

APPLYING QUALITATIVE HAZARD ANALYSIS TO SUPPORT QUANTITATIVE SAFETY ANALYSIS FOR PROPOSED REDUCED WAKE SEPARATION CONOPS

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Abstract

This paper describes a scenario-driven hazard analysis process to identify, eliminate, and control safety-related risks. Within this process, we develop selective criteria to determine the applicability of applying engineering modeling to hypothesized hazard scenarios. This provides a basis for evaluating and prioritizing the scenarios as candidates for further quantitative analysis. We have applied this methodology to proposed concepts of operations for reduced wake separation for closely spaced parallel runways. For arrivals, the process identified 43 core hazard scenarios. Of these, we classified 12 as appropriate for further quantitative modeling, 24 that should be mitigated through controls, recommendations, and / or procedures (that is, scenarios *not* appropriate for quantitative modeling), and 7 that have the lowest priority for further analysis.

KEYWORDS: Safety analysis, wake vortices, hazard analysis.

Introduction

NASA and the FAA are currently investigating concepts of operations (Conops) for dynamically reducing wake vortex separation standards for closely spaced parallel runways during periods of favorable wind conditions [1], [2], [3]. These Conops are predicated on a reliable prediction of wind conditions, coupled with accurate models of wake behavior.

The basic idea is that, for parallel runways, when a sufficient cross-wind exists, the upwind aircraft is not in danger of encountering a wake from the downwind aircraft. When these wind conditions are sustained over a period of time (and when they can be accurately predicted), the minimum required separation between trailing aircraft on the upwind runway and leading aircraft on the downwind runway can be reduced – thereby increasing the net capacity of the airport. When the cross-winds do not exist (or

when they cannot be predicted with sufficient reliability), the runways operates using today's operating procedures [4]. During instrument meteorological conditions, the parallel runways operate effectively as a single runway at a significantly reduced capacity.

This paper describes a scenario-driven hazard analysis process that has been applied to identify, eliminate, and control safety-related risks associated with the proposed Conops. In addition, the safety process helps to develop quantitative engineering criteria in order to mitigate the identified risks.

In order to evaluate the safety-related risks associated with wake vortices and involving closely spaced parallel runways, a number of system safety processes must be applied. Both qualitative and quantitative approaches are to be used in order to identify risks and to identify mitigations to eliminate or control these risks to an acceptable level.

This paper describes a scenario-driven hazard analysis process to identify possible risks [5]. In this paper, we further develop the process to identify and prioritize candidate hazard scenarios that are most appropriate for inclusion in future quantitative modeling. Quantitative modeling of wake vortices (e.g., [6], [7], [8], [9]) has been applied within Monte-Carlo simulations to provide estimates of wake-related risk (e.g., [10], [11], [12]).

Figure 1 shows this phased approach. Based on the defined Conops, we conduct a scenario-based hazard analysis to describe possible wake-related accidents that may occur using the proposed system. We then rank and categorize these scenarios based on an initial estimate of severity, likelihood, and quantitative modeling difficulty. This provides a basis for evaluating and prioritizing the scenarios as candidates for further quantitative analysis. The outputs of this process are safety-related metrics, such as wake encounters per operation. The ultimate objective is to such modeling to develop quantitative engineering criteria to mitigate the identified risks to an acceptable level. Quantitative engineering criteria include, for example, the required wind prediction

reliability, availability, and response time, to ensure safe operation of the proposed system.

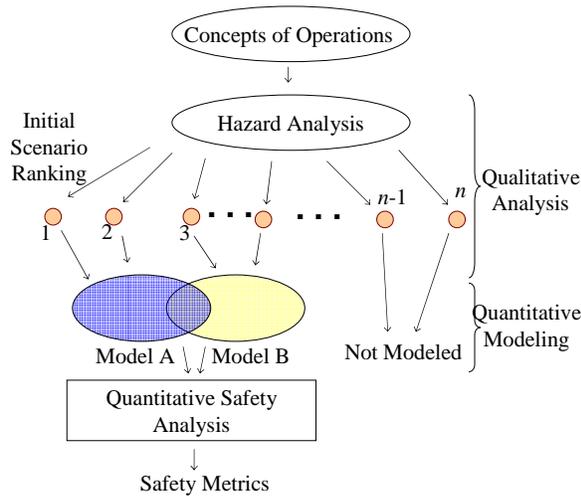


Figure 1. Integration of qualitative and quantitative analysis.

Analysis Methodology

Initially, the proposed system was defined and bounded with the development of a *concept of operations* or *Conops*. This was completed by the WakeVAS Conops Evaluation Team (CET), commissioned by NASA [1]. The team consisted of over 50 members representing expertise in air traffic control, flight operations, system integration, certification, safety analysis, wake vortex modeling, and other related areas. Conops were developed for both arriving and departing traffic. The CET also completed a preliminary safety hazard identification for both arrival and departure Conops [13], [14].

This paper describes additional analysis completed by the authors. (A core subset of members of the CET has also contributed to this follow-on work.) In the first follow-on step, we have taken the preliminary hazard list generated by the CET and described each hazard within a scenario-based framework. (As part of this process, we have also identified several hazard scenarios not previously identified in the preliminary hazard analysis.) The philosophy of the scenario-based framework is that accidents are generally the result of *multiple* contributing hazards – not just a single hazard. Thus, it can be helpful to describe hazards in the context of a complete accident. This type of description is easy to communicate and well-suited for qualitative risk assessment.

Generally speaking, a hazard scenario is described by a sequence of events, starting from initiating causes to final outcomes. Table 1 (below) describes fields in a worksheet that we have used to analyze hazard scenarios. The fields include initial causes, subsequent causes, final outcomes, and controls to mitigate the risk to an acceptable level. The table discusses each field in more detail and also gives a sample entry for each field.

Table 1. Description and examples of fields in hazard scenario table.

Field Name	Definition & Example
Scenario Number	A numeric identifier for the scenario. (Alpha-numeric schemes can be defined for sorting and grouping of scenarios.)
Hazard Scenario Description	A brief narration of the hazard scenario from initiating causes to final effects. <i>Example: Less than adequate detection of altitude errors while on vector (on intermediate approach course) occurs to leading aircraft and affects displacement. Situation results in wake encounter for trailing aircraft. Loss of aircraft control occurs and pilot/aircrew unable to regain control. Collision with ground/structure occurs.</i>
Initial Causes / Contributors	A description of the events or circumstances that are latent hazards due to oversights or omissions within the initial design of the system, including a list of possible reasons for the initiating cause. <i>Example: Altitude errors while on vector occur due to: Controller error, pilot error (early or late descent to assigned altitude), malfunction of avionics or ground system. Situation is undetected on board trailing aircraft due to: pilot or controller loss of situational awareness, malfunction of avionics or ground system.</i>
Subsequent Causes / Contributors	A description of events that occur after the initiating causes and that can lead directly to harmful outcomes. <i>Example: Controller unable to warn pilot in time to avoid exposure. Position variation results in wake</i>

	<i>encounter for trailing aircraft. Loss of control occurs to trailing aircraft. Pilot unable to regain control.</i>
Possible Harmful Outcome	A description of the possible harmful outcomes of the scenario. <i>Example: Collision with ground or structure</i>
Phase	A specific interval of time in which the potential hazard scenario (accident) can occur. <i>Example: Intermediate Approach</i>
Recommendations for Controls & Mitigations	Recommendations to eliminate and control the identified risk to an acceptable level. <i>Example:</i> <ol style="list-style-type: none"> 1. ATC use 7110.65 procedures for validating aircraft ID, position and altitude. 2. Use existing engineering and administrative controls associated with the detection of position errors to ensure aircraft position accuracy. 3. Use existing FAR's associated with aircraft maintenance and aircrew proficiency. 4. Continue to design, develop, and implement engineering and administrative controls associated with aircraft altitude accuracy, to ensure aircraft altitude error during approach is less than TBD accuracy. 5. Continue to design, develop, and implement engineering and administrative controls associated with the <u>detection</u> of altitude errors. Errors shall be detected with TBD probability within TBD seconds. 6. Conduct analysis, studies, simulations and/or flight tests to identify aircraft altitude error parameters to ensure aircraft separation, pilot situational awareness, and contingency response.
Initial Risk	The indication of worst-case risk associated with an initial design, given that minimal controls are in place. Risk is defined as the combination of severity and likelihood (these metrics are discussed in more detail later, see Tables 2 and 3) <i>Example: I-C (Catastrophic – Remote)</i>

Modeling Difficulty	The indication of level of difficulty required to model the given hazard scenario quantitatively, including the difficulty of collecting data necessary to determine statistical parameters in the model. (This metric is discussed in more detail later, see Table 4) <i>Example: ii (Moderately Difficult)</i>
Comments	Other information and references to support the hazard scenario under study, including the rationale for indicated risks, recommendations, and modeling difficulty. <i>Example: Rationale for modeling difficulty metric of ii (moderately difficult): Altitude measurements are directly observable from Mode C data. However, heuristics are needed to parse out from the data when an aircraft's altitude is not the one to which it is assigned.</i>

For every hazard scenario, we have given an initial evaluation of each field in the worksheet. This was then reviewed by a safety sub-group of members from the CET, with expertise in safety, including pilots and controllers. Two of the last fields in this table – initial risk and modeling difficulty - are metrics that we assess qualitatively for each scenario. This assessment is discussed in the next sub-section.

Scenario Classification Criteria

We have classified each hazard scenario based on its estimated *initial risk* and *modeling difficulty*.

We first discuss the initial risk metric. *Risk* is defined as the combination of two sub-metrics – likelihood and severity. Tables 2 and 3 below define the categorical criteria for these metrics used in this paper. Table 2 is adapted from the FAA System Safety Handbook [5].

Naturally, scenarios that have a high severity and a high likelihood have an unacceptable risk. But, a scenario with a low likelihood (e.g., very remote (D)), coupled with a high severity, (e.g., catastrophic (1)), can also have a risk that is considered unacceptable. Generally, the likelihood of each scenario must be controlled to a sufficiently low level, given a specified severity level for that scenario. For example, scenarios with a catastrophic severity level (1) are usually controlled to a likelihood of extremely remote (E) or less.

Initial risk is the risk associated with an initial design where minimal controls are in place. Estimates represent a conservative, worst-case assessment of the severity and likelihood. The initial risk is modified after further controls, redesign, or analysis indicate the assessment can be changed.

Table 2. Severity criteria

1 – Catastrophic	- Hull loss - Multiple fatalities
2 – Hazardous	- Fatal injury to small number
3 – Major	- Significant reduction in safety margin or functional capability - Major illness, injury - Physical distress
4 – Minor	- Slight reduction in safety margin or functional capabilities - Minor illness or damage - Some physical discomfort
5 – Negligible Effect on Risk	- Inconvenience

Table 3. Likelihood criteria

Frequent A	Expected to occur more than once every month at a facility
Probable B	Expected to occur once every 1-12 months at a facility
Remote C	Expected to occur once every 1-10 years at a facility
Very Remote D	Expected to occur once every 10-100 years at a facility
Extremely Remote E	Expected to occur less than once every 100 years at a facility

Severity and likelihood are widely used metrics in risk analysis. In this paper, we define a third metric – modeling difficulty. This metric captures the complexity of describing a scenario quantitatively using a mathematical or computer model, including the difficulty in acquiring sufficient data necessary to estimate required parameters in the model. We apply selective criteria based on this metric to determine the applicability of quantitative modeling for each hypothesized hazard scenario.

Table 4 defines four categories for this metric – *straight-forward*, *moderately difficult*, *difficult*, and

extremely difficult. Modeling difficulty can result from several causes including:

- Difficulty in quantifying or modeling the initial hazard mathematically using a small number of easily defined variables.
- Difficulty in collecting un-biased data to give statistically valid estimates for parameters in the model.
- Difficulty in enumerating possible events that occur after the initial hazard.

Table 4. Modeling difficulty criteria

Straight-Forward i	<u>All</u> of the following conditions are met: 1. Initial hazard can be modeled by a single random variable (continuous, discrete, or Boolean). 2. Sufficient data exist to obtain statistically valid estimates for the distribution function of the random variable. 3. Subsequent effects of initial hazard (a) require only <u>parameter</u> changes to the baseline model (that is, they do not require adding new structures to the model, and (b) sufficient data exist to estimate these parameter changes.
Moderately Difficult ii	<u>One or more</u> of the following conditions is relaxed to: 1. Initial hazard can be modeled by <u>three or fewer</u> random variables (continuous, discrete, or Boolean). 2. Sufficient data <u>could be collected</u> to obtain statistically valid estimates for the distribution function of these random variables. Actual data may require substantial manipulation to make relevant to task at hand. 3. Subsequent effects of initial hazard (a) require only <u>simple, logical</u> changes to the baseline model, and (b) sufficient data exist to estimate these parameter changes.
Difficult iii	<u>One</u> of the following conditions is relaxed to: 1. Initial hazard can be modeled by <u>ten or fewer</u> random

	<p>variables (continuous, discrete, or Boolean).</p> <ol style="list-style-type: none"> Relevant data could be collected, but quantitative estimates from the data are difficult to obtain, either because the data are anecdotal, heavily biased, or too small in number to make reasonable statistical estimates. Subsequent effects of initial hazard (a) require <i>major structural</i> changes to baseline model, and (b) sufficient data exist to estimate these parameter changes.
Extremely Difficult iv	<p><u>One</u> of the following conditions is relaxed to:</p> <ol style="list-style-type: none"> It is not clear that the initial hazard can be modeled using less than 10 or fewer random variables – or if it can be even modeled mathematically at all. Data on initial hazard would be extremely difficult, if not impossible, to collect. Subsequent effects of initial hazard are extremely difficult, if not impossible, to model and / or to collect data for.

To illustrate the metric, we give an example of a hazard scenario appropriate for each level of modeling difficulty.

- Straight-forward (i) hazard scenario: Wake encounter due to lateral deviation from the localizer. Lateral deviation is directly obtainable from multi-lateration data. In addition, previous studies have fitted probability distributions to observed flight-track data on approach (e.g., cite [15],[16],[17]).
- Moderately difficult (ii) hazard scenario: Wake encounter due to localizer intercept error. Although flight tracks are directly observable from multi-lateration data, heuristics must be developed to parse out from a flight path (a) when the plane intercepts the glide-path and (b) how to measure the overshoot. A quantitative model would require several variables including the probability of an overshoot, and the distribution of the size of overshoot.
- Difficult (iii) hazard scenario: Wake encounter due to excessive pilot workload. Pilot workload is difficult to measure quantitatively. A very

rough measure for the likelihood of workload contributing to a wake encounter could be obtained from anecdotal or narrative wake reports, but such data collection would be highly biased, limited in number, and not appropriate for quantitative statistical estimates. In addition, there is an issue of extrapolating existing data based on today's system to a future, proposed system

- Extremely difficult (iv) hazard scenario: Inappropriate contingency in response to wake alert. (The proposed Conops include a system to alert the pilot and/or controller when favorable wind conditions suddenly cease and reduced separations are no longer safe.) It would be extremely difficult to enumerate the set of possible inappropriate contingency responses to a wake alert, since the response could be any number of actions. However, it may be possible to model a core set of well-defined break-out maneuvers as a subset of this hazard scenario. Thus, conservatively, this scenario may be rated as (iv), but if properly bounded, possibly as (iii).

Results

The hazard analysis identified 43 core arrival hazard scenarios and 40 core departure scenarios. Each core scenario involves a unique initiating hazard and a final outcome of a catastrophic wake encounter (i.e., a collision with the ground). Note: The quantity of hazard scenarios does not imply that the proposed system is unsafe. The hazard scenario list is a brainstorm of possible things that can go wrong. Some scenarios have an acceptable risk level, so not every scenario represents an unsafe event. Secondly, the risk assessment is based on an *initial* assessment with minimal controls and mitigations in place. Thus, for those scenarios that have an unacceptable initial risk, controls and mitigations are developed to reduce the risk to an acceptable level.

There is some overlap of scenarios between arrivals and departures. For example, scenarios involving inadequate wind prediction appear in both arrival and departure lists. In many cases, there are analogous, but different, scenarios between arrival and departure Conops. For example, arrival scenarios involving incorrect selection of the approach runway have similar counterparts as incorrect selection of waypoints in the departure scenarios.

We have also created an expanded set of scenarios by taking the core scenarios and considering different final outcomes (e.g., wake encounters resulting in major injuries, but no

fatalities), and by considering initiating hazards applied to either the leading or trailing aircraft. The complete list of scenarios includes over 200 scenarios each for arrivals and departures.

Figure 2 shows the combined classification of the likelihood and modeling-difficulty metrics for the 43 core arrival scenarios. The rows identify the operational risk classification (1-B, 1-C, 1-D) and the columns identify the modeling-difficulty classification. The numbers in the table identify the number of scenarios in each category (the sum of these numbers is 43). For simplicity, we have only included the *core* arrival scenarios. These all have a catastrophic severity level. In other words, of the three metrics – severity, likelihood, and modeling difficulty – we have held severity fixed. This helps to identify trends and make comparisons of the initiating hazards.

We first make several qualifying statements about the methodology:

1. The assignment of metrics is not precise; the intent is to identify trends and provide guidance for future analysis.
2. The *relative* metrics (not the absolute metrics) are important (for the purposes evaluating scenarios as candidates for quantitative analysis).
3. *The assigned likelihoods are **conservative**, based on an initial assessment of risk. The actual risk may be much lower, but we choose to err on the conservative side until future analysis shows that the true risk is much lower.*
4. The assigned metrics will likely change as further analysis is done. The classification is intended to be part of on-going research program in which the metrics are periodically re-evaluated.

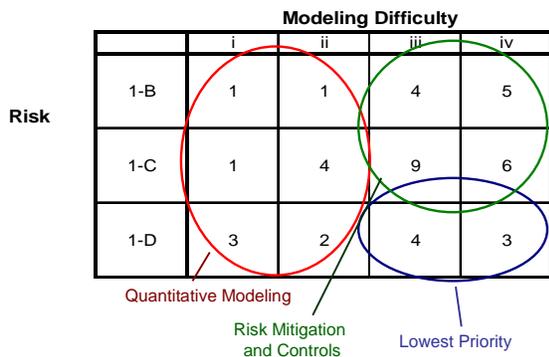


Figure 2. Preliminary classification of core arrival hazard scenarios.

We now discuss general trends observed by noting the types of scenarios that appear in individual columns and rows. Looking at the columns, scenarios that appear in the first column (straight-forward (i) modeling difficulty) generally involve initiating hazards that are directly observable from sources of positional data, such as Mode C and multi-lateration data. Examples include lateral, vertical, and longitudinal errors, and speed errors. Scenarios in the second column generally involve hazards that are indirectly observable from these sources of data, or must be correlated with other data sources. For example, effects of weather on lateral, vertical, and longitudinal displacement must be correlated with weather data from other sources. Scenarios in the third column (iii) generally involve hazards related to human factors or workload issues for which there would be limited data or for which only anecdotal or narrative data exist. Examples include hazards related to missed approaches (missed approaches are infrequent events, so it may be difficult to accurately statistically quantify flight tracks on missed approaches), and hazards related to pilot and controller workload. Items in the last column (iv) generally involve unforeseen contingencies or synergistic effects between hazards that are extremely difficult to model (for example, emergency evasive actions – it is very difficult to capture the range of possible emergency evasive maneuvers or to collect data on such maneuvers).

Looking at the rows, scenarios classified with a higher likelihood (B) generally involve hazards associated with unknown effects of implementing the new system – for example, hazards related to unreliable wind predictions, where the accuracy of such predictions is not well known at this point. Again, the philosophy has been to err on the side of assigning a conservative initial likelihood, in the absence of prior knowledge. Scenarios in the lowest risk category (1-D) generally involve hazards that exist today, that have already been controlled to an acceptable risk level, and for which it is estimated that implementing the proposed Conops would not significantly change effects of the hazard. Examples include lateral deviation from the localizer and ILS frequency selection error.

Combining the two metrics (Figure 2) provides a basis for evaluating direction for future quantitative analysis. Hazard scenarios in the lower right corner – that is, scenarios that have the least risk and that are extremely difficult to model have the lowest priority for quantitative analysis. 7 out of 43 (16%) of the core scenarios fall into this category.

Hazard scenarios in the upper right corner are also extremely difficult to model, but they have a (relatively) high risk, so they are important. For these risks, controls and mitigations must be developed to ensure that risk is controlled to an acceptable level, since modeling and analysis are likely not capable of demonstrating acceptable risk related to these scenarios. 24 out of 43 (56%) of the core scenarios fall into this category.

Finally, scenarios in the left side of the table are appropriate for quantitative analysis. 12 out of 43 (28%) of the core scenarios fall into this category. The final step within our system safety process was to make judgment upon the identified risks. The set of scenarios that are suited for quantitative analysis must represent the risks within the wake exposure that we are evaluating. Consequently, it is expected that the quantitative analysis will enable us to meet our objectives of determining appropriate quantitative engineering design criteria.

Further Observations

We applied the system safety process previously discussed for both arrival and departure Conops and compared the likelihood, severity, and modeling difficulty metrics for the core scenarios involved. In other words, we created an analogous table as in Figure 2 for departures. From this parallel analysis, we make a number of additional observations. First, we estimate that there is more risk related to departure-path errors than to arrival-path errors. This is due to the requirement in the departure Conops that successive aircraft fly to different waypoints to minimize the likelihood of wake exposure. We estimate a higher likelihood of hazard-scenarios related to *flying to the incorrect waypoint* versus similar hazard-scenarios for arrivals related to flying an approach path to the wrong runway. Secondly, from a modeling perspective, departures are more difficult to analyze statistically. This is because there is higher variability in the flight tracks, so it is more difficult to reliably predict the locations of airplanes, and it is also more difficult to distinguish between good and bad data.

Finally, we estimate that there is more risk for arrivals than for departures *during contingencies*. From a workload perspective, departures can be grounded during a contingency. But for arrivals, controllers must simultaneously deal with the contingency and also continue to direct aircraft.

Conclusions

This paper has addressed both qualitative and quantitative analysis techniques in support of applying system safety processes in the evaluation of safety-related risks associated with wake-vortex risk. This qualitative method discussed the scenario-driven analysis process. The process was used to enable risk identification and risk ranking in order to apply selective criteria for hazard scenario modeling. Selective criteria were developed which enabled us to identify hazard scenarios that can be quantitatively modeled in order to develop quantitative engineering criteria needed such as reliability, availability, and response time associated with wake vortex prediction and avoidance.

Quantitative analysis is not appropriate for all types of safety investigations. Safety analysis inherently deals with unusual and hard-to-predict events. Often these events are difficult to describe mathematically. And, it may be extremely difficult, if not impossible, to collect data on these rare events. Thus, care must be taken when incorporating these types of rare events into mathematical models.

As a result of the system safety process, a number of additional observations were made comparing arrivals and departures. For departures, there is more risk related to deviations from the intended flight path. Departures are also more difficult to analyze statistically because of the higher variability in the flight tracks. On the other hand, there is more risk for arrivals during contingencies.

This paper is part of an on-going effort to assess safety and capacity related to proposed concepts of operations for dynamically reduced wake separation standards for closely spaced parallel runways based on wind conditions.

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Disclaimer

This paper solely represents the opinions of the authors and does not reflect the opinion of the United States government.

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