Wake Vortex Encounter Risk Assessment for Crosswind Departures

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DOI: 10.2514/1.C031522

In the European research project, CREDOS (Crosswind-Reduced Separations for Departure Operations), the feasibility of a concept for reduced wake turbulence separations upon departure in crosswind conditions has been investigated. The safety assessment of this concept includes risk assessment with respect to wake vortex encounters. This paper describes the methodology developed for this assessment and its application during the project. The methodology employs two simulation tools, the Wake Vortex Scenarios Simulation Package for Departure (WakeScene-D) and the Vortex Encounter Severity Assessment for Departure (VESA-D), which are extensions of existing tools related to the departure flight phase. WakeScene-D primarily determines the frequency of wake encounters, whereas VESA-D estimates the severity of these encounters. Both can be combined to quantify and compare wake encounter risk for various departure scenarios. In the risk assessment, departures with variable aircraft separations and varying crosswind conditions were investigated to determine which crosswind level is necessary to suspend wake-turbulence-related separations during departure without degrading safety. Monte Carlo simulations have been conducted comparing medium and heavy aircraft type departures with 2 min. of separation to departures with a separation of 1 min. under varying crosswind strengths. The results not only give an indication of which crosswind magnitudes could be sufficient to safely suspend wake-turbulence-related separations upon takeoff, but they also reveal significant influences, such as the departure route layout and the change of wind direction with altitude, on wake encounter risk.

I. Introduction

AIRCRAFT-generated wake vortices, although being an inevitable by-product of lift, can be dangerous to aircraft encountering them not only during approach, where the margins for recovery are limited, but also in all flight phases. For this reason, wake-turbulence separation standards, which have become an increasingly limiting factor to capacity, especially at busy airports, were established by the International Civil Aviation Organization (ICAO) in the 1970’s [1]. On the other hand, research over the past years has shown how the transport and persistence of wake vortices depend on weather conditions and that, in some situations, it might be possible to reduce the existing separation standards while maintaining today’s level of safety. For single-runway operations, for example, de Bruin et al. [2] and Frech and Holzäpfel [3] suggest that, above a certain crosswind threshold, vortices are blown out of the flight corridor and pose no further threat to following aircraft.

The experiences gained in earlier research projects (such as S-WAKE [2] or ATC-WAKE [4]) lead into the CREDOS (Crosswind-Reduced Separations for Departure Operations) project [5]. In this European Commission (EC) cofunded project, which ran from 2006–2009, the feasibility of a concept that allows for the suspension of wake-turbulence separations for single-runway operations under the condition that a sufficient crosswind is prevailing on the departure runway was investigated. During the project, a concept of operations was developed as well as possible human-machine interface solutions and procedures, and real-time tower simulations as well as piloted wake encounter simulations were performed. Furthermore, one of its work packages was tasked with developing and applying a wake encounter risk assessment to quantify the relative risk of significant wake encounters for different situations. In this work package, two tools, the Wake Vortex Scenarios Simulation Package for Departure (WakeScene-D) and the Vortex Encounter Severity Assessment for Departure (VESA-D), were developed. WakeScene-D was developed by Deutsches Zentrum für Luft- und Raumfahrt and estimates the probability of encountering wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation. In cases with potential wake encounters, all relevant parameters can be provided to VESA-D, which subsequently performs accurate flight dynamics simulations of the encounters to assess their severity. Both results together allow for an assessment of the wake encounter risk, i.e., the probability to have wake encounters of a certain severity. Although the results that will be presented in this paper have been achieved by using both tools in conjunction, the description of the simulation models will focus on the additions and improvements made to the VESA-D platform during the CREDOS project. A detailed description of the WakeScene-D platform and simulations performed on it can be found in Holzäpfel et al. [6] and Holzäpfel and Kladetzke [7], respectively.

II. Description of Simulation Platforms

A. WakeScene-D

WakeScene-D simulates departures from runway 25R at Frankfurt-Main International Airport (FRA) along five different standard departure routes (TOBAK2F, BIBOS6F, SOBRA1F, ANEKI5F, and DKB2F [8], see also Fig. 1) and the resulting wake vortex evolution up to an altitude of 3000 ft. Via simulation control using the software tool MOPS [9], the types of heavy generator aircraft (A300-600, A310, A330-300, A340-300, B747-400, and B777-200) and medium follower aircraft (A320, ATR42-500, B737-300, and Bombardier CRJ) are selected. The traffic mix is modeled according to FRA statistics [10]. The aircraft trajectory model [11]

Received 26 May 2011; revision received 19 July 2011; accepted for publication 19 July 2011.

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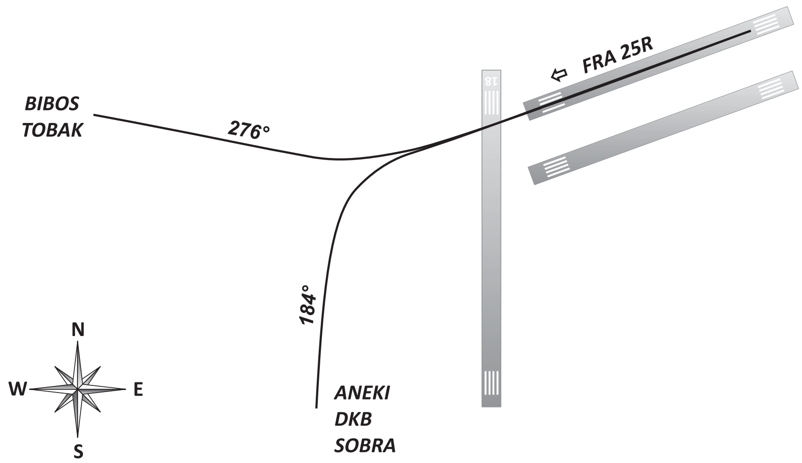

Fig. 1 FRA SID layout used in simulations.

provides time, speed, position, attitude, lift, and mass of generator and follower aircraft along the flight paths. The prevailing meteorological conditions are picked randomly from a one-year database that has been established for the FRA terminal area with the nonhydrostatic mesoscale weather forecast model system, Nowcasting Wake Vortex Impact Variables (NOWVIV) [12].

Based on vertical profiles of wind speed, wind direction, air density, virtual potential temperature, turbulent kinetic energy, and eddy dissipation rate as well as aircraft position, speed, attitude, lift, and span, the deterministic two-phase wake-vortex decay model (D2P) [13,14] simulates the wake vortex trajectories and circulation. Wake vortex evolution is predicted within planes, also termed gates, which are released along the flight path of the wake vortex generator aircraft in time increments of 5 s. The gates' orientations are perpendicular to the aircraft's true heading and to the flight path angle. For the identification of potential encounters, the wake vortex tracks are interpolated between the gates.

From all these data-defined criteria, such as minimal distance between the wake vortex and follower aircraft, the respective vortex circulation and height are computed and statistically analyzed. This already allows for an assessment of the scenarios with regard to encounter probabilities without considering the aircraft response to an encounter (see also Holzäpfel and Kladetzke [7,15]). The results are optionally visualized in graphs of these statistics, two-dimensional and three-dimensional (3-D) views or animations of the departures of subsequent aircraft. Only for those identified encounters that exceed a predefined threshold of expected strength, which shall be further investigated with VESA-D, the data needed is deduced and stored (see also section II.C). This preselection reduces the computing effort for VESA-D significantly.

A detailed description of the design of WakeScene-D with its employed submodels and their validation status is available in Holzäpfel et al. [6]. Comprehensive sensitivity analyses regarding the effects of various crosswind scenarios, departure route combinations, flight path adherence, wake vortex modeling, the development of aircraft separations during the departures, the sample size of the Monte Carlo simulations, aircraft type combinations, aircraft takeoff weights, meteorological conditions, airport operation times, and a comparison of approach and landing are reported in Holzäpfel and Kladetzke [7,15].

B. VESA-D

In the EC-funded project S-WAKE [2], which ran from 2000–2003, modeling tools were developed that were assembled into the wake vortex encounter simulation platform, VESA [16,17], by Airbus, which has been continuously further developed. The platform is able to simulate the effect of wake vortex encounters on the encountering aircraft by using an aerodynamic interaction model to couple wake vortices and aircraft aerodynamics. The work in the S-WAKE project focused on the approach phase of flight. Within the CREDOS project, the capabilities were extended to the departure flight phase, and existing submodels were further refined. VESA-D is thus the result of extending VESA to the departure situation. VESA-D is composed of several core models: 1) a six-degree-of-freedom aircraft flight simulation; 2) the representation of the vortices in space; 3) an aerodynamic interaction model (AIM) that computes the forces and moments imposed on the aircraft by the vortices when it passes them; 4) a pilot model allowing for the control of the aircraft and, in particular, recovery from wake vortex encounters in a realistic way during fast-time simulations; and 5) a severity model that rates the severity of each simulated encounter by taking into account measurable dynamic parameters.

These core models will be briefly described in the following subsections.

1. Aircraft Simulation

In VESA-D, an Airbus A320 flight simulation is used to simulate wake vortex encounters. It is a simulation validated by Airbus for use in investigations on handling qualities. It contains the aerodynamics, fly-by-wire control laws, and autopilot functionalities of an A320-200 series aircraft. These elements remain unchanged for the wake encounter investigations with respect to the validated aircraft simulation.

Performance-related parameters, such as the takeoff mass, configuration, and thrust settings, can be varied. The ambient atmospheric conditions are modeled according to the International Standard Atmosphere model. The simulation takes into account wind influence on the aircraft (apart from the specific wake vortex encounter model) either from a simplified uniform wind field or from a synthetical wind field. That way, either a specific wind condition can be set or varied within a Monte Carlo simulation, or realistic wind conditions from a database, such as the NOWVIV database [12] used in WakeScene-D, can be included.

For the departure simulations conducted within CREDOS, the aircraft is placed on the ground at the runway threshold. The takeoff is simulated from brake-release up to a maximum altitude of 4000 ft Mean Sea Level. The airport environment is that of FRA in Germany. All departures are simulated off runway 25R. Five different standard instrument departure (SID) routes of runway 25R are included (ANEKI5F, BIBOS6F, DKB2F, SOBRA1F, and TOBAK2F, see Fig. 1). All other SIDs have a routing equal to one of these five SIDs up to the considered altitude. To assess the simulated wake vortex encounters, all necessary parameters can be recorded for analysis, including those flight-dynamical parameters that are used in the multiparameter severity criteria.

2. Vortex Model

WakeScene-D uses several so-called control gates to calculate the time and space evolution of the vortices (see also section II.A). In each of these gates, the evolution of the wake vortex characteristics is

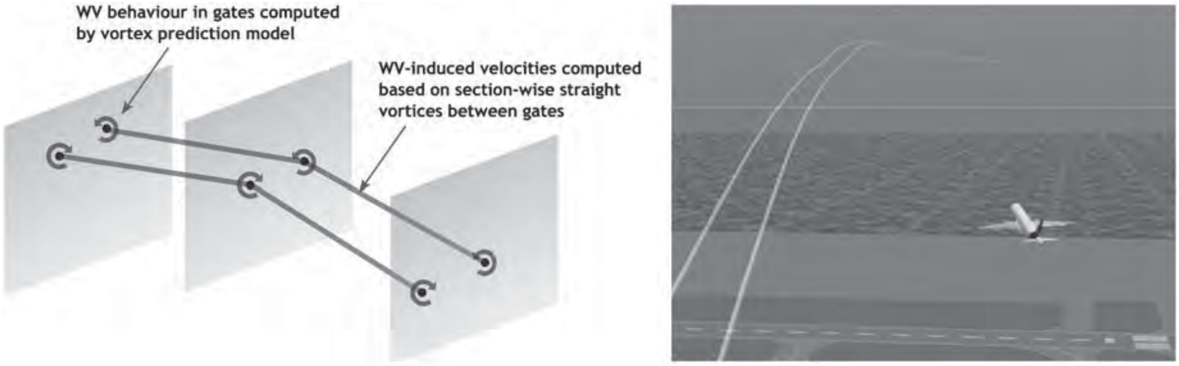

Fig. 2 Representation of vortices in VESA-D: schematic and view in VESA-D.

computed using the D2P wake vortex prediction model for a certain amount of time after the creation of the vortices (and thus the gate). For computation of the induced velocity field in VESA-D, straight vortex segments are assumed between the vortex positions in each gate with an induced velocity distribution according to the Burnham-Hallock model [18] and by using the Biot-Savart law. The circulation of each segment is assumed to be the mean of the circulations in the two gates between which the segments extend (see Fig. 2). The induced velocity contributions of all segments on each aerodynamic control point on the aircraft (see Fig. 3) are then computed in each time step of the simulation, taking into account the current relative position of the aircraft and the vortices. In ground proximity, the wake vortex prediction model additionally generates secondary and tertiary vortices as well as the respective image vortices. These also contribute to the induced velocity field. An example of a representation of a wake vortex coming from WakeScene-D is shown in Fig. 2. Kinks along the vortices resulting from the piecewise representation of the vortices by straight vortex segments are only barely visible, as the curvature between the segments is usually small. Thus, the error made by discretizing the vortices in that way is expected to be small as well.

3. Aerodynamic Interaction Model

The forces and moments acting on the aircraft when it encounters the wake are computed using an AIM that is coupled to the base flight simulation. In VESA-D, a strip method is used (Fig. 3) to calculate the additional forces on the aircraft due to induced velocity components and the resulting moments due to these forces. The method is based on a linear aerodynamic approach, calculating the incremental forces relative to a nominal flight condition at several discrete positions on the aircraft's wings and the horizontal and vertical tailplane based on the local incremental angle of attack. This yields the aerodynamic y- and z-forces, as well as pitch, roll, and yaw moments. No impact on the drag force is considered, however. 3-D effects are taken into account in a simplified way by an elliptical weighting of the lift distribution. This wake vortex interaction model was developed and validated mainly within the S-WAKE project (2000–2003) [2,19]. It provides good modeling quality with little computation effort in comparison with more detailed approaches like lifting surface methods.

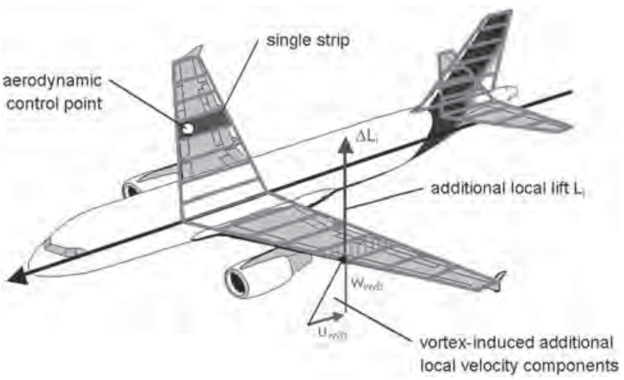

Fig. 3 Strip method as aerodynamic interaction model in VESA-D.

4. Pilot Model

In the previous version of VESA, a pilot model was included that was developed during earlier projects that focused on the approach phase of flight. Apart from the wake encounter recovery capability, it is designed to follow a steady glide slope. Hence, this pilot model is not suited for the different requirements of controlling an aircraft during departure, comprising the takeoff run from brake release to rotation speed, rotation, initial climb, reconfiguration (landing gear, flaps and slats), and following a designated SID route. Furthermore, pilot reactions to a wake encounter during the takeoff phase do not necessarily need to be the same as during approach. For these reasons, a specific pilot model was developed in the CREDOS project by Amelsberg et al. [20]. This pilot model has the following functionalities:

1) Set thrust levers to initiate the takeoff roll and use pedals on the ground to correct lateral deviations from the centerline under crosswind conditions;

2) Rotate at a specified rotation speed, V_{Rot}, with a specified target pitch rate, and capture the pitch angle commanded by the flight director (commanded pitch and roll attitude displayed on the primary flight display by means of horizontal/vertical bars);

3) Follow the flight director along a designated SID route;

4) Set gear, flaps, and thrust levers according to specified transition altitudes or speeds; and

5) In the case of a wake encounter, recover the aircraft in a realistic way representative of real pilots.

The pilot submodel for wake encounter recovery is based on a neural net, which was trained to the recorded sidestick inputs of human pilots reacting to an encounter. These were obtained in dedicated simulator sessions in a fixed-base A320 development simulator (using the same aircraft simulation as was used in VESA-D) and a level-D A330 full-flight simulator [21]. To validate the resulting parameter sets for the neural net, the fidelity of the pilot model was assessed in closed-loop VESA-D A320 wake encounter simulations. The resulting response of the aircraft as well as the stick commands given by the pilot model were compared with those from piloted simulator tests with real pilots. Figure 4 shows, as an example, the bank angle time histories during a departure for the same external vortex-induced disturbances. The bank angle during the same encounter flown by eight different pilots is compared with the bank angle of the aircraft controlled by the pilot model. The beginning of the wake encounter is at $t = 0s$, whereas takeoff occurs at about $t = -20s$ in this example. The roll disturbance seen just after takeoff is caused by the crosswind, which was set during all the simulation scenarios and which tends to lift one wing just after the aircraft leaves the ground. This example shows the generally good behavior of the pilot model, which leads to a dynamical response of the aircraft lying within the variation that was observed for the piloted simulations. More details about the pilot model development and its validation can be found in Amelsberg et al. [20].

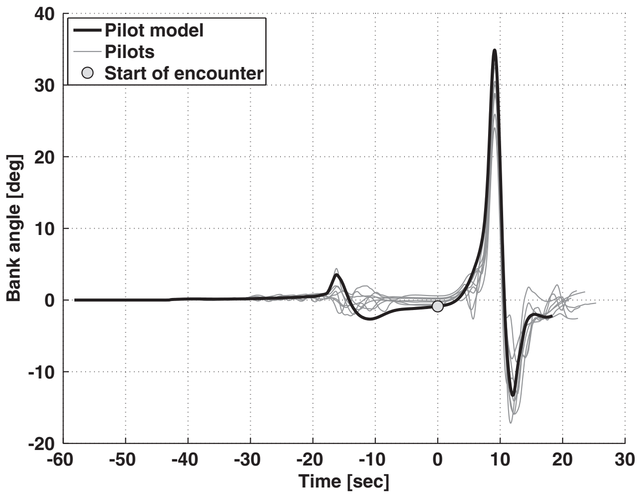

Fig. 4 Pilot model in comparison to real pilots, bank angle response during departures with wake vortex encounter.

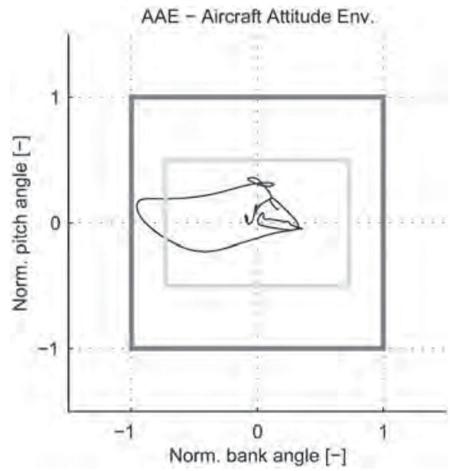

Fig. 5 Example of severity envelope (here AAE, from Amelsberg [22]).

5. *Severity Model*

To judge the hazard of a wake vortex encounter under certain conditions, hazard criteria need to be available that give a good indication of whether or not an encounter is a safety hazard to an aircraft. In VESA, criteria have been applied that have consisted of one or a combination of a few dynamic parameters. Those were used to assess the hazard of a simulated encounter and were correlated with simulator test results [16]. Within CREDOS, these criteria have been extended to cover more objectively measurable dynamic parameters of the encountering aircraft. For this purpose, Amelsberg [22] developed an advanced severity model. It takes into account several aircraft parameters, such as load factors, air flow incidence angles, aircraft attitude, and control inputs. The predictions of the model have been validated by the subjective judgement of pilots, who had to rate simulated encounters flown in two different simulators with regard to the perceived safety hazard [21]. Those simulations were also used for the development of the pilot model. This model was implemented in VESA-D and is used to determine the severity of each simulated encounter. It allows for the analysis of the influence of different parameters, such as vortex characteristics or encounter geometry, on the wake hazard as well as a statement on which fraction of the encounters identified by WakeScene-D are actually hazardous. As WakeScene-D only provides potentially severe encounters, i.e., cases in which the vortex-induced rolling moment exceeds a certain threshold, this is an important model for risk assessment. It allows weighting the encounters with their severity and comparing the results between varying separation distances and crosswind conditions.

The structure of the severity criteria follows an approach initially suggested by Wilborn and Foster [23] and first applied to wake vortex encounters by Reinke [24]. 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 should stay. In CREDOS, four such envelopes have been defined: 1) the aircraft attitude envelope (AAE), which takes into account bank and pitch angle attitude; 2) the cabin acceleration envelope (CAE), which takes into account the maximum lateral and vertical accelerations in the cabin; 3) the attitude control envelope (ACE), which takes into account the control inputs (sidestick roll and pitch) necessary to recover the aircraft with respect to the actual aircraft motion; and 4) the air flow envelope (AFE), which takes into account the angle of attack and sideslip.

For each envelope or, more precisely, for each of the considered parameters in the envelopes, a boundary of normal operation (light gray) and one of the maximum allowed limit (dark gray) have been defined (see Fig. 5). They are based on objectively defined aircraft data like allowed load factors or maximum flow angles. The recorded time histories during an encounter, then, allow for detection of a violation of these boundaries. Figure 5 shows, as an example, one encounter for which the time histories of the aircraft attitudes normalized by the boundary values are plotted into the AAE. To take into account an altitude dependency as well, the boundaries of the AAE and ACE are linearly reduced to smaller values close to ground below an altitude of 1000 ft.

If all parameters stay within the light gray boundary for normal operational limits, no safety problem for the aircraft is assumed. The criterion value associated with the envelope is then 0. A violation of the light gray boundary means an excursion from normal operation. The criterion value is then interpolated between 0 and 1, reaching 1 when a parameter reaches or exceeds the dark gray boundary. For each time instance, the criterion values of each envelope are computed in this way, and the four different severity envelope values are then added to take into account that an excursion in several areas at the same time (aircraft attitude, loads, flow angles, or control) is more severe then an excursion in only one of these areas. The maximum of the sum of these four values during the encounter is called the severity criterion (SC) value. It is limited to values between $SC = 0$ and $SC = 1$ (see Fig. 6).

For validation, the severity model was applied to recorded simulator data, and the predictions were compared with subjective pilot ratings for each encounter. Pilots had to rate the severity of a simulated encounter on a scale of 1 to 6 (see also Amelsberg and Kauertz [21]). For comparison with the model prediction, these six levels were grouped into three categories, as is shown in Fig. 7, and were correlated with the predictions. The light gray boxes on the diagonal represent the encounters that are assumed to be predicted correctly by the model (45.7% of total cases). A considerable portion of the encounters (46.8%, midgray) has been rated one category higher by the model than by the pilots. This is considered acceptable, as it is still a conservative prediction. The model cannot be expected to perfectly match the pilot ratings because not all of the parameters taken into account in the severity model, such as flow angles or cabin accelerations, can be accurately judged by the pilots. The severity model rated about 7.5% of the encounters either two categories higher or one category lower than the pilots. Both are considered to be wrong predictions.

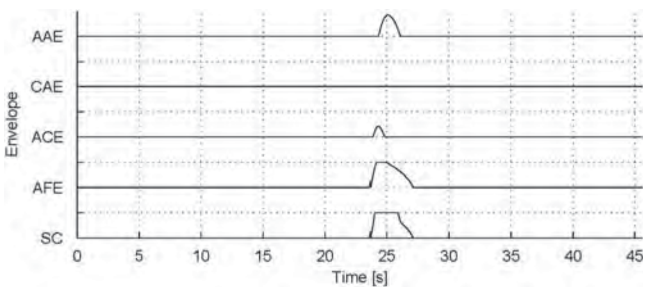

Fig. 6 Typical evolution of severity envelopes and summed up criterion SC for one encounter [22].

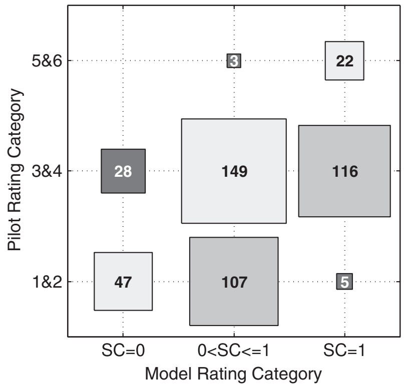

Fig. 7 Correlation of severity model prediction with subjective pilot rating for 477 simulated encounters [22].

Further development of these severity criteria is required to refine their structure and the allowed boundaries of the different parameters they contain. Nevertheless, the prediction quality was judged sufficient for the current application. For details on the setup of the criteria, their validation, and the chosen boundaries see Amelsberg [22].

C. Simulation Setup

VESA-D can be used either alone to conduct parametric studies or worst-case searches or by using data coming from WakeScene-D. The latter approach was used for the simulations that are described in this paper. Both parts, the WakeScene-D as well as the VESA-D simulations, are separate Monte Carlo simulations allowing for the set up of different scenarios. VESA-D, however, specifically investigates those encounters that have been identified by WakeScene-D as potentially significant encounters in a previous WakeScene-D simulation. A schematical view of the interaction between the two tools is given in Fig. 8. A detailed explanation of how the risk is calculated is given in section III.B.

The identification of encounters in WakeScene-D is done in the following way. The WakeScene-D simulation platform contains a hazard area model called the simplified hazard area prediction (SHAPe) [25], which predicts areas around the vortices within which an estimated encounter strength is exceeded. The encounter strength is characterized by means of the roll control ratio (RCR), which relates the rolling moment induced by the vortices to the maximum roll control power of the encountering aircraft. These hazard areas have been calibrated using flight test and simulator data. SHAPe takes into account the varying strength of the decaying vortices and the diminishing influence of the vortices depending on the distance to their centers. Violation of the hazard area corresponding to a specified RCR limit leads to identification of a potential encounter, which is then investigated using VESA-D. The encounter detection with SHAPe, in comparison with a simple minimum distance criterion, has the advantage that it takes into account the actual effect on the encountering aircraft depending on its distance to the vortices. On the other hand, it only considers the roll axis and assumes a flight parallel to the vortex lines, which in reality is only rarely the case. A comparably low value of $RCR_{limit} = 0.2$ has been chosen for the simulations in order to not miss any potentially severe encounters. It can be assumed that all encounters giving a lower RCR value in SHAPe are happening sufficiently far away from the vortices so that no other parameters, such as vertical load factors or sink rates, exceed any threshold either. Note that, due to the structure of SHAPe, even a perpendicular crossing of the vortices or a passing between the vortices that would cause an increase in sink rate would violate the hazard area and, thus, be detected by SHAPe, even if, in reality, no significant roll reaction would occur. A more accurate severity assessment considering all of these effects in addition to the induced roll moment can be given after the simulation in VESA-D.

For each encounter to be investigated in VESA-D, WakeScene-D saves the wake vortex prediction model output for five gates before and behind the encounter, the follower aircraft position and orientation, the NOWVIV weather data file used, and the inputs to the trajectory model for the follower to allow for the setting of the correct initial aircraft state in VESA-D. No temporal evolution of the wake vortex takes place in VESA-D during the encounter. Considering the usually short duration of an encounter of about 5–15 s, this is assumed to be an acceptable simplification, which allows for a considerable reduction in storage and memory space. With this data, it is possible to reconstruct the WakeScene-D scenario as closely as possible with respect to aircraft performance (e.g., regarding climb angle), wake vortex characteristics, and encounter geometry in VESA-D. Nevertheless, there remain differences between the simulations in both tools due to their different designs. The most obvious difference is that the influence the vortices have on the flight path of the encountering aircraft is not taken into account in WakeScene-D, so the actual flight path through the vortices computed in VESA-D with a six-degree-of-freedom dynamic simulation will not be as predicted by WakeScene-D. This is perfectly expected behavior, which is caused by the different design of the two platforms. To simulate the encounter as realistically as possible in VESA-D, it is thus necessary that the initial distance between the aircraft and vortices before the encounter is sufficiently large to ensure that the vortices do not yet have an influence on the encountering aircraft. A point where the aircraft is at a minimum distance of $R_{min} = 75$ m from the closest vortex has been chosen here. At this distance, there is

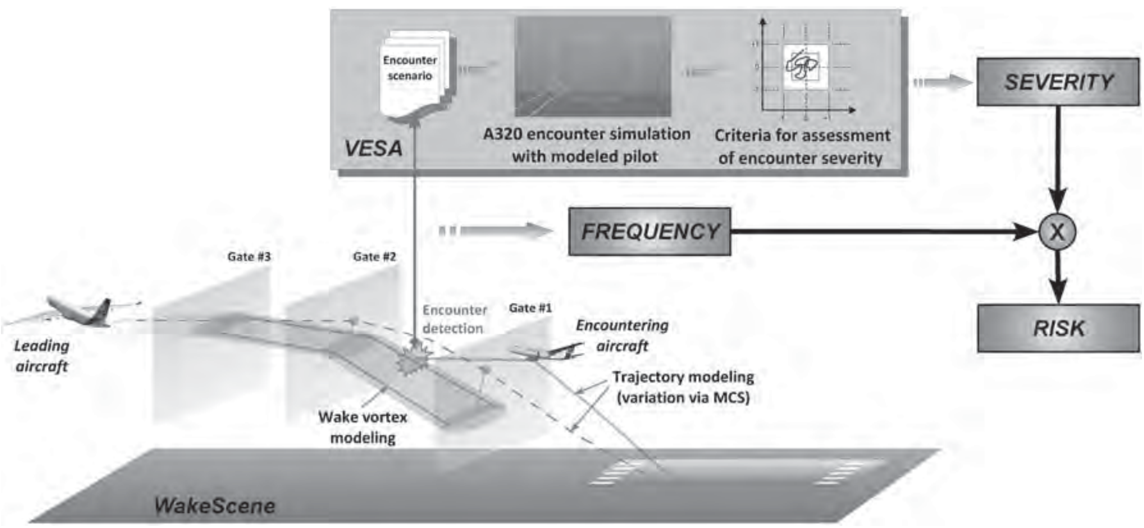

Fig. 8 Interaction between WakeScene and VESA.

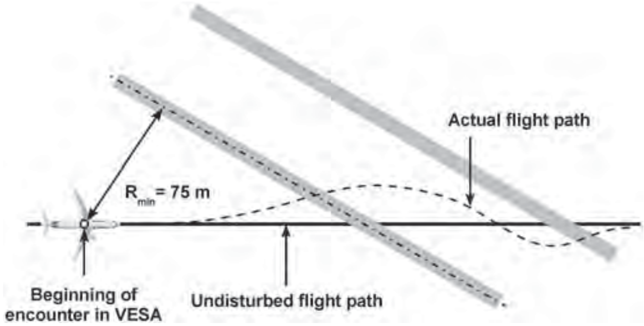

Fig. 9 Undisturbed (WakeScene) and actual flight path (VESA).

no noticeable influence of the wake on the aircraft yet, even for the strongest vortices that can be expected. Figure 9 shows the situation schematically.

In a VESA-D takeoff run simulating the encounters detected in WakeScene-D, the aircraft starts from the ground until it reaches the position where the encounter takes place. The vortices, however, cannot be placed at a geodetically fixed position within the departure corridor due to the fact that already small differences between the WakeScene-D-predicted and the actual flight path in VESA-D would make the aircraft miss the vortex. Such differences have to be expected, as the simulation of the aircraft in WakeScene-D is less detailed than in VESA-D, using only three degrees of freedom to model the flight path. Therefore, the vortices are placed in front of the aircraft shortly before the encounter. The condition used for activation is the aircraft altitude, which means the vortices are placed once the aircraft in VESA-D reaches the altitude that was determined in WakeScene-D. This is important because the severity criterion also takes into account the altitude at which the encounter takes place. Furthermore, the orientation of the vortices in space is corrected for the difference in the encountering aircraft's orientation between WakeScene-D and VESA-D. This is necessary to ensure the correct wake intercept angles between the aircraft and wake vortices.

III. Application

A. CREDOS Simulation Scenarios

The simulation platforms WakeScene-D and VESA-D described in the preceding section have been applied in CREDOS to compare the risk of having significant wake encounters for different combinations of crosswind and aircraft separation time. All other parameters like the traffic mix were chosen to be as close as possible to real operational conditions. The simulation scenarios are based on FRA in Germany. Most of the data that was made available or that was generated within the CREDOS project and was used for development and validation of the models described in this paper are from this airport. Therefore, FRA was chosen as a baseline for the computations, although some of the findings can be generalized for other airports, as will be discussed in section III.C. For the separations between leading and following aircraft, the nonradar longitudinal wake turbulence separations were chosen according to ICAO rules [1]. Departures from intermediate parts of the runway were not considered, so the reference separation time is 2 min. On the other hand, the goal of the CREDOS project was to allow suspension of these wake-turbulence-specific separations, which leads to an application of minimum radar separation (2.5 or 3 NM, depending on equipment) or a corresponding time separation of about 1 min. Therefore, 1 min was chosen as the separation for CREDOS operation. These times were always kept fixed, not considering a natural variation in the actual separation times occurring in real operation.

The remaining parameters defining the simulation scenarios are summarized in Table 1. All parameters are common to the leading and following aircraft. Although the leading aircraft types were varied according to the FRA traffic statistics, only the A320 was used as a follower (wake-encountering) aircraft, as currently only this aircraft type is available in VESA-D. The results, therefore, cover a large part but not the whole of the ICAO medium wake turbulence category.

Furthermore, in each simulation, a crosswind within a specified range of 2 kt wide was employed (e.g., 6–8 kt). In contrast to the operationally simpler solution assuring that a crosswind is always greater than a certain threshold, this way allows a better interpretation of the dependency of wake encounter risk on crosswind magnitude and direction. In addition, the assumption that a higher crosswind also means a lower risk to encounter wake vortices is not always true, as we will see later. The crosswind referred to here is always the wind component perpendicular to the departure runway at an altitude of 10 m above the ground, although the wind directions and magnitudes evolve in vertical profiles along the departure.

B. Evaluation Criteria

The evaluation of the simulation results with respect to encountering risk shown in the following section is based on the multiparameter severity criterion, which was developed within CREDOS [22] and was described in section II.B. This allows for the assessment of the probability of encounters exceeding a certain level of severity. By additionally weighting each encounter with its actual severity value, SC, the severity of each single encounter can be taken into account. This means that scenarios including a lot of low-severity encounters will yield a lower value then those with a lot of high-severity encounters. The resulting value is called the "risk". It is computed according to the following:

$$\text{Risk} = \frac{1}{N}\sum_{i=1}^{N} \text{SC} \tag{1}$$

where N represents the total number of simulated departures in WakeScene-D. All departures not identified as potential encounters in WakeScene-D are attributed a severity of SC = 0 and, therefore, do not increase the risk. Note that this kind of interpretation does not take into account the frequency of the specific crosswind condition over a longer period. Typically, high crosswind conditions occur much less frequently than low crosswind conditions, thus contributing less to an overall encounter probability over, e.g., a one-year period. The interpretation of the shown values could, therefore, be

Table 1 Parameters of CREDOS simulation scenarios

Parameter	Value/Range	Comment
Leading a/c types	A300-600/A310/A330-300/A340-300/B747-400/B777-200	Distribution according to FRA traffic mix
Following a/c type	A320	Only a/c currently available in VESA
Max. altitude	4000 ft	
Aircraft mass	Normal distribution, limited between 50% load and MTOW	
Thrust	TOGA or Flex. thrust	
Configuration	Takeoff (1 + F)	
Start point on runway	Half-normal distribution between THR and 1st taxiway entry (750 m)	
Departure route	Straight or FRA 25R SIDs	
Wind conditions	Crosswind at 10 m ±(0–10) kt Tailwind at 10 m <5 kt	Vert. profiles from NOWVIV database

worded as the following: if the crosswind is between 6 and 8 kt and the separation time is 60 s, the wake encounter risk is $x\%$.

C. Results

This section contains some of the results from the simulations done with WakeScene-D and VESA-D during the CREDOS project. A comprehensive description of all of the conducted simulations and the evaluation of the results, including sensitivity studies, can be found in Kauertz [26]. The principal representation of the results that will be used here is a plot of wake encounter risk versus crosswind. Simulations in WakeScene-D have been performed with 500,000 departures (representing one generator-follower aircraft pair) for each crosswind bin of $|\Delta u_{\mathrm{cw}}| = 2$ kt, of which a fraction was investigated further in VESA-D. These have been split by the principal direction of the crosswind that prevailed on the ground during the departure and the altitude at which the encounter occurred, as explained here. Figure 10 first shows the results with every aircraft departing straightout, not following a specific departure route. During the simulations, it was noted that the altitude of the wake encounter had a major influence on how the encounter risk changes with crosswind magnitude. Therefore, the results are split here into those encounters happening at an altitude below 300 ft (in the lower half of the plot) and those above 300 ft (in the top half of the plot). Furthermore, the plot distinguishes between cases where the crosswind component on the ground came from the left of the runway (negative sign, southerly crosswind) and from the right of it (positive sign, northerly crosswind, see also Fig. 1). As can be seen, the distributions in the two altitude domains are significantly different. Close to the ground, the decrease of wake encounter risk with increasing crosswind magnitude is as expected and is, in fact, so effective that above a crosswind component of 6 kt the risk is nearly 0, even at 60 s separation. However, at higher altitudes, the wake encounter risk first increases with an increasing crosswind before dropping to smaller values again for high crosswinds. This is the case for reduced separations as well as for the reference case with a separation of 2 min., which is representative of today's operations.

The behavior is caused by several interacting effects. First of all, the wind at 10 m above ground, which is used here to differentiate the results, does usually change considerably with increasing altitude above ground. Within a layer of the atmosphere between approximately 300 and 2000 ft, the wind direction usually veers with altitude while wind speed increases at the same time, which is caused by a balance between friction, the horizontal pressure gradient, and Coriolis force [27]. On the northern hemisphere, this leads to the wind direction turning clockwise when climbing, looking towards the ground. The veering of the wind direction, in reality, rarely exceeds 30 deg., although other effects can partially or fully counteract or intensify this veering. The weather profiles used in the simulations do contain this behavior of the wind direction, as they are taken from a numerical weather database containing realistic vertical wind profiles. The effect of the wind veering with altitude is also known as the Ekman spiral. It has an important effect on wake encounter risk.

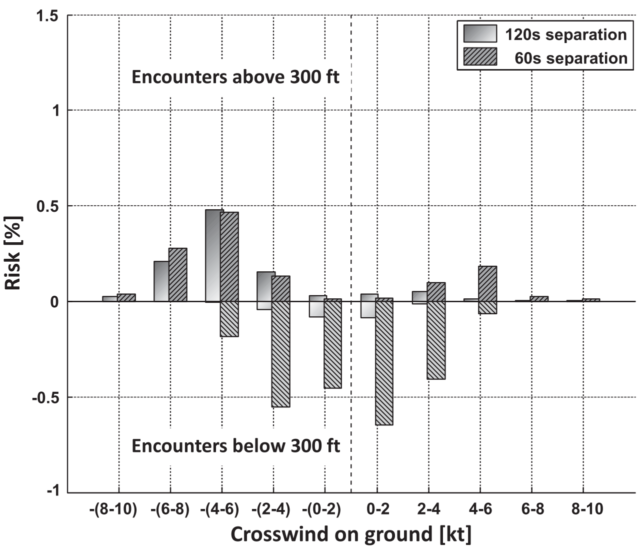

Fig. 10 Wake encounter risk vs crosswind, straightout departures only.

The fact that the wind direction changes with height compared with the ground means that a crosswind component at the ground can partially or fully disappear at a certain height. Especially when the wind is coming slightly from the left of the departure direction, it will usually turn further into a headwind a few hundred feet higher. On departure, a headwind increases the probability of encountering a wake of a leading aircraft, as the natural descent of the vortices is counteracted by the wind component, blowing the vortices towards the following aircraft. This is the reason that the encounter risk in Fig. 10 is higher for negative crosswinds (coming from the left of the runway) than for positive ones (coming from the right). Even below 300 ft, this tendency is already noticeable. After 120 s, the wakes are typically weaker than at 60 s vortex age and, thus, do not affect an encountering aircraft as much. This is why the risk at that separation is generally lower than at 60 s of separation. On the other hand, they have more time to be transported laterally and/or longitudinally into the follower's flight path by the wind, especially out of ground effect. This could be an explanation for the peak in encounter risk at around 4–6 kt crosswind being equally pronounced at 60 s and 120 s separation. The results, however, suggest that for crosswind components of 8 kt or more, regardless of direction, the risk at a separation of 60 s is only marginally higher than that at 120 s.

Further analyses of the results show that almost all of the high-altitude encounters occur between 1000 and 2000 ft above ground, which is where the aircraft usually start to reduce their climb angle, which can lead to situations where the follower aircraft intercepts the path of the wake generator and its wake. This region of the departure seems to be the critical one in terms of wake encounter risk at high crosswinds. Figure 11 shows another representation of the results, with the severity of each simulated encounter plotted versus the height above ground at which it occurred. Here, a case with low crosswind magnitudes is compared with cases with medium and high crosswind for straightout departures based on the same data as Fig. 10. The plots show very clearly how the strong crosswind effectively blows all wakes far enough out of the way up to heights of about 400 ft. It also shows the accumulation of encounters in the region between 1000 and 2000 ft, of which a certain number remains at high crosswind levels.

Another strong influence on the encounter risk that has been identified from the simulations is that of departure routing. The SID layout of the chosen runway (see Fig. 1) is such that two of the five routes turn about 26° to the north (or right with respect to the takeoff direction) at about 1 NM from the runway end, whereas the other three turn by about 66° to the south (or left with respect to the takeoff direction).

A simulation scenario has been set up in which all departing aircraft follow the two northerly SIDs. As those are in fact identical up to the considered altitude, all aircraft depart along the same route. This is the scenario corresponding to probably the most common operational condition at FRA, as traffic going to the south is usually handled from runway 18, unless wind conditions prevent its use. Figure 12 shows the results from this simulation scenario, which apart from the routing uses the same parameter sets than the straightout scenario discussed already. In this case, no simulations for crosswinds between 0 and 2 kt magnitude and 60 s separation are available. But it shows essentially the same characteristics as the straightout scenario, as the routes that were used are very close to straight routes. In particular, the asymmetry with respect to the crosswind directions caused by the Ekman effect is also visible.

On the other hand, significant differences can be seen once all SID routes are used for the departing aircraft. A further set of simulations has been performed with all aircraft departing on random combinations of the five SIDs of FRA runway 25R. Hence, about 50% more generator and follower aircraft takeoff towards a southern direction

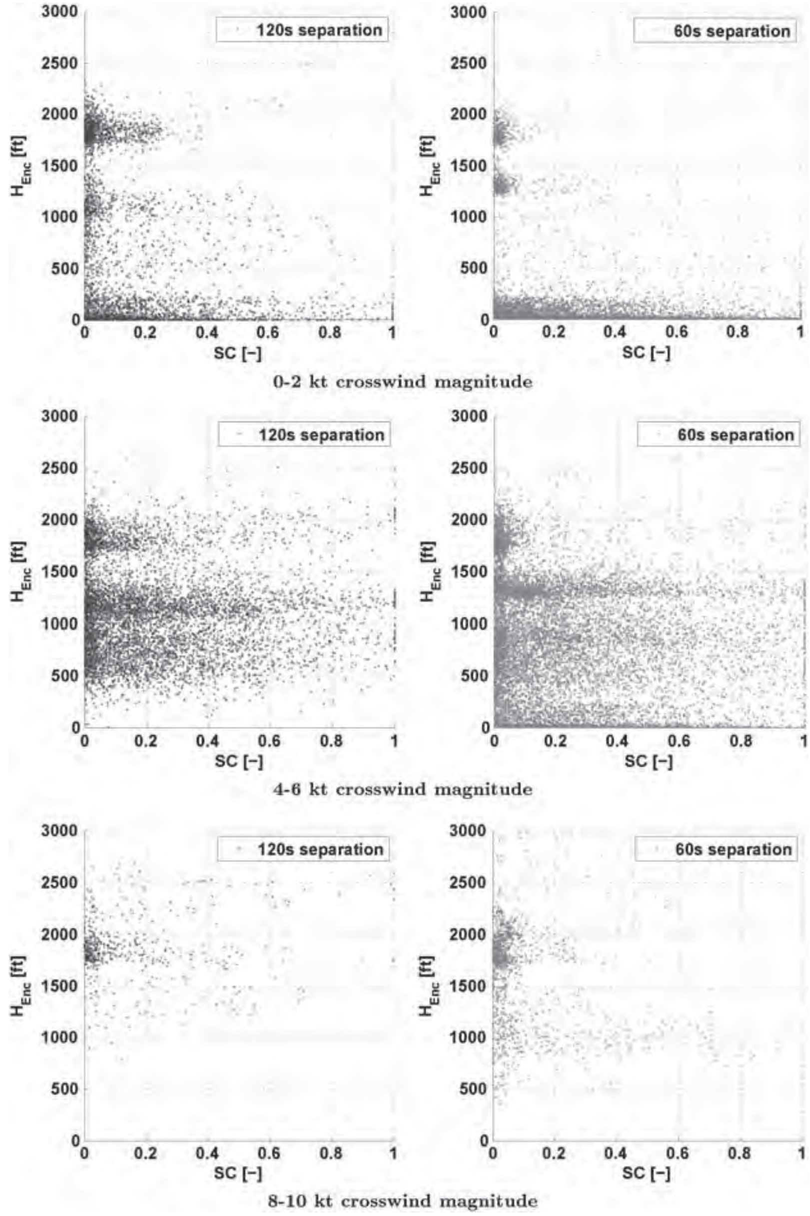

Fig. 11 Wake encounter severity SC vs encounter height, straightout departures only.

than towards a northern one. This is a realistic operational scenario when wind conditions prevent the use of runway 18, which usually handles all traffic going in southerly directions. Those wind conditions, usually a tailwind of greater than 5 kt on runway 18, would then mean a considerable crosswind from northerly directions for runway 25. Therefore, it does also make sense to investigate this constellation. Again, no simulations for crosswinds between 0 and 2 kt magnitude and 60 s separation have been performed. The plot in Fig. 13 shows that in comparison with Figs. 10 and 12 the encounter risk at higher altitudes does not decrease as clearly for high crosswinds as it does in the case of straight departure routes. The asymmetry with respect to the crosswind direction is still seen, however. The higher encounter risk above 300 ft, especially seen at high southerly crosswinds, can be explained by the wind blowing the descending vortices back towards the following aircraft's flight path when the generating aircraft departed along a southern route. This leads to an increased risk of encountering the wake for an aircraft following on either a southerly or a northerly route. It should be mentioned, however, that this is not a very common configuration as long as runway 18 is operational. For northerly winds (positive crosswind), the encounter risk also increases with respect to the straightout departure scenario, although not as significantly as for southerly winds. This is probably because the northern departure

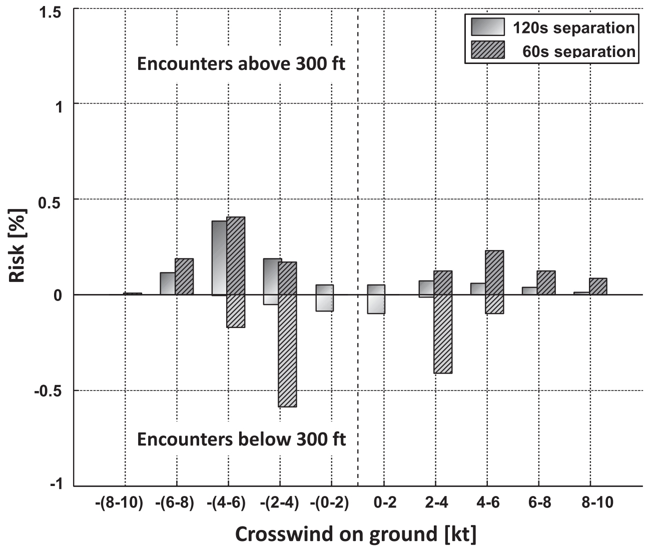

Fig. 12 Wake encounter risk vs crosswind, departures only on northerly SIDs (no data for 0–2 kt crosswind magnitude at 60 s sep.).

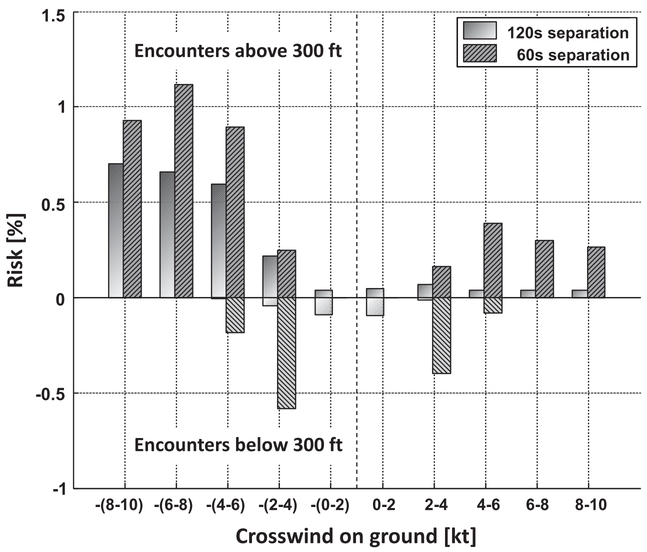

Fig. 13 Wake encounter risk vs crosswind, departures on all FRA 25R SIDs (no data for 0–2 kt crosswind magnitude, 60 s).

routes do not turn as far into the wind as the southern routes do during southerly wind conditions. Similar to the straightout departure scenario, most of the higher-altitude encounters also occur between 1000 and 2000 ft. In the case of the FRA departure route layout, the northerly and southerly routes usually start to separate there but are still close enough that vortices can be transported from one route to another.

D. Sensitivity Analyses

In this section, some sensitivity analyses that have been performed to show the robustness of the results are described. These exemplary results concern the sample size, i.e., the number of departures used in a simulation case, and the sensitivity of the severity assessment to additional turbulence. Sensitivity analyses performed with the WakeScene-D platform alone have shown that a sample size of 500,000 departures is sufficient to obtain converged statistics of the encounter probabilities [7]. Therefore, in each simulation case consisting of a certain crosswind range combined with one of the two separation times, the sample size was 500,000 departures. This results in a total sample size of five million departures upon which each plot shown in section III.C is based. Nevertheless, the assumption of converged results should be corroborated by additional analyses using VESA-D. For this purpose, two of the cases with the smallest amount of encounters have been repeated using one million departures each, instead of 500,000, to see if the encounter probability or risk differs significantly between the two sample sizes. The scenarios using only northerly departures at 8–10 kt crosswind and with 60 s as well as 120 s of separation have been chosen for this comparison. These are scenarios that yield comparably low numbers of encounters, as shown in the preceding section. The results are summarized in Table 2. Two criteria are used to judge the sensitivity of the sample size: the number of encounters having a severity of SC > 0 and the risk according to Eq. (1).

The table shows an excellent agreement for encounter probability and risk between both sample sizes. This shows that 500,000 departures seem to be also sufficient to draw robust conclusions after the severity assessment in VESA-D. For all other scenarios yielding a larger number of encounters, the convergence of the results is assumed to be comparable due to a larger statistical basis for calculation of the criterion.

A second example shows the influence of turbulence on the severity assessment with the severity model in VESA-D. Although the wake vortex evolution models take into account the ambient turbulence to compute vortex decay, all VESA-D simulations performed for the risk assessment described in the preceding section have been simulated in calm air without turbulence. Only the wind

Table 2 Sensitivity of wake encounter risk to sample size, *N*-departures only, 8–10 kt crosswind

Criterion	500 k departures	1 M departures
	60 s separation	
SC > 0	0.364%	0.365%
Risk	0.049%	0.050%
	120 s separation	
SC > 0	0.063%	0.063%
Risk	0.0068%	0.0069%

profile from the NOWVIV weather database that is used in WakeScene-D has been reconstructed in VESA-D. As the severity model used to judge the encounter risk takes into account the dynamic reaction of the aircraft, it is valid to ask what influence an additional ambient turbulence has on this severity rating. To estimate how large the influence of turbulence is on the severity rating done within VESA-D, a simulation scenario was repeated with two different levels of turbulence added. For this evaluation, again, the scenario with a crosswind of 8–10 kt and with a separation of 60 s has been chosen. Within VESA-D, the ambient turbulence is modeled based on Dryden spectra with a variable standard deviation of the gust wind speed, σ_w. The magnitude of σ_w determines the strength of the turbulence. Table 3 shows the encounter probability for the two different severity classes for the baseline without turbulence compared with two different turbulence levels, corresponding to light–moderate turbulence.

For a turbulence level of $\sigma_w = 0.25$ m/s, the encounter probability remains practically the same, but the encounter risk is reduced slightly. Both quantities are only raised somewhat at a turbulence level of $\sigma_w = 1.00$ m/s. This raise in encounter risk is expected, as the turbulence adds dynamic aircraft reactions, which are considered in the severity criterion. This would lead to a certain number of encounters close to the boundaries of normal operation defined in the criterion, which then exceed the boundary due to the added dynamics. Looking at the results in Table 3, this effect, however, does not seem to be very pronounced. Also, it is expected to be independent of aircraft separation, so that it can be concluded that added moderate levels of turbulence do only have a marginal influence on the overall risk assessment.

E. Discussion of Results

The evaluation of the results indicates that a crosswind threshold of around 8 kt could be necessary to sufficiently reduce wake encounter risk up to altitudes of 4000 ft when reducing aircraft spacing in a straightout departure scenario (see Fig. 10). Below altitudes of about 300 ft, even a crosswind component of 6 kt could be sufficient. However, the simulations also showed that, when considering realistic departure route layouts, further constraints could be necessary, as a nonstraight routing of the aircraft can increase wake encounter risk in certain situations. In this case, it could be envisaged, for example, to introduce restrictions on the departure route combinations of aircraft pairs when operating with reduced separations. Similarly, asymmetric crosswind thresholds could be used depending on the crosswind direction. Both of these measures are depending on the considered airport, its SID route layout, and site-specific meteorology.

Some of the findings obtained from the conducted simulations do not seem to be specific to the airport environment chosen. The fact that wake encounter risk depends differently on crosswinds at different heights should be independent of the specific airport,

Table 3 Sensitivity of wake encounter risk to turbulence, all SIDs, 60 s separation, 8–10 kt crosswind

Criterion	$\sigma_w = 0.0$ m/s	$\sigma_w = 0.25$ m/s	$\sigma_w = 1.0$ m/s
SC > 0	1.56%	1.55%	1.80%
Risk	0.594%	0.572%	0.609%

although the exact dependency will also be determined by the local distribution and frequency of crosswind directions and magnitudes. Likewise, the finding that the departure routing has a considerable influence on the risk can be retained as a general conclusion from the simulations. Some more dependencies between routing, wind direction, and encounter risk have been discovered by analyzing the simulations; however, more generic simulation scenarios would be helpful to fully understand the interdependencies. In any case, a local assessment should be conducted at any airport where a concept such as that explored within CREDOS shall be implemented, taking into consideration the local departure airspace layout and meteorology.

The authors want to emphasize that the risk values shown in the results should not be reduced to the following statement: five out of 1000 departures are likely to lead to a significant wake encounter. Rather, the way the risk is calculated does not directly allow us to infer the number of encounters to be expected, as it includes probability as well as the severity of the encounters. Also, the simulations used here did only model departures of A320 behind heavy aircraft, which only represent a fraction of the total traffic. Encounter risk for the rest of the traffic, e.g., for medium-medium pairings that make up a large part of the traffic mix at many airports, could be lower or higher than the results presented here. Finally, as already mentioned, the frequency of the different crosswind conditions investigated also influences the overall absolute frequency of wake encounters. The results shown before, thus, do only constitute a relative assessment between different scenarios.

The fact that only an A320 follower aircraft behind heavy class generators was used in the simulations limits the applicability for a complete safety case. The choice to consider only heavy generators was due to the fact that only for heavy-medium pairs a benefit could be expected with the concept envisaged in CREDOS. It would be comparably simple to extend the assessment to other wake-generating aircraft, as these only have to be available in WakeScene-D. Extending the simulations to other follower aircraft than the A320 would require more effort. To reach the same level of fidelity as in VESA-D, sufficiently realistic six-degree-of-freedom dynamic simulations are needed, which are not usually publicly available . Today, Airbus is able to simulate most of its own aircraft types in VESA but not those of other manufacturers. However, trends introduced by the inclusion of other follower aircraft types have been estimated in stand-alone parameter studies with WakeScene-D [7].

The simulation platforms described here and the investigations carried out with them in the frame of the CREDOS project present an unprecedented level of detail for wake vortex encounter simulations of this type. Considering the numerous submodels employed in the two platforms, the question of validity of the simulation results arises, of course. As it is very difficult to perform a validation of the full, integrated simulation platform, because the necessary real-world data for wake encounters is usually missing, a validation must remain limited to the different submodels. For each of these, extensive validation exercises have been performed and are cited in this paper (as well as in Holzäpfel et al. [6] for WakeScene-D). They show a good quality of the models throughout. Additionally, a direct comparison of WakeScene-D outputs with light detection and ranging measurements of departing aircraft wake vortices acquired during the CREDOS project has been performed, showing good agreement as well [7]. This is why the presented results are assumed to be of good quality.

Of course, several areas of improvement can be identified. The severity criterion used for assessment of the wake encounters, for example, uses an initial parameter set as set up using engineering judgement and validation with simulator results (which themselves contain uncertainties). The boundaries defined in the envelopes and the way a final judgement of safe or unsafe encounters is derived from them will, however, be subject to further work in upcoming projects, for example in the frame of the European Single European Sky Air Traffic Management Research (SESAR) program [28,29]. These modifications might change the quantitative results presented here, although the authors do not expect substantial qualitative changes in the conclusions. Furthermore, it is obvious that the limitation of the VESA-D simulations to an A320 allows for only the assessment of a part of the traffic mix concerned by modified separation distances. In WakeScene-D, however, several other medium-class aircraft types are available, which allowed us to show trends already without the detailed severity assessment in VESA-D [7].

IV. Conclusion

This paper describes the setup of simulation tools that were used for a wake encounter risk assessment in the project CREDOS and the results produced with them. The assessment was applied to an example scenario of reduced departure separations under varying crosswind conditions. The simulations show that, for the considered scenario of FRA, a crosswind threshold of 8 kt seems to be necessary to ensure safe operations with respect to wake-turbulence risk when reducing the associated separation distances from today’s required 2 min. to only 1 min. The simulations took into account situations close to the ground but also at up to an altitude of 3000 ft. The extensive simulations performed with VESA-D in conjunction with WakeScene-D have also revealed several influences and interdependencies concerning wake encounter risk during takeoff and departure. A strong influence of the veering wind has been identified, leading to the fact that the encounter risk versus crosswind behaves differently depending on the principal direction of the crosswind and the altitude above ground. Furthermore, an influence of the departure routing of the aircraft on the encounter risk at higher altitudes has been found.

During the project, the tools were significantly improved and extended by new models. Simulations of wake encounter risk in this flight phase have been conducted for the first time at this scale and in this detail. The gathered insight may be very helpful for future developments of weather-dependent separation schemes, as will be undertaken, e.g., in the European Air Traffic Management research program SESAR. Further work to improve the simulation platforms will address the definition of the severity model used in VESA-D, with the goal of coming to a wide agreement on how to determine safe and unsafe wake encounters. This also includes investigating the applicability of the model to other flight phases than departure.

Acknowledgments

The work presented in this paper was performed in the frame of the specific targeted research project CREDOS (contract number AST5-CT-2006-030837). The financial support by the European Commission is greatly acknowledged. The authors would like to thank the CREDOS consortium members for their contributions and support throughout the project, in particular TU Berlin and Université Catholique de Louvain, who provided necessary models and simulation results.

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