- Aircraft Attitude Envelope (AAE), taking into account bank and pitch angle attitude
- Cabin Acceleration Envelope (CAE), taking into account the maximum lateral and vertical accelerations in the cabin
- Aircraft Control Envelope (ACE), taking into account the necessary side stick roll and pitch control inputs to recover the aircraft with respect to the actual aircraft motion in the corresponding axis
- Air Flow Envelope (AFE), taking into account the angle of attack and sideslip

This report describes the process of defining these envelopes as well as their verification with available simulator data. For the verification the prediction performance, defined as the ration between model predicted hazard rating and subjective human pilot hazard rating, of the developed severity rating model was derived. For the A320 the model rated in 55% encounter cases the same hazard category as the human pilot rated for the same encounter situation, in 34% cases one category higher (more severe), and in 11% one category lower or two higher in comparison to the airline pilots. For the A330 the model rated in 57% of the encounter cases the same category as the human pilots, in 37% one category higher, and in 6% cases one category lower or two higher in comparison to the human pilots.
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1. INTRODUCTION

The CREDOS (Crosswind - Reduced Separations for Departure Operations) project, funded by the European Commission, studies the concept of reduced wake turbulence separation between consecutive departing aircraft for single runway operations [1]. For the validation of this concept, a risk assessment with respect to wake vortex encounter risk is required. The chosen method computes wake vortex encounter probabilities and encounter severities by means of fast-time Monte Carlo simulations (MCS). This approach is commonly used for risk assessment as real-time pilot-in-the-loop simulations are too time-consuming and therefore not suitable for MCS. The aim of the MCS is to assess the potential impact of the proposed reductions in separation on flight safety and the efficiency of airport operations in crosswind conditions. As simulation results shall be used to revise separation standards without negative impact on safety, they have to be accepted by the authorities. Therefore all models need to have a high fidelity and strict validation requirements apply for all parts of the simulation including the aircraft model, the aircraft vortex interaction model, the model for the pilot control behaviour, and a model to assess the effect of the wake vortex encounter on pilot workload and flight safety, see FIG 1-1..

As a part of CREDOS, Technische Universität Berlin (TU Berlin) has developed Wake Vortex Encounter (WVE) severity criteria for risk assessment that shall quantify the effect of a WVE on flight safety while correlating reasonably well with subjective pilot assessment.

The objective data for the WVE severity criteria development was recorded in flight simulator tests, in which pilots experienced vortex encounters during climb out. The tests were performed on an Airbus A330 Level D Full-Flight Simulator and on an A320 development simulator. Commercial pilots from several airlines with varying flight experience participated in the tests. The subjective data of pilot’s assessment of flight safety were gathered with questionnaires, the pilot had to fill in after each test run. The hazard rating scale ranges from slight aircraft upsets with no pilot reaction required up to extreme disturbances with temporary loss of control. The purpose of this questionnaire was to assess the effect of the wake vortex encounter on pilot workload and flight safety.

The objective is to develop severity metrics that assess the effect of WVEs on flight safety. That way the severity metrics shall be suitable for CREDOS risk assessment and applicable in Monte Carlo simulations, see FIG 1-1.
2. DESIGN DATA

2.1. DESCRIPTION OF SIMULATOR DATA

A detailed description of the piloted simulator tests can be found in [7]. Hence, this chapter gives only a brief overview of how the flight simulator data was gathered.

Two flight simulators were used to investigate piloting techniques and pilot control behaviour:

The Airbus A330 Full-Flight Simulator, that was located at TU Berlin, Institute of Aeronautics and Astronautics and is operated by the "Zentrum für Flugsimulation Berlin" (ZFB).

The A320 THOR Simulator, an Airbus development simulator, was located at Airbus Deutschland GmbH in Hamburg.

Both simulators are equipped with research facilities that allow efficient modifications of the simulator software for scientific experiments. The simulator software has been supplemented with the wake vortex encounter software package that was developed in the S-WAKE (Assessment of Wake Vortex Safety) project [3]. This allows highly realistic simulations of wake vortex encounters. A major difference is that the A330 simulator has a motion system whereas the THOR simulator is fixed-based. The importance and limits of motion simulation during wake vortex encounters was investigated in [2] reporting indications that pilot behaviour is affected by the cues from motion simulation. However, a final conclusion was not drawn as the statistical data base was too small. Therefore the hypothesis here is that the impact of motion on pilot response lies within the statistical variations.

Using the simulation tool WakeScene-D [4], a number of different test cases for the piloted simulator campaigns were developed that cover the most probable encounter conditions during take-off. Test cases are defined by the encounter geometry, encounter altitudes and vortex characteristics. The test scenarios were the same for both simulators and the conditions are given in TAB 2-1. For each test run, a constant crosswind was defined that is typical for a CREDOS scenario. The aircraft parameters are summarized in TAB 2-2.

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<td>Runway / SID</td>
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</tr>
<tr>
<td>Crew</td>
<td>Pilot flying from the left or right hand seat; supported by an engineer</td>
</tr>
<tr>
<td>Visibility</td>
<td>CAVOK</td>
</tr>
<tr>
<td>Wind</td>
<td>190° / 10kt</td>
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<tr>
<td>QNH</td>
<td>1013.5hPa</td>
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**TAB 2-1: Simulator test scenarios**

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<td>A/C gross weight</td>
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<td>160000 kg</td>
</tr>
<tr>
<td>CG</td>
<td>25% MAC</td>
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<td>$V_{rot}$</td>
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<td>126 kts (Flaps 2)</td>
</tr>
<tr>
<td>$V_2$</td>
<td>142 kts (Flaps 2)</td>
<td>133 kts (Flaps 2)</td>
</tr>
</tbody>
</table>

**TAB 2-2: Aircraft data for simulator tests**
During a simulator campaign, the pilots were flying departures, in which they experienced wake vortex encounters that varied in magnitude and character. As the pilots’ actions on the controls should be recorded, they were asked to fly most departures manually.

After each test run the pilot had to fill in a questionnaire, see FIG A-1. The purpose of this questionnaire was to assess the effect of the wake vortex encounter on pilot workload and flight safety.

First the pilot was asked to judge the type of the encounter as being roll-, pitch- or yaw-dominant. In the following the pilot should 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. The first level of the decision tree distinguishes between 3 categories:

- **HR 5-6**: An extreme upset, causing loss of control (temporarily)
- **HR 3-4**: Moderate upset, requires corrective control inputs
- **HR 1-2**: Slight or no noticeable disturbance

A decision between two ratings in each category is possible to account for variation in encounter strength. Explanations with regard to the strength of the experienced disturbance itself, the pilot’s workload and possible injuries in the cabin shall aid the decision between the ratings.

The second question tries to capture pilot decisions like initiating a Go-Around or disconnecting the Auto Pilot (AP)/ Auto Thrust (ATHR), and in case such a decision was taken by the pilot, which event triggered it. Such a trigger can be the aircraft reactions in the pitch, roll or yaw axis, a system warning or possible other events.

A third question is asking the pilot for the maximum desired alerting level for the encounter, if there was a system available in the cockpit which allows an alerting of the cockpit crew up to a few minutes in advance of a wake vortex encounter. Based on the experienced encounter in the simulator, the pilot shall decide if in reality, he would prefer to be cautioned of that encounter, or if the encounter was even strong enough to justify an evasive action, e.g. a heading or flight level change, to avoid the encounter. In case of an encounter during take-off, the pilot may also imagine being advised before beginning his take-off run.

In summary, 15 simulator sessions were carried out in the A330 simulator. 11 different airline pilots (6 captains, 5 first officers) flew 690 wake vortex encounters in total. On the A320 simulator, a total of 576 wake vortex encounters in 14 simulator sessions with 14 different pilots (5 captains, 9 first officers) were flown.

### 2.2. EVALUATION OF PILOTED SIMULATOR TESTS

The subjective pilot rating on each encounter situation was collected to develop safety guidelines for wake vortex encounters and to classify encounter severity for risk assessment of new flight procedures. The evaluation of the questionnaires shows that the personal assessment of encounter severity differs a lot between the pilots. The aircraft upset depends strongly on the pilot delay time, which can explain the differences in hazard ratings. Accordingly it will be tough to find generalized correlations between aircraft upset parameters and pilots hazard ratings, see FIG A-2. The Figure shows that the parameters representing the lateral a/c motion have a high correlation to the pilot hazard ratings, like bank angle, roll rate, roll acceleration, yaw rate, lateral load factor, and angle of sideslip. The pilot sidestick roll input gives also a good indication of the subjective hazard rating. Parameters of the longitudinal a/c motion, like delta pitch angle (pitch angle due to a reference depending on the stationary flight phase), pitch acceleration, and vertical load factor show also a significant correlation to the subjective pilot hazard ratings.
2.2.1. Distribution of Hazard Ratings

A320 THOR Simulator

The overall bandwidth in Hazard Ratings from all 14 simulator sessions in the A320 THOR simulator is shown in Figure 2-1. The statistics given in Figure 2-1 includes all flown encounter scenarios, hence it is impossible to conclude pilots rating tendencies based on this figure. Hazard Ratings ranges from 1 to 6 during the tests, with a weighting in the lower middle category (Ratings 2-3), and sufficient numbers of very strong and also very light encounters. This is considered a good mix to represent real life conditions.

![Figure 2-1: A320 overall distribution of Hazard Ratings (576 encounters in total)](image)

Figure 2-2 contains the correlation with the Alert Level desired by the pilots with the Hazard Rating they gave to each encounter. It shows the expected trend to higher Alerting Levels with higher Hazard Ratings. Based on a qualitative assessment of the distribution shown in the plot the following relation could be made:

- Alert Level 1 (No Alert) ⇒ Hazard Rating 1-2
- Alert Level 2 (Caution) ⇒ Hazard Rating 3-4
- Alert Level 3 (Avoid) ⇒ Hazard Rating 5-6

![Figure 2-2: Correlation of 3-scale Alert Level with Hazard Ratings, A320](image)
A330 Full Flight Simulator

Figure 2-3 shows the overall bandwidth in Hazard Rating for all fifteen A330 full-flight simulator sessions. The figure shows a similar distribution as for the A320 simulator.

![Figure 2-3: A330 overall distribution of Hazard Ratings (691 encounters in total)](image)

Figure 2-4 shows the correlation between the Alert Level expected by the pilots and the Hazard Rating for each encounter. It shows the expected trend to higher Alerting Levels with higher Hazard Ratings. The relation between Hazard Rating and Alert Level is not as clear as for the A320 tests. The Hazard Ratings for each desired Alert Level are in general distributed wider.

![Figure 2-4: Correlation of 3-scale Alert Level with Hazard Ratings, A330](image)

A correlation between a/c parameters and pilots hazard ratings was performed to identify relevant parameters that influence pilots' decisions in the view of the hazard of a wake vortex encounter situation. The results can be found in TAB 2-3. The correlation coefficient R with its corresponding level of relevance σ between a/c parameters and pilot hazard rating is given in TAB 2-3. The correlation coefficients from TAB 2-3 are visualized as a barplot in FIG A-2.
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<td></td>
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**TAB 2-3: Correlation between a/c parameters and pilot hazard rating**
3. SEVERITY CRITERIA DEVELOPMENT

3.1. REQUIREMENTS FOR WAKE ENCOUNTER SEVERITY CRITERIA

Wake vortex encounter severity criteria should be an objective measure for the question whether, and if possible to what extent, flight safety is impaired by a wake encounter. They should take into account all relevant parameters for different encounter hazards. These parameters, or metrics, can be determined using engineering knowledge as well as input from pilots experiencing actual wake encounters.

A good severity criterion should be general enough to be applicable to different flight phases as well as different aircraft types with only minor adaptations.

As a severity criterion will most likely be used also in simulation-based risk assessments, using large-scale computational assessments, it should be easy to integrate into a simulation environment without requiring too many computational resources. All required parameters and inputs must be well defined.

3.2. PREVIOUS WORK

Recent developments in the field of severity criteria took place e.g. during the project S-WAKE (“Assessment of Wake Vortex Safety”, 2000-2003). Results from this work published in [5]. These approaches were based on assessing one single metric, usually only in the lateral axis, to determine the hazard of the encounter. Furthermore these criteria were applied only to encounters during approach and it is not sure if they can easily be extended to other flight phases as well.

The definition of envelopes for the present work is primarily based on an approach initially suggested by Wilborn [8]. He combined multiple dynamic parameters like aircraft attitudes into a two-dimensional envelope while defining limits within which the parameters were allowed to stay for normal operation. These envelopes were not specifically aimed at wake vortex encounters but could be applied to different types of in-flight events. Further work by Reinke was done to apply this concept to wake vortex encounters [12]. Based on this work the criteria to be used in CREDOS should be set up.

3.3. DETERMINATION OF SUITABLE METRICS

To define the envelopes to be applied to assessment of wake encounters, the relevant metrics to be taken into account need to be identified. This was done using engineering judgement, parameter correlation of simulator data with pilot ratings as shown in FIG A-2 and by testing the performance of the severity criterion when applying it to the available simulator data. While all relevant metrics of the aircraft dynamics should be taken into account, care has to be taken that single parameters are not weighted disproportionately higher than others (e.g. by using load factors in a Cabin Acceleration criterion and a Load Factor at CG criterion at the same time).

Also, while the correlation with the pilot ratings in the simulator trials is considered a good way of verification, these ratings are not to be seen as the ultimate truth. Pilots sitting in the cockpit concentrating on flying the departure naturally cannot monitor and judge all of the influence parameters relevant in a wake encounter. Furthermore, being humans, they can always simply be wrong in their judgement of the hazard of a single encounter. Thus during the development of the severity criterion it was accepted that its prediction quality is not perfect when compared with pilot ratings, knowing that certain parameters, like air flow angles or cabin accelerations, were simply not assessed by the pilots.
A main challenge in the development is the proper determination of the applicable limits for each metric used in the envelopes. The limits for the different severity metrics presented in TAB 3-1 are based on handbook data published e.g. in the Flight Crew Operating Manual (FCOM), airline standards for passenger transport and own assumptions. They were determined keeping in mind that they should be easily adaptable to other aircraft types when needed.

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<thead>
<tr>
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<th>Metric</th>
<th>Envelopes</th>
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<tr>
<td>Unusual aircraft attitude</td>
<td>Bank angle $\phi$</td>
<td>Aircraft Attitude Envelope (AAE)</td>
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<td>Pitch angle $\theta$</td>
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<td>Exceedance of normal</td>
<td>Angle of attack $\alpha$</td>
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<td>aerodynamic envelope</td>
<td>Sideslip angle $\beta$</td>
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<tr>
<td>Large accelerations within</td>
<td>Vertical load factor $n_z$</td>
<td>Cabin Acceleration Envelope (CAE)</td>
</tr>
<tr>
<td>the cabin</td>
<td>Horizontal load factor $n_y$</td>
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</tbody>
</table>

**TABLE 3-1: Hazard, metric, and envelope definitions**

The envelopes and limits in the following sections are described based on A330 data. However, the qualitative setup is the same for the A320, only the values of the limits vary slightly. They can be found for both aircraft listed in TAB A-1 for the A320 and in TAB A-2 for the A330.

### 3.4. GENERAL ENVELOPE SHAPE

Each envelope combines two metrics that are 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". Unacceptable are situations leading to one of the consequences listed in TAB 3-1 under "Hazard".

An additional inner (green) envelope represents the area of "Normal" operation. Both envelopes can depend e.g. on height, aircraft type and/or configuration. The region between both envelopes is a transition region, characterized by operation outside usual operational boundaries, but not yet exceeding the limit.

![FIG 3-1: Metric shape](image)

The time history of the two metrics can then be plotted into the envelope to quickly visualize if a certain boundary is exceeded. Moreover, a criterion value for the specific envelope can be calculated for each time step based on the position in the envelope. Should the time
history plot exceed the red limit the severity criterion is one, if it stays inside the green region (normal operation) the severity criterion is set to zero. In the transition region the criterion is linearly interpolated between zero and one. This leads to 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

In the following the four envelopes used in CREDOS risk assessments are described, as well as how one combined severity criterion (SC) is computed from these envelopes.

3.4.1. Aircraft Attitude Envelope (AAE)

The aircraft attitude envelope reflects the aircraft attitude in bank angle and pitch angle. The bank angle is typically associated with WVE hazard. Large bank and pitch attitudes are inherently unsafe. The bank angle and pitch angle limits are linearly interpolated between 100ft (transition phase of rotation is finished and A/C climbs stationary) and 1000ft AGL, see FIG 3-3 and FIG 3-4.

The constant limits above 1000ft are derived from the FCOM. The critical bank angle limit is assumed as the bank angle at which the Autopilot would disconnect automatically (Φ=45°). The bank angle limit of 10° at 100ft is derived from the ground clearance (9.1°-16° depending on the actual pitch angle). A linear transition between 100ft to 1000ft is assumed.

The normal operation limit is the bank angle to which the aircraft will return guided by its Electronic Flight Control System when no stick input is given (Φ=33°). The operational limit of 7° at 100ft is derived according to the percentage difference between the red and green limit in 1000ft.
Regarding the pitch angle the limits are defined as a difference to a reference pitch angle. The reference pitch angle for take-off was defined as $\theta_r = 15^\circ$. The critical limit is a deviation of $15^\circ$ to each side of this reference. This results in a possible pitch angle between $\theta = 0^\circ$ and $\theta = 30^\circ$, which is the pitch angle at which a pitch attitude protection is activated in the flight control system of the A320 and A330. The normal operational limit is based on the range of normal display on the Primary Flight Display (PFD) which ranges up to $\theta = 22^\circ$.

Both limits are combined to the Aircraft Attitude Envelope (AAE). The complete list of the limits for bank and pitch angle can be also found in TAB A-1 and TAB A-2.
3.4.2. Cabin Acceleration Envelope (CAE)

The cabin acceleration limits are evaluated at the four locations where the highest accelerations can be expected. As it is shown in FIG 3-5 the locations are in the front cabin, left and right, as well as in the rear of cabin, also left and right.

For the CAE the vertical and lateral acceleration is computed for all simulation steps using the load factors at CG and the rotational accelerations of the aircraft. For each timestep the maximum of the absolute values of the deviations from the reference values \((n_y = 0, n_z = 1)\) of the four positions is then taken in the lateral and vertical direction and used to calculate the CAE envelope.

The chosen limits for the lateral and vertical cabin acceleration can be found in TAB A-1 and TAB A-2. They are based on allowed load factors defined in the aircraft operational documentation as well as typical accelerations encountered during flight in moderate to high atmospheric turbulence.

The vertical load factor and the lateral load factor were combined to the Aircraft Control Envelope (AFE), where 60% of lateral load factor and 50% of the vertical load factor are assumed as normal operation limits; see TAB A-1 and TAB A-2.
3.4.3. Attitude Control Envelope (ACE)

The aircraft control envelope consists of two sub-envelopes. These are the “Dynamic Roll Control Envelope” (DRCE) and the “Dynamic Pitch Control Envelope” (DPCE). Reference [8] explains the dynamic envelopes as follows. The DPCE criterion maps the pitch axis control authority against dynamic pitch attitude $\theta'$ as shown in FIG 3-6. Dynamic pitch attitude represents the sum of the current pitch attitude with its expected change after 0.2 second:

$$\theta' = \theta + q \cdot 0.2s$$

In general a positive sidestick pitch deflection initiate a pitching up aircraft reaction, this means quadrants I and quadrants III allow normal maneuvering. So the limits of this envelope reflects whether the trend in $\theta'$ is consistent with the pitch control command.

In case of a vertical upset induced e.g. by a wake the aircraft is pitching down, and the sidestick pitch control is given in the opposite direction to counter it the situation can end up in quadrant IV, if the pilot reaction was too slow or the disturbance is too strong. If this happens the other way around the envelope will be violated in quadrant II. For both situations the pilot get the feeling of a temporary loss of control, this is why such situations are assessed as critical. So the tapered envelopes in quadrant II and IV represent the case where the airplane is pitching in one direction while the pilot is using control to counter it. In this case the limits on $\theta'$ and pitch control envelope authority trade against one another.

The limits for the A320 on $\theta'$ can be found in TAB A-1 and for the A330 in TAB A-2, while the limits on control authority are ± 100%.
The DRCE criterion maps roll axis control authority against dynamic roll attitude \( \phi' \), as shown in FIG 3-7. Dynamic roll attitude represents the sum of the current roll angle with the expected change after 0.2 seconds.

\[
\phi' = \phi' + p \cdot 0.2s
\]

During a standard turn a positive sidestick roll commands initiates a positive bank angle, this means quadrants I and quadrants III allow normal maneuvering. So the limits of this envelope reflects whether the trend in \( \phi' \) is consistent with the roll control command.

In case of a lateral upset induced e.g. by a wake the aircraft is starts to turn in one direction, and the sidestick roll control is given in the opposite direction to counter it. Such a situation can end up in quadrant IV or II, if the pilot reaction was too slow or the disturbance is too strong. Such situations where the pilot gets the feeling of a temporary loss of control are assessed as critical. So the tapered envelopes in quadrant II and IV represent the case where the airplane is rolling in one direction while the pilot is using control to counter it. In this case the limits on \( \phi' \) and roll control envelope authority trade against one another.

The dynamic pitch and the dynamic roll envelope provide a value between 0 and 1 depending on the position of the two metrics within the envelope. A value of 1 here corresponds to a position on the boundary. Both these values are then taken over into the Aircraft Control Envelope (ACE), with the DRCE value being on the x-axis and the DPCE value on the y-axis. Normal operational limits are defined by 80% in DRCE direction and 50% in DPCE direction.

In addition the limits for DRCE and DPCE are linearly interpolated between ground limit and 1000ft, down to 50% of their values at 1000ft, see TAB A-1 and TAB A-2.
3.4.4. Air Flow Envelope (AFE)

The air flow envelope reflects the aircraft air flow angles as angle of attack and angle of sideslip. The limit for the sideslip angle $\beta$ is determined based on the maximum allowed take-off crosswind using the following formula:

$$\beta_{\text{max}} = \arctan \left( \frac{V_{\text{CW}}}{V_{\text{TAS}}} \right)$$

Where $V_{\text{CW}} = 32$ kt (29 kt for the A320) is the maximum allowed takeoff crosswind component for the A330, and $V_{\text{TAS}}$ is the actual true airspeed during take-off. FIG 3-8 shows for the A330 how the sideslip angle limits change depending on speed. For the A320 a constant angle of sideslip of 12° is assumed.

![AFE - Beta limit](image)

FIG 3-8: Sideslip angle envelope

Similar to the pitch angle, the angle of attack metric is calculated as a difference to a reference angle of attack:

$$\alpha_{\text{max}} = \alpha - \alpha_{\text{ref}}$$

Where $\alpha_{\text{ref}}$ is a reference angle of attack in takeoff condition, see TAB A-1 and TAB A-2. It was assumed to $\alpha_{\text{ref}} = 6^\circ$ for the A330 by examining recorded simulator data during take-off. The critical upper limit of the angle of attack is defined as the one at which a stall warning is emitted (with flaps/slats extended), this lead to an $\alpha_{\text{max}}$ of 14°. The critical lower limit is based on the highest zero-lift angle of attack, which is $\alpha = -2.5^\circ$ in Clean configuration. To keep a little margin and for simplification a value of $\alpha_{\text{lim}} = -2^\circ$ was chosen.

Both metrics are combined into the Air Flow Envelope (AFE), where 40% of sideslip angle and 40% of angle of attack are assumed as normal operational limits for the A330 (TAB A-2); see also TAB A-1 for the A320 values.
3.5. CALCULATION OF SEVERITY CRITERION

A situation can be identified as unacceptable (severity criterion SC= 1) if a single critical limit (red) is violated in one envelope or if several normal (green) limits are violated at the same time. For example the severity criterion reaches 1, if all four envelopes were violated beyond 25% of the green limit.

Mathematically the severity criterion is the sum of each envelope criteria, described in the sections above.

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

FIG 3-9 shows the time histories of one WVE example where all parameters which were combined in the severity criterion are illustrated. A violation of the critical bank angle limits leads two times to a value of app. 1 for the AAE envelope. The violation of the normal limits for lateral and the vertical load factor leads to a value of 0.8 for the CAE envelope. Furthermore the dynamic roll control envelope and the critical limit of the angle of sideslip were exceeded. The sum of all these envelopes is the severity criterion, which is defined as a value with a maximum of 1. This is why the severity criterion, given in the last subplot doesn't exceeds a value of 1.

FIG 3-9: Example of the severity criterion
4. VERIFICATION OF SEVERITY CRITERIA

The prediction performance of this criterion has been evaluated using the subjective severity ratings of the pilots during the simulated wake encounter tests [7]. Pilots were asked to rate the severity of each encounter flown in the simulator on a scale of 1 to 6, where 1 described no noticeable wake vortex encounter and 6 an encounter potentially causing injuries and possible temporary or total loss of control over the aircraft. To compare the human pilot ratings with the Severity Criterion described here, these ratings were grouped according to TAB 4-1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Pilot Rating</th>
<th>Description</th>
<th>Severity Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2</td>
<td>Slight or no noticeable disturbance</td>
<td>SC=0</td>
</tr>
<tr>
<td>2</td>
<td>3-4</td>
<td>Moderate upset, requires corrective control inputs</td>
<td>0 &lt; SC &lt; 1</td>
</tr>
<tr>
<td>3</td>
<td>5-6</td>
<td>An extreme upset, causing loss of control (temporarily)</td>
<td>SC = 1</td>
</tr>
</tbody>
</table>

TAB 4-1: Severity categories related to pilot ratings

The category predicted by the Severity Criterion for each encounter recorded in the simulator can then be compared to the category the pilots gave to this encounter. The grouping of the pilot ratings as done here seems to be supported by the correlation with the "Alert Level" rating the pilots gave as well (see Figure 2-2).

Depending on how conservative the analysis shall be; an encounter can be considered as hazardous as soon as it reaches Category 3 or already when Category 2 is reached, which is the more conservative assumption. Obviously, the last option will always yield more encounters rated as severe from a given number of simulations.
4.1. A320 VERIFICATION RESULTS

To verify the developed “severity rating model”, its hazard ratings for all wake vortex encounter cases (flown in the simulator test) were compared to the human pilots ratings for such encounters.

The model prediction performance of the encounter hazard was defined as the ratio between “model predicted hazard rating / subjective human pilot hazard rating”.

The severity rating model of the A320 rated in 55% encounter cases in the same hazard category as the human pilots did. In 34% cases the model rated one category higher (more severe) than the pilots and in 11% the model rated one category lower or two higher in comparison to the airline pilots.

The numbers are represented in the matrix in FIG 4-1.

The numbers in the boxes indicate the number of encounters falling in the corresponding category. All encounters falling into the green fields are such encounters that were rated in same hazard category by the model and the human pilots. Those in the yellow fields are conservatively predicted. Conservative predicted means the model rated the encounter situation one category higher than the pilots did. While those in the red fields, consider all cases where the model rated the encounter one category lower as the pilots, or two categories higher.

FIG 4-1: Correlation between pilot and severity criterion predictions for A320

This prediction quality is judged as sufficiently good, keeping in mind that the pilots cannot assess all the metrics that are important and that are contained in the criteria equally well. Therefore a perfect match with the pilot ratings cannot be expected either.
The limits of the envelopes, which were combined in the severity rating model, can be found in TAB A-1.

### 4.2. A330 VERIFICATION RESULTS

The severity rating model of the A330 rated in 57% of the encounter cases the same category as the human pilots rated for the same encounter situation. In 37% the model rated one category higher than the airline pilots, and in 6% cases is the category rated by the model one category lower or two higher in comparison to the human pilots. The limits for the envelopes which were combined the severity rating model can be found in TAB A-2.

![Model Predictions](image)

**FIG 4-2: Correlation between pilot and severity criterion predictions for A330**
5. CONCLUSION

A severity criterion has been developed based on a multi-parameter approach and using extensive simulator data with airline pilots for verification. This criterion is applied specifically to take-off within the CREDOS project; however it is sufficiently general to be easily adapted to other flight phases, as well as other aircraft types.

Most parameters needed to adapt the criterion to a specific aircraft can be taken from readily available handbook data. However, some "soft" parameters remain, which have so far been determined only by engineering judgment. Future application of the criterion and wider discussion should give some more insight into possible improvements of the criterion.

The prediction performance of this criterion with respect to the simulator data is very good, even though metrics are included that are difficult to judge by a pilot in a simulator. These metrics have been included as they are seen as important to characterise the main wake encounter hazards. The fact that this criterion might predict hazard ratings, which are on average higher than pilot assessment, is deliberately accepted. Within this context it should also be noted that this criterion at the present stage is not suited to determine absolute probabilities of severe wake encounters in reality. It is primarily intended to perform in relative assessments, as is the case in CREDOS. To make it useable in absolute assessments, more validation work especially with real-life encounter data would need to be performed.
6. RECOMMENDATIONS

The following recommendations are made for further development of the presented criteria. So far the criterion values of all four envelopes are added up with equal weightings to the full SC value. Not all hazards however have to be weighted equally, but maybe according to their actual importance to safety. Also, adding consideration of other hazards with additional envelopes would increase the overall severity value whereas leaving one or more out of the assessment reduces it, which might not be the proper solution. Therefore a more sophisticated way to combine several encounter hazards into one final severity value should be identified.

Furthermore the altitude dependency in the criterion could not be validated very well, as the encounter altitude distribution in the simulator data was too limited. Sensitivity analyses performed with this version of the severity criterion [13] have shown moreover that the influence of altitude on the severity criterion value for different encounter conditions is rather limited. It could be worthwhile to refine the altitude dependency in the severity criterion in future versions of the model.

The simulator scenarios used to verify the model consisted mainly of roll-dominant encounters. The final risk assessment simulations in WP3 have shown however that in certain scenarios a lot of encounters on departure occur also with higher encounter angles resulting in less roll disturbance and more influence on the longitudinal parameters. Therefore additional simulator tests also addressing encounters with larger encounter angles could be proposed to provide additional validation data for these conditions.

It is felt necessary that the severity criterion methodology be also applied and verified for other flight phases.

Finally, the methodology and its internal safe limits need to be validated by an expert group comprising at least pilots as well as handling qualities, flight dynamics and aerodynamic specialists.
7. REFERENCES

[1] EUROCONTROL; CREDOS – Crosswind- Reduced Separations for Departure Operations; URL: http://www.eurocontrol.int/eec/credos, 06/15/09


A. APPENDIX

A.1. PILOT QUESTIONNAIRE

Wake Vortex Encounter Investigations

FIG A-1: Pilot questionnaire used in piloted simulator tests

Pilot Briefing Information

Pilot : Date :
Run No. : Case No. :

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

1b. Hazard Rating:

2a. Which action was taken:

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

3. Max. Alert level:

Remarks: (e.g. how was API/THR disengaged?)

FIG A-1: Pilot questionnaire used in piloted simulator tests
A.2. A/C Parameter Correlation to Pilot Hazard Ratings

FIG A-2: Overview of a/c parameters correlated to the pilot ratings
# A.3. Envelope Limits for Criteria Metric

<table>
<thead>
<tr>
<th>Envelope</th>
<th>Parameter name</th>
<th>Range</th>
<th>Normal operation limits</th>
<th>Critical limits</th>
<th>Description/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AAE</strong></td>
<td>Bank angle</td>
<td>( \Phi_{ref} = 0^\circ )</td>
<td>73 %</td>
<td>( \left</td>
<td>\Phi_{limit} \right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Phi \in [100 \text{ ft} , 1000 \text{ ft}] ) ( \rightarrow [7.3^\circ , 33^\circ] )</td>
<td>( f : [100 \text{ ft} , 1000 \text{ ft}] \rightarrow [10^\circ , 45^\circ] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pitch angle</td>
<td>( \Theta_{ref} = 15^\circ )</td>
<td>50 %</td>
<td>( \left</td>
<td>\Delta \Theta_{limit} \right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta \Theta = \Theta - \Theta_{ref} )</td>
<td>( f : [100 \text{ ft} , 1000 \text{ ft}] ) ( \rightarrow [3.5^\circ , 7.5^\circ] )</td>
<td>( f : [100 \text{ ft} , 1000 \text{ ft}] \rightarrow [7^\circ , 15^\circ] )</td>
<td></td>
</tr>
<tr>
<td><strong>DRCE</strong></td>
<td>Dynamic Roll Control Envelope</td>
<td>( \Phi + p \cdot 0.2 \text{ s \ grad} = 0.5 )</td>
<td>85 %</td>
<td>( \left</td>
<td>\Phi \right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Phi \in [100 \text{ ft} , 1000 \text{ ft}] ) ( \rightarrow [30^\circ , 60^\circ] )</td>
<td>( f : [100 \text{ ft} , 1000 \text{ ft}] \rightarrow [35^\circ , 70^\circ] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ACE</strong></td>
<td></td>
<td>( \Delta \theta + q \cdot 0.2 \text{ s \ grad} = 0.7 )</td>
<td>50 %</td>
<td>( \left</td>
<td>\Delta \theta \right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta \theta \in [100 \text{ ft} , 1000 \text{ ft}] ) ( \rightarrow [7.5^\circ , 15^\circ] )</td>
<td>( f : [100 \text{ ft} , 1000 \text{ ft}] \rightarrow [15^\circ , 30^\circ] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta \theta + q \cdot 0.2 \text{ s \ grad} = 0.7 )</td>
<td>50 %</td>
<td>( \left</td>
<td>\Delta \theta \right</td>
</tr>
<tr>
<td><strong>SSRO</strong></td>
<td></td>
<td>( \pm 1 )</td>
<td>60 %</td>
<td>( \pm 0.5 \text{ g} )</td>
<td></td>
</tr>
<tr>
<td><strong>DPCE</strong></td>
<td>Dynamic Pitch Control Envelope</td>
<td>( \Delta \theta + q \cdot 0.2 \text{ s \ grad} = 0.7 )</td>
<td>50 %</td>
<td>( \left</td>
<td>\Delta \theta \right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta \theta \in [100 \text{ ft} , 1000 \text{ ft}] ) ( \rightarrow [7.5^\circ , 15^\circ] )</td>
<td>( f : [100 \text{ ft} , 1000 \text{ ft}] \rightarrow [15^\circ , 30^\circ] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \pm 1 )</td>
<td>50 %</td>
<td>( \pm 1.0 \text{ g} )</td>
<td></td>
</tr>
<tr>
<td><strong>CAE</strong></td>
<td>Ny cabin</td>
<td>( n_{y_{ref}} = 0 )</td>
<td>60 %</td>
<td>( \pm 0.5 \text{ g} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nz cabin</td>
<td>( n_{z_{ref}} = 1 )</td>
<td>50 %</td>
<td>( \pm 1.0 \text{ g} )</td>
<td></td>
</tr>
<tr>
<td><strong>AFE</strong></td>
<td>Alpha</td>
<td>( \alpha_{ref} = 6^\circ )</td>
<td>70 %</td>
<td>( \alpha_{min-max} = -2^\circ \ldots 14^\circ )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \alpha_{norm} = -1.4^\circ ) ( 10^\circ )</td>
<td>( \alpha_{min-max} = -2^\circ \ldots 14^\circ )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beta</td>
<td>( \beta_{ref} = 0^\circ )</td>
<td>50 %</td>
<td>( \pm \beta_{max} )</td>
<td>maximum takeoff crosswind component (29 kt)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \beta_{ref} = 0^\circ )</td>
<td>( \pm \beta_{max} )</td>
<td>( \beta_{max} = 12^\circ )</td>
<td></td>
</tr>
</tbody>
</table>

**TAB A-1: A320 Envelope limits**
<table>
<thead>
<tr>
<th>Env.</th>
<th>Parameter name</th>
<th>Range</th>
<th>Normal operation limits</th>
<th>Critical limits</th>
<th>Description/ Source</th>
</tr>
</thead>
</table>
| **AAE** | Bank angle | $\phi_{ref} = 0^\circ$ | 73 % | $|\phi_L| = f(H)$  
$f : [100 \text{ ft}, 1000 \text{ ft}]$  
$\rightarrow [7.3^\circ, 33^\circ]$ | Linear interpolation in intermediate region |
| | | $\phi_{ref} = 0^\circ$ | 73 % | $|\phi_L| = f(H)$  
$f : [100 \text{ ft}, 1000 \text{ ft}]$  
$\rightarrow [7.3^\circ, 33^\circ]$ | Linear interpolation in intermediate region |
| | Pitch angle | $\theta_{ref} = 15^\circ$ | 50 % | $|\Delta \theta_{L}\mid = f(H)$  
$f : [0 \text{ ft}, 1000 \text{ ft}]$  
$\rightarrow [3.5^\circ, 7.5^\circ]$ | Pitch deviations are based on pitch angle before encounter |
| **ACE** | Dynamic Roll Control Envelope | $\phi + p \cdot 0.2 \text{ s}$  
$grad = 0.5$ | 70 % | $|\phi| = f(H)$  
$f : [0 \text{ ft}, 1000 \text{ ft}]$  
$\rightarrow [25^\circ, 50^\circ]$ | (see FIG 2-7) |
| | | $\Delta \theta + q \cdot 0.2 \text{ s}$  
$grad = 0.7$ | 50 % | $|\Delta \theta| = f(H)$  
$f : [0 \text{ ft}, 1000 \text{ ft}]$  
$\rightarrow [7.5^\circ, 15^\circ]$ | (see FIG 2-6) |
| SSRO | ± 1 | | | |
| DPCE | Dynamic Pitch Control Envelope | $\Delta \Theta + q \cdot 0.2 \text{ s}$  
$grad = 0.7$ | 50 % | $|\Delta \theta| = f(H)$  
$f : [0 \text{ ft}, 1000 \text{ ft}]$  
$\rightarrow [7.5^\circ, 15^\circ]$ | (see FIG 2-6) |
| SSPI | ± 1 | | | |
| **CAE** | Ny cabin | $n_y^{nye} = 0$ | 60 % | ± 0.5 g | |
| | Nz cabin | $n_z^{nze} = 1$ | 50 % | ± 1.0 g | |
| **AFE** | Alpha | $\alpha_{ref} = 6^\circ$  
$\alpha_{norm} = 5.6^\circ$ | 40 % | $\pm \beta_{max}$  
$\beta_{max} = \text{atan}(32 \text{kt/V})$ | maximum takeoff crosswind component (32 kt) |
| Beta | $\beta_{ref} = 0^\circ$ | 40 % | | |

**TAB A-2: A330 envelope limits**
A.4. EXAMPLES FOR THE HAZARD ASSESSMENT OF WAKE VORTEX ENCOUNTERS WITH THE DEVELOPED SEVERITY CRITERIA

FIG A-3: Example of pilot hazard rating class 1 vs. severity criteria metric rating
FIG A-4: Example of pilot hazard rating class 2 vs. severity criteria metric rating.
FIG A-5: Example of pilot hazard rating class 3 vs. severity criteria metric rating