A REDUCED AIRCRAFT SEPARATION RISK ASSESSMENT MODEL

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Improved safety and increased capacity are usually viewed as conflicting goals. The recent Gore Commission report set a goal for civil aviation of reducing the accident rate by a factor of five over ten years while enabling increased capacity. In order to achieve these goals, new technologies and procedures will have to be introduced. Many capacity initiatives are related to the safety-critical procedures for approach and landing and other terminal area operations. There is currently no accepted method to quantify the relationship between safety levels, aircraft separation standards, and new applications of technology in the terminal area. This paper presents a modeling approach to quantify the risk associated with changing aircraft separation. The model can be used to assess the overall level of safety associated with reducing separation standards and the introduction of new technology and procedures.

Acknowledgments*

The authors gratefully acknowledge the support and contributions of Dr. Mary Connors of NASA Ames Research Center, Mr. Jack Wojciech of the FAA's Office of System Safety and Mr. Alexander Smith of Rannoch Corp.

Introduction

The objective of the research presented in this paper is to develop a computer model that will link aircraft separation to quantitative safety risk. The model under development is called the Reduced Aircraft Separation Risk Assessment Model (RASRAM). The modeling approach taken is to evaluate safety risks for a variety of flight scenarios relating to final approach, landing, and roll-out for parallel and single runways. The basic approach of RASRAM is to quantify and compare the risk associated with current separation standards to that of reduced separation operations during instrument meteorological conditions, considering procedural and technological changes. The research is being performed for NASA as an integral part of NASA's Terminal Area Productivity (TAP) program, and in coordination with the FAA.

NASA's TAP program has the goal of achieving clear weather capacities in instrument weather conditions. The TAP program anticipates procedural changes for terminal area operations along with the introduction of new technologies. These new technologies include Differential GPS (DGPS), Automatic Dependent Surveillance (ADS-B), and several technologies under development by the NASA TAP program: Center-TRACON Automation System (CTAS), Aircraft Vortex Spacing System (AVOSS), Dynamic Runway Occupancy Measurement (DROM), and Airborne Information for Lateral Spacing (AILS). RASRAM begins the process of quantifying the safety risk associated with the effects of these technologies on separation standards.

Overview

Scenarios help to focus the emphasis of a model and define its scope. RASRAM methodology has been developed for three scenarios as shown in Figure 1.

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* Sponsor: NASA Ames Research Center
Research Triangle Institute:
Prime Contract NAS1-19214(34)
Rannoch Subcontract 26-81U-4903

The operational focus of these scenarios is separation between aircraft on final approach and landing, when flight risks are greater than during any other phase of flight.[†]

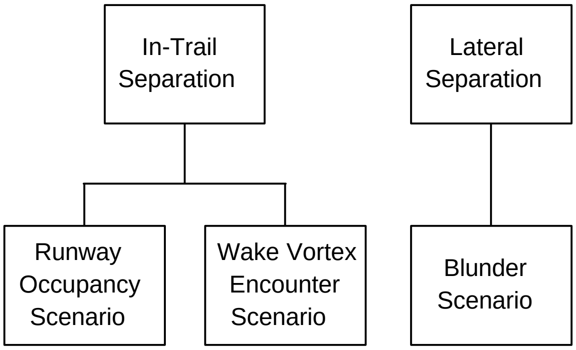

Figure 1. Model Scenarios

The final result for each scenario is a consolidated risk of incident and accident from all sources applicable to the scenario. RASRAM produces a variety of risk measures. In the lateral blunder scenario there is a fairly well established target level of safety for the risk of near misses. For the other scenarios as defined here there is as yet no consensus on target measures of safety nor on the target levels of safety for the target measures. The approach used in RASRAM quantifies the connection between a number of risk measures. In this way, RASRAM can remain useful as the aviation safety community explores different alternatives for target measures and levels of safety.

Separation Standards

The RASRAM modeling has been formulated to provide relative risk information in comparing changes in separation criteria that affect the principal encounter geometry for a scenario. RASRAM does not model all of the elements that can potentially cause incidents and accidents on final approach and landing. Rather it is limited to only those elements associated with aircraft separation and the incidents and accidents that can result from the loss of safe separation. The major separation value considered in the lateral scenario is the distance between a pair of parallel runways that are to be used for independent approaches in Instrument Meteorological Conditions (IMC). The major separation value considered in both of the in-trail scenarios is the distance between a leading and trailing aircraft making successive landings on the same runway during adverse weather conditions. In-trail separations depend primarily on weight categories for both the leading and the trailing aircraft. Table 1 shows the current values of these separation standards. The values in Table 1 are distances expressed as nautical miles. The 2.5 nautical mile standard (in parentheses) is dependent on airport-specific operational conditions, including a survey to ensure that runway occupancy times average less than 50 seconds.

Table 1. In-Trail Separation Standards[1]

Leading Aircraft Trailing Aircraft	Heavy	B-757	Large	Small
Heavy	**4 miles**	**4 miles**	**3 (2.5) miles**	**3 (2.5) miles**
Large	**5 miles**	**4 miles**	**3 (2.5) miles**	**3 (2.5) miles**
Small	**6 miles**	**5 miles**	**4 miles**	**3 (2.5) miles**

An aircraft is classified as heavy if it weighs more than 255,000 pounds; large for lower weights down to 41,000 pounds; and as small otherwise. The Boeing 757 is given its own category as a leading aircraft because of its wake vortex characteristics.

The existing justification for in-trail separation standards in IMC are based largely on empirical determinations of the strength of wake vortices. Separations based solely on runway occupancy are normally 3 miles, but can be reduced to 2.5 miles when the average runway occupancy is less than 50 sec[1]. The extent of the difference is the potential gain from tightening or eliminating the wake vortex component of in-trail separation standards. Lateral separation standards do not currently include the hazards of encountering the wake vortex of the other aircraft. RASRAM also does not yet include this source of risk.

RASRAM computations have been formulated and organized to exhibit the effects of changes in technology without modeling all of the implementation details that are necessary to produce these effects. With this type of formulation, risk modeling is complementary to the science of designing and applying new technology. For instance, radar update rates are critical determinants of the diagnostic value of information delivered to an air traffic controller who is monitoring an aircraft for compliance with an assigned route of flight. A controller will be able to recognize potentially unsafe situations and respond with corrective instructions more quickly with better data quality displayed on the monitoring console. The safety effects of the results of controller action, however, can be computed effectively by representing the controller actions strictly in terms of the time between the start of an

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[†] Departures are not included in this model.

unsafe maneuver and the completion of a response by the controller. Within this time budget, human factors analysis is required to determine the effects of radar update rates and display technology on the recognition and confidence levels of the controller. The RASRAM methods incorporate the timing of the resulting behavior, but do not attempt to model all of the parameters that might contribute to modifications of this timing or the cause of unsafe maneuvers. To apply the RASRAM approach, technology effects have to be estimated on the crucial performance factors included in the RASRAM computational model.

The modeling approach for RASRAM has been designed to simplify computational requirements for producing useful risk analyses. Analytical methods are applied to reduce the requirements for exploring a complex parameter space with the random sampling of Monte Carlo simulation methods. Whenever possible, separate computational components are used for physical geometrical relationships, for dynamic relationships based on timing, and for statistical relationships expressed as continuous probability functions. By separating, or de-coupling, these relationships, it is easier to compute and report the results of changes in any one area. For instance, computing the parameters that determine which aircraft will pass within 500 ft in an encounter geometry makes it simple to explore different statistical statements of the probability of a combination of parameters.

Methodology

Scenarios provide a context for evaluating specific operational procedures. The first step is to design a scenario to isolate some specific procedures and the applicable separation criteria. The scope of the scenario should be complete enough to include the effects of different technologies, changes in separation criteria, and other sources of random variation in scenario outcomes. Within a scenario, the RASRAM method incorporates fault trees and event trees. In RASRAM, both fixed probabilities and time-dependent probabilities are modeled. A fault tree exhibits the fixed probability events for the scenario (see references 2 and 3 for descriptions of fault trees). The event trees are used to show the dynamic events that are modeled. The probabilities of the dynamic and time dependent events occurring are computed separately from the fault tree. These are typically events whose probabilities are characterized by time distributions, which is primarily the case for modeling response times. An example is the time it takes an air traffic controller or pilot to respond to an event. This is typically characterized by curves where there is a high probability of response initially followed by decreasing probabilities over time. Many of the dynamic elements of computation are organized into a computational model of the encounter geometry. The results of the time-dependent computations are then inserted into the fault tree.

Time-budget analyses compute the effect of dynamic interactions among multiple participants in a scenario, each with defined roles, responsibilities, information sources, and performance functions. A performance function is generally expressed as a probability function for the timing of a specific interval between two clearly defined, observable events. Probability risk measures link incident and accident risks to the fail-safe mechanisms characterized by procedures and interventions. The RASRAM methodology works directly with the functional form of probability distributions. This is an improvement on models that rely entirely on Monte Carlo simulation techniques because the effect of the distribution of a particular parameter is fully reflected in the result, as opposed to Monte Carlo techniques where the result is based on statistical sampling.

In the operational encounter geometry, some crucial response times are simply the sum of other, known response times. Serial combinations refer to events that happen one after the other; the composite event starts from the initial time of the first event to the termination of the last event. Mathematically, all the uncertainty information about an event can be summarized as a single probability function. The probability of a (serial) composite event is expressed mathematically as the convolution of the constituent probability functions.

A cumulative distribution function (CDF) of a single parameter, $Q(x)$, takes values between 0 and 1. The value of $Q(x)$ is defined as the probability that the duration of the event will be less than x. The same event can also be represented by its probability density function (PDF), which is the derivative of its CDF.

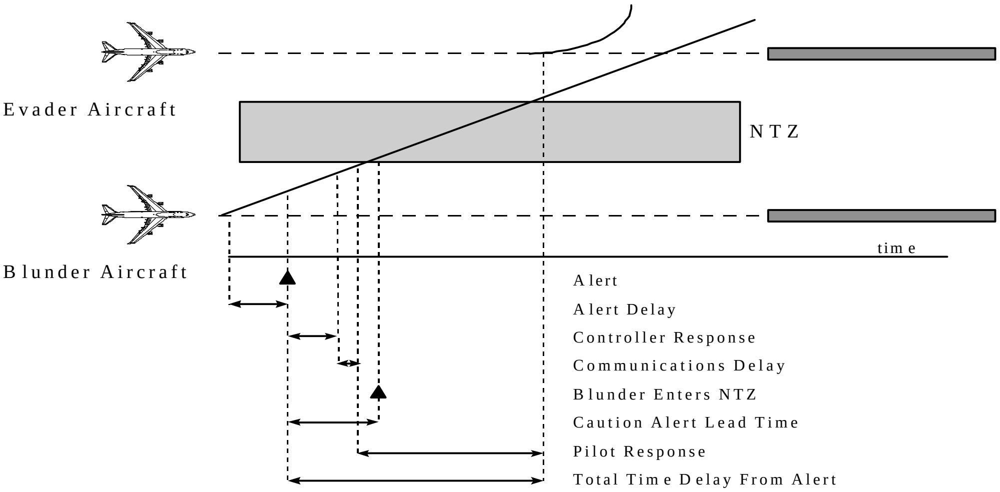

Figure 2. Lateral Blunder Scenario (PRM operations)

An example of a serial combination of performance functions is shown in Figure 5, which illustrates the convolution of controller and pilot response times. The individual controller and pilot response times are represented by probability density functions, call them c(t) and p(t). The distribution, r(t), of the sum of these times is determined as the convolution integral

$$sum(t) = \int_{-5}^{t} c(x)\,p(t-x)\,dx$$

that represents all the different ways that r(t) can occur as the sum of c(x) and p(t-x). Despite the complex shape of the individual distributions, the combined curve shown in Figure 5 is clearly less complex. In fact, the resulting convolution is usually simpler, smoother, and more stable than the individual distributions that are being added together. When the individual curves are represented as splines, the convolution can be computed efficiently.

Splines are piece-wise polynomial functions that are at least twice continuously differentiable. In the RASRAM approach, splines are used to represent continuous probability density functions. Splines offer a number of computational advantages, including the allowance of the approximation of a set of sample points in the usual least squares sense using straightforward linear regression techniques. When the approximated function is a statistical distribution, a spline can be fitted efficiently without knowing the parametric form of the underlying distribution.

The complex mathematical modeling for RASRAM uses Mathcad®, which provides both numerical and symbolic computational capabilities. The appearance of Mathcad® formulas and equations are designed to match the usual mathematical forms of expressions. This combined with the ability to intersperse text and equations means that Mathcad® worksheets can be very readable documentation as well as efficient computational tools.

Lateral Blunder Scenario

The operational context for this scenario is a pair of independent approaches to parallel runways. The primary separation criterion is the distance between the runway center lines for the two approach paths. FAA safety studies have directly linked the separation distance between center lines to the successful outcome of a single scenario that is chosen to represent a worst-case threat to one of the streams of traffic. This blunder scenario eliminates the need to consider complex, interacting alternatives forms of threat. It also reduces the need to aggregate many different types of outcome into a single measure of risk.

The defining characteristic of the scenario is a blundering aircraft that strays from its own final approach path, crossing the path of the other approach stream. The encounter geometry is three dimensional. The blundering aircraft is assumed to continue on its path without responding to controller directives. The target risk measure is the probability that the blundering aircraft will approach within 500 ft of an aircraft in the other approach stream.

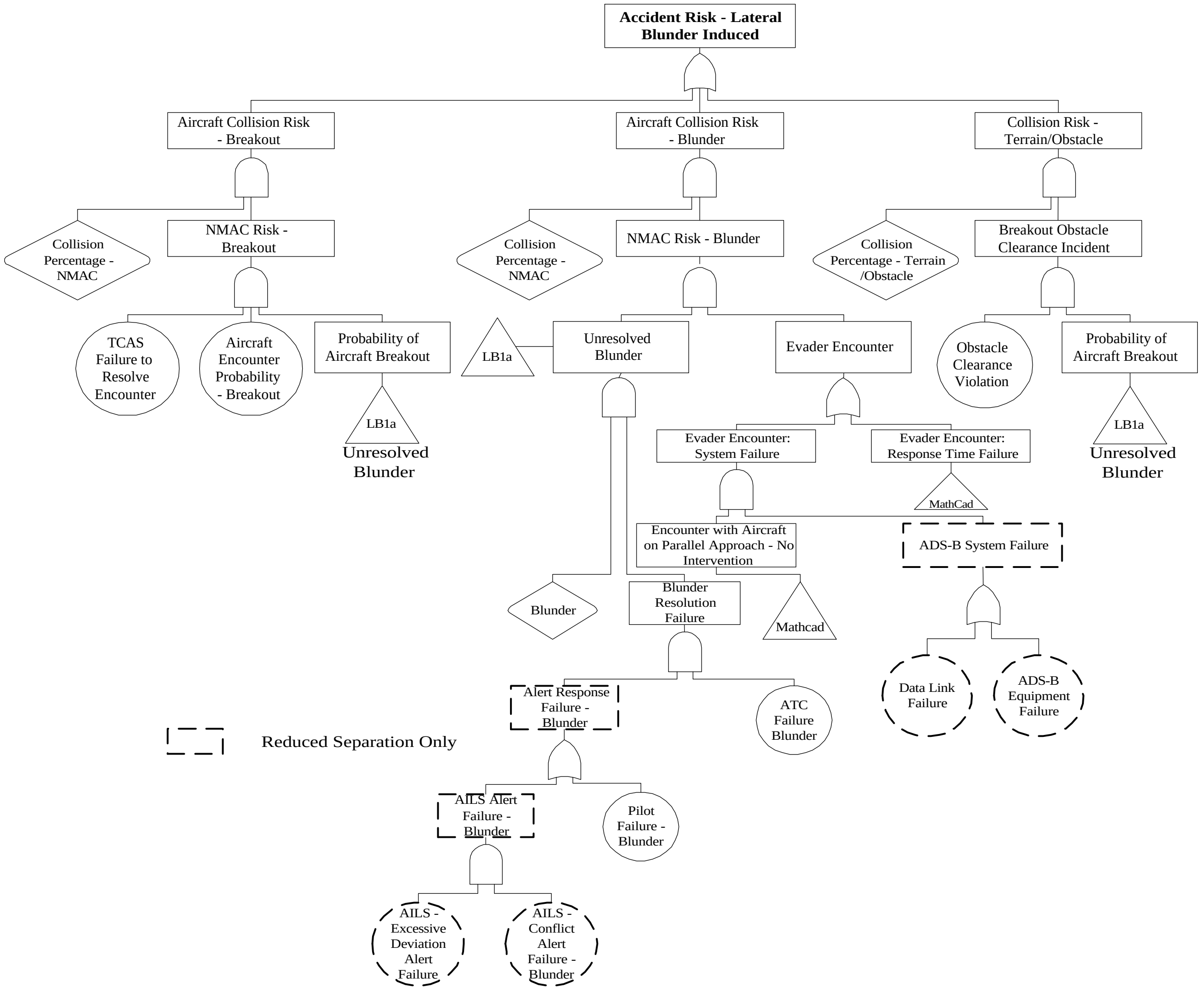

Figure 3. Lateral Blunder Scenario Fault Tree

The operational encounter geometry is shown in Figure 2. The target measure of safety of the scenario is determined by the performance of the controller in detecting the blunder and issuing breakout instructions to the evader aircraft, and the performance of the pilot and aircraft in completing the evasive maneuver. Not shown here but also included in the model is the normal navigation performance of the two aircraft in which both aircraft will normally deviate laterally about the extended runway centerline. The lateral deviation distribution of the aircraft has been modeled statistically and included in the model.

Fault and Event Trees

Fault Tree

The fault tree for the lateral scenario is shown in Figure 3. Three possible types of collision risk are identified: collision risk for aircraft on parallel approaches, risk of a mid-air collision between the evader and a third aircraft following a breakout, and risk of collision with terrain or obstacle following a breakout. The latter two are secondary risks in that a blunder of some duration or other non-normal event must occur first, causing a breakout from the approach. Of primary interest is the risk of collision for aircraft on parallel approaches.

The initial event that must occur is a blunder as illustrated in Figure 2. After the initial blunder there is the probability that ATC and the pilot of the blundering aircraft intervene. If not, it becomes an unresolved blunder that will cross the path of the parallel approach. Assuming this occurs, the model then accounts for the likelihood of encountering another aircraft. This portion of the model is a dynamic simulation performed separately from the fault tree, and is explained further with the event tree. The probability of the blunder and the probability of failure of evasive action given to the blunder are multiplied since both events must occur to result in a NMAC (Near Mid-Air Collision), which is defined to be a slant range separation less than 500 ft. As shown in the top right and top left portions of the fault tree, the model includes risks associated with the breakout maneuver. There is a risk of violating obstacle clearance criteria, which can lead to collision with the terrain or an object. There is also a risk of encountering another aircraft during the breakout. In this case it is assumed that TCAS will safely resolve those situations most of the time. The total accident risk is determined after factoring in an estimated ratio of NMACs to accidents, since only a portion of NMACs result in a collision.

Finally, the fault tree incorporates the application of ADS-B to provide CDTI (Cockpit Display of Traffic Information) and the TCAS-like function Airborne Information for Lateral Spacing (AILS), a TAP technology currently under development. For reduced separation operations this replaces PRM in providing alerts when an aircraft deviates significantly from the approach. In this scenario, ATC and communications elements are eliminated, leaving only pilot and aircraft response time. This illustrates why a TCAS-like function has the potential for allowing reductions in separation since it eliminates at least two delay factors in initiating aircraft breakouts. For the baseline safety model the TAP technologies are not used, with only PRM being assumed available for conflict detection and resolution.

Event Tree

The events that must occur in order for the blundering and evader aircraft to actually encounter each other are shown in Figure 4. These events follow those illustrated in Figure 2. When the blundering aircraft crosses the parallel aircraft's path, the model factors in the probability of encountering another aircraft depending upon traffic density, geometry, and relative velocities. Geometry factors include the turn rate, final turn angle and climb rate of the evader aircraft. The remaining portions of the event tree are the effectiveness of ATC surveillance to detect and initiate evasive action by the endangered aircraft. Dynamic encounter scenarios are modeled in Mathcad®.

Several sources of variation in the RASRAM lateral model are based on simulations and analyses that were performed with the Precision Runway Monitor (PRM) system[4,5]. The key parameters associated with PRM are controller response time, communications delay, and pilot/aircraft response time. In the computational encounter geometry, this serial combination of delays is treated as a single random variable, resulting from a convolution as shown in Figure 5.

Description of Key Input Parameters

The blunder scenario simulation for parallel approaches is a function of several input parameters (see Figure 2). Some of the parameters stated below are constants while others are statistical distributions (stochastic processes). The model takes into account the following parameters:

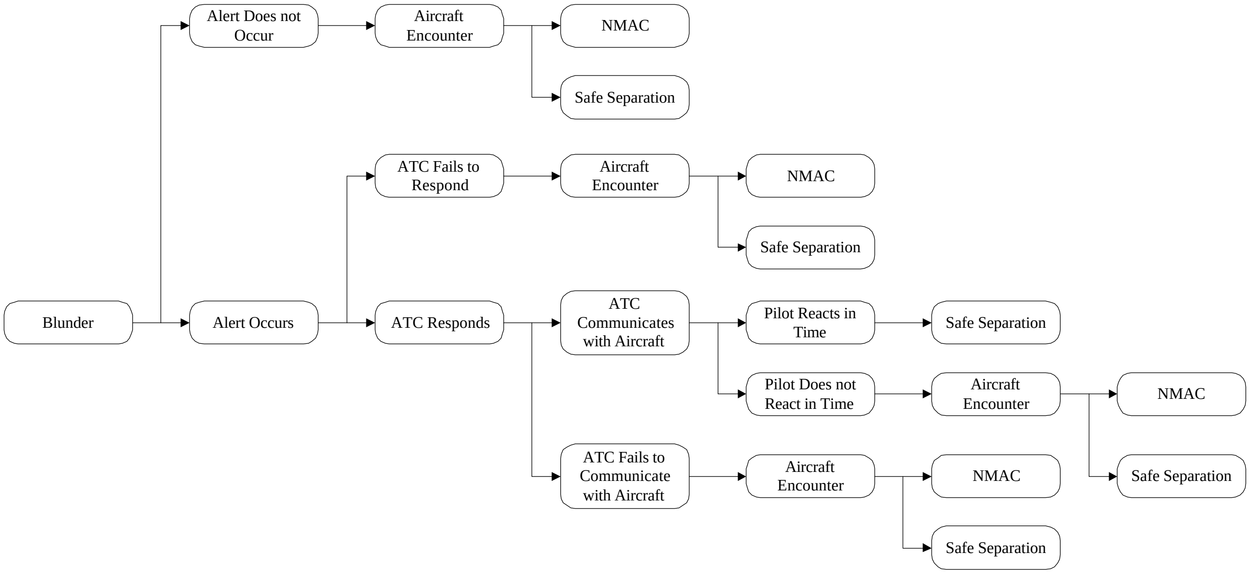

Figure 4. Lateral Blunder Evader Encounter Event Tree

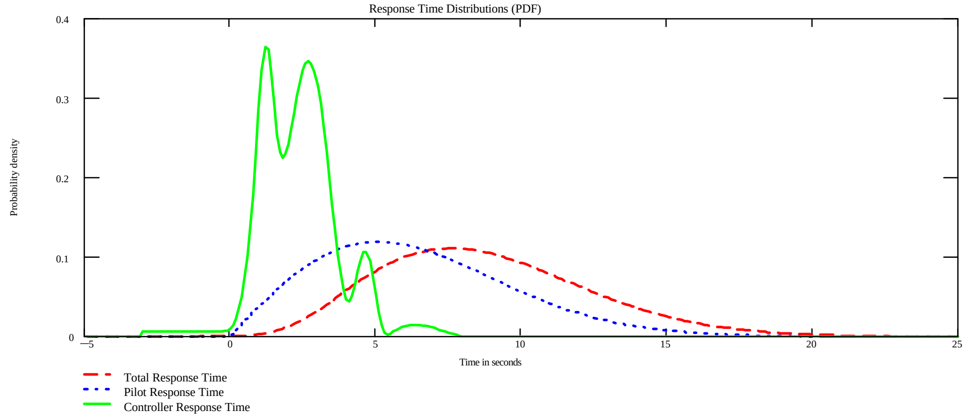

Figure 5. Controller, Pilot and Combined Response Times for Baseline Case

Runway Separation: The runway separation is defined as the lateral separation between the center line of a pair of parallel runways. For the baseline case, the simulations use 3400 feet as the input for lateral separation.

Velocities of individual aircraft: The velocities of the blunderer and evader are assumed to be constant throughout the blunder scenario and are variable inputs. In the simulation, the velocities are typically 170 knots at a distance of 9 nautical miles from the threshold and 150 knots at 2 nautical miles from threshold.

Evader threat window: The computed probability results are conditional on an evading aircraft being threatened by the blunder. In the simulation this means assuming that the in-trail or longitudinal separation between the blunderer and evader is a uniform distribution with a defined separation. The baseline case assumes a separation of 3 (modeled as ±1.5) nautical miles.

Blunder maneuver: The blundering aircraft makes a constant-speed, constant-radius turn at a fixed turn rate, while leveling out from the descent angle of the glide slope. After completing the turn, the blundering aircraft continues in a straight line at level altitude. This final turn angle has a strong impact on the scenario results. The turn rate has very little impact on the results.

Response times: The response time of the evader aircraft is composed of several individual response times - controller response time, communications delay and pilot/aircraft response time.

Evader maneuver: The evader turn begins after a delay due to the alert time and the cumulative response times. The evading aircraft makes a constant-speed, constant-radius turn at a fixed turn rate until reaching a final turn angle, while climbing to a final climb angle. After completing the turn, the evading aircraft continues in a straight line at the final climb rate. This final turn angle has very little impact on the scenario results; it has been set at 60 degrees in these simulations. The turn rate can have a significant impact on the results.

Total system error: Aircraft deviation about the runway centerline is modeled as a statistical distribution. Since the magnitude of the deviations varies with distance from the runway, the range of the aircraft determines the parameters of the specific distribution used. RASRAM applies the centerline distributions to the evader aircraft. The TSE of the blundering aircraft only affects the number of false alarms; since the blunder scenario begins with an alert, the path of the aircraft prior to the alert is irrelevant.

Model Computations

Response time for the evader to take appropriate action

Based on an instance of the lateral blunder scenario, RASRAM computes miss distances for a large sample of encounters between blundering and evading aircraft. These results are used to estimate the probability of a NMAC.

One key input is the probability distribution for the total response time, which comprises three individual response times.

$\tau_{controller}$ = controller response time
τ_{comm} = communication delay time
τ_{pilot} = pilot/aircraft response time

Each performance time is represented by its probability distribution, derived from reported observations in PRM experiments. The probability distribution of the total response time is computed by taking the convolution of the three individual distributions. An example of this computation is shown in Figure 5. (In Figure 5, the communications delay time is very small and has been consolidated with the pilot response time.) The pilot distribution used in the baseline model is a Rayleigh distribution with a sigma of 5.1 seconds.

The alert time τ_{alert} is an event or instant in time from which the response times are measured. For this version of RASRAM, it is defined as a constant time (the caution alert lead time) before the blunderer enters the NTZ (non-transgression zone). The Precision Runway Monitor demonstration report defines the caution alert lead time as a function of range or distance from threshold. Thus the total time to safely resolve the blunder and take evasive action is:

$$\tau_{res} = \tau_{controller} + \tau_{comm} + \tau_{pilot}$$

Another key input is the evader maneuver. The MathCad® simulation uses constant-radius, constant-speed turns to approximate these maneuvers. The key parameters of such a turn are turn rate for the lateral portion and climb rate for the vertical portion. The final angles of turn and climb are also needed, but are not as crucial in the final results. This approach is different from the Blunder Resolution model which include the actual track data for a small sample of evader tracks that were observed during man-in-the-loop test sessions.

Computation of miss distance

The physical quantity of interest is the distance between two aircraft at their point of closest approach (see Figure 6). This is defined as the miss distance. The MathCad® equations model a fixed flight path for the blundering aircraft. In response to this blunder, the aircraft on the other parallel approach, designated as the "evader," makes a turn and climbs away from the blundering aircraft. The initial position of the evader with respect to the blunderer is a uniform distribution within a fixed window. The computations assume that there is one evader somewhere in this window; the resulting probability distribution is conditional on this assumption.

Each trial involves making random selections from the parameters that determine miss distance. The start time for the evader's turn is determined by drawing a random number from the distribution of the total response time. The starting position for the evader is determined by drawing a random number from the uniform distribution for the fixed window.

RASRAM solves the encounter by computing positions and velocities of the motion of the evader with respect to the blunder. Determination of miss distance involves both location and timing because, at a minimum distance, the relative motion of the two aircraft must be at right angles to their relative position. The RASRAM computational formulation leverages this computation by computing the results of any fixed blunder trajectory against all evader aircraft that approach at the same speed and are ordered to perform a common evasive maneuver in response to the blunder threat.

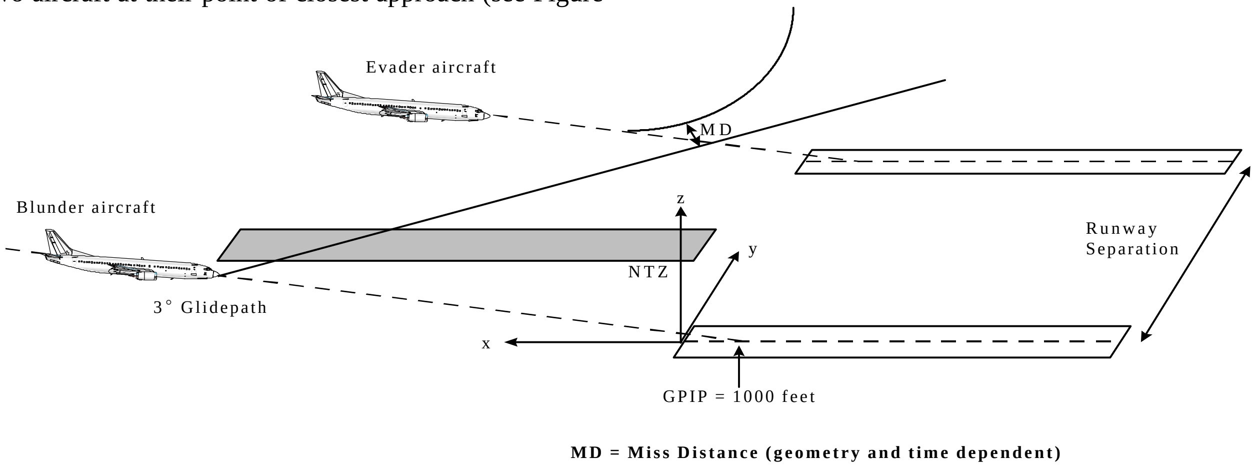

Figure 6. Blunder Scenario - Two Aircraft Approach Parallel Runways on 3° Glide Slope

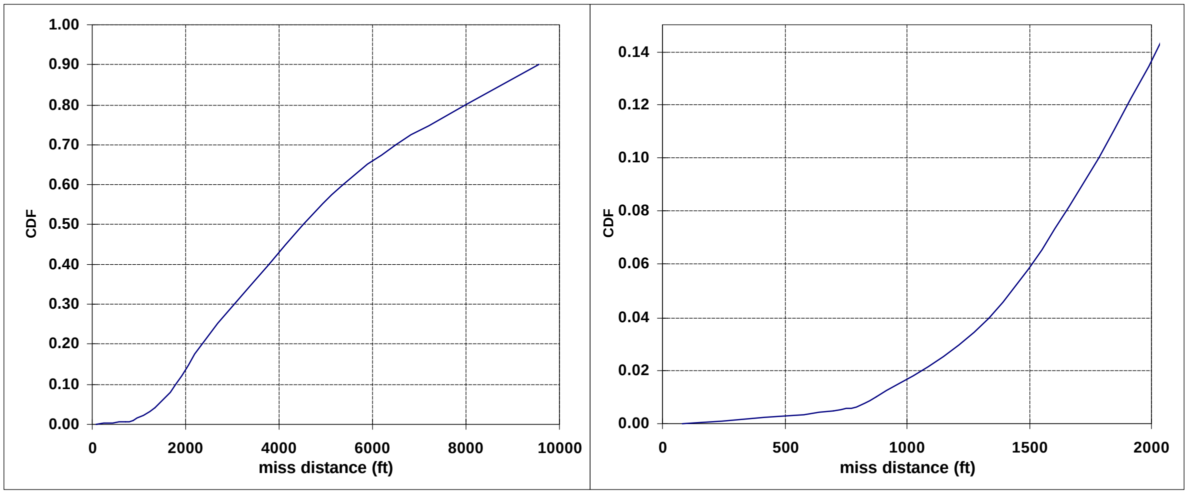

Figure 7. Lateral Miss Distance Distribution

The physical encounter is modeled starting from the blunder trajectory and the common approach path of the threatened traffic, before any maneuver begins. These are considered fixed trajectories in the computations, but some of the sources of variation in the operational encounter geometry can be represented by changing the parameters that "fix" the blunder and evader common trajectories. For instance, the lateral dispersion of the evaders can be represented as a simple change in the timing of the closest approach, with or without a small adjustment in the angle of the blunder path with respect to the evader stream.

The movement of the blundering aircraft and the evader is computed relative to reference points on the fixed, three dimensional trajectories. Preliminary computations establish reference points on the blunder trajectory and on the evader trajectory (before any maneuver) so that the vector between them is the smallest distance between any two points on the two trajectories. The scenario timing is then adjusted so that the blundering aircraft is assumed to arrive at the blunder reference at scenario time zero. A set of evading aircraft is parameterized by the time at which the evader will cross the evader reference. A time is used to identify the "evader" that would arrive at the evader reference at a specific scenario time. Results are computed treating time as a variable along with the scenario time at which the evader maneuver begins.

From this information and a description of the common evader maneuver, it is possible to compute the physical relationships that are required to hold for a local minimum for the relative distance between the blundering and evading aircraft. Figure 7 illustrates the cumulative probability distribution of miss distance for one lateral blunder case. The right hand illustration is an enlargement of the region of interest, for miss distances less than 500 ft (NMAC), which in this case is a probability of 0.002.

In-Trail Runway Occupancy Scenario

In-trail separation refers to the distance or time between a leading aircraft and a following aircraft that are navigating along the same trajectory in space. For aircraft making an approach to a landing at an airport, two major risk elements affect in-trail separation: wake vortices and runway occupancy time. Wake vortex risks will be treated in the following section. This section is concerned with how runway occupancy time interacts with in-trail separation.

The runway occupancy scenario emphasizes the risk of simultaneous runway occupancy (which will be referred to as SIMROC). In general, air traffic procedures do not allow two aircraft to make simultaneous use of an active runway, regardless of the distance between them. SIMROC is an incident measure. The risk of collision is much lower than the risk of an incident. The scenario further emphasizes IMC during which air traffic controllers are responsible for enforcing separation standards that the pilots do not have sufficient visibility to observe for themselves.

The in-trail separation standard applies a minimum distance criteria between two aircraft when the leading aircraft is directly over the runway threshold. The exact distance required depends on the aircraft types of both the leading and the trailing aircraft, as well as the operational procedures that are in effect for the runway. In good visual conditions, the pilot of the trailing aircraft is supposed to go-around as soon as it is clear that the leading aircraft will not clear the runway before the trailing aircraft reaches the threshold. In IMC, a controller is responsible for determining when it is necessary for the trailing aircraft to go around.

Fault and event trees

Fault tree

The fault tree is shown in Figure 8. SIMROC is one element of this fault tree that requires dynamic computation by Mathcad®. Simultaneous occupancy requires both that the trailing aircraft would arrive too soon if there were no intervention, and that attempts at intervention be unsuccessful. These appear in the fault tree as "projected excessive runway occupancy" and "failure to go around: runway occupancy," respectively. These computations are described below as the "required go-around probability" and the "probability of unsuccessful go-around." Static computations in the fault tree complete the computation of the risk of the two aircraft colliding. In addition to computing the probability of simultaneous runway occupancy and collision, the model also accounts for the risks associated with the go-around. For those instances where the go-around is required, the probability of incidents and accidents is computed. This includes the risk of a NMAC with a third aircraft (and potential collision), and the risk of striking the terrain or an obstacle. TAP includes the potential application of CDTI to provide alerting information to the pilot of the trailing aircraft when a conflict exists. This is not used in the baseline scenario.

The other dynamic element of the fault tree is the computation of risks due to runway incursions. As applied here runway incursions are defined as an aircraft or vehicle movement on the ground that creates a hazard or loss of separation with an aircraft on final approach. This accounts for the probability of an incursion and the failure of the landing aircraft to execute a go-around. The computations of this element are nearly identical to those for "failure to go around: runway occupancy." The two differ only in the assumed timing of the controller's instruction to execute a go-around.

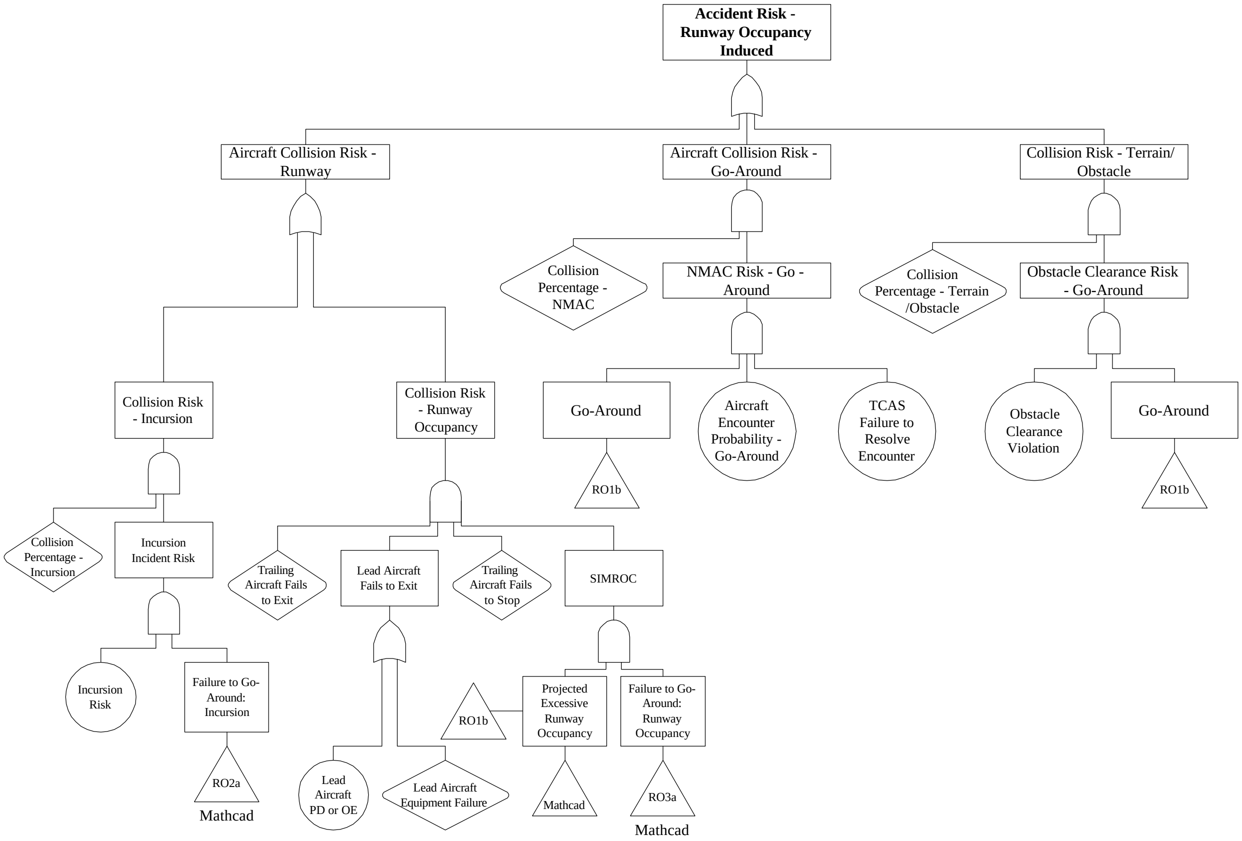

Figure 8. In-Trail Runway Occupancy Scenario Fault Tree

Description of Key Input Parameters

The model takes into account the following parameters:

Inter-Arrival Time Distribution: An example of this distribution for the large/large case is shown in Figure 10 (dotted line with mean of 120 seconds). Inter-arrival time was based on the time difference between contiguous arriving aircraft over the threshold.

Runway Occupancy Distribution: The runway occupancy time (ROT) distributions are considered to be truncated normal distributions cut off after five sigma. Therefore, they are characterized by a mean and standard deviation. It is assumed that these vary according to aircraft category (measured data indicates this to be the case[6]). Figure 10 shows an example distribution with a mean of 50 sec.

Model Computations

This describes the time-budget Matched® models for required go-around probability and the probability of unsuccessful go-around.

Required Go-Around Probability

As random variables, the taxi time of the leading aircraft at the moment the trailing aircraft arrives is equal to the inter-arrival time minus the ROT of the leading aircraft. If this taxi time is negative, both the leading and trailing aircraft are occupying the runway at the same time. Adding (or subtracting) random variables is computed by using the convolution of their probability distributions. The required go-around probability calculation uses empirical data for each category of arriving aircraft: the mean ROT, the standard deviation of the ROT, and the percentage of arriving aircraft that fall in that category. A pooled ROT distribution is computed from the weighted mean and variance of the constituent distributions. The pooled PDF is represented as a spline approximation to a truncated Gaussian distribution.

The inter-arrival time PDF for aircraft pairs is also characterized as a spline curve. The difference between the inter-arrival time and the runway occupancy is "the time since the leading aircraft left the runway." The PDF for this distribution is computed by convolution; an example PDF is shown in Figure 10. A CDF is then taken from the resulting curve and evaluated at x = 0. This gives the probability that the leading aircraft might *not* have left the runway when the trailing aircraft was due to appear over the threshold. This assumes no intervention. In reality the controller and pilot will normally intervene, resulting in the trailing aircraft executing a go-around instead of landing.

Probability of Unsuccessful Go-Around

This scenario assumes that the go-around instruction is issued by the air traffic controller who is monitoring the active runway. RASRAM does not model the myriad triggering events that the controller might recognize in order to determine that a go-around is required. The model assumes only that the alert will be issued to the trailing aircraft when it is between 0.5 NM (Category I decision height) and threshold. This distance is translated to a "cut-off time" by taking into account the velocity of the trailing aircraft. This portion of the model computes the probability that the trailing aircraft successfully initiates a go-around when instructed by ATC. The pilot response times are modeled as a simplified Rayleigh distributions (sigma = 2 seconds) as shown in Figure 11.

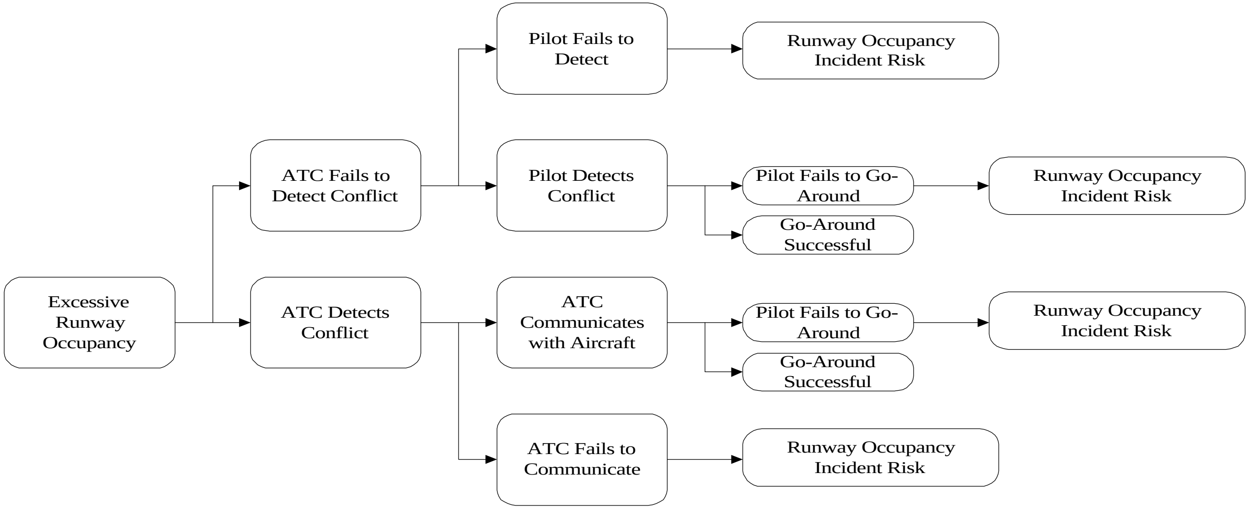

Figure 9. In-Trail Runway Occupancy Scenario Event Tree

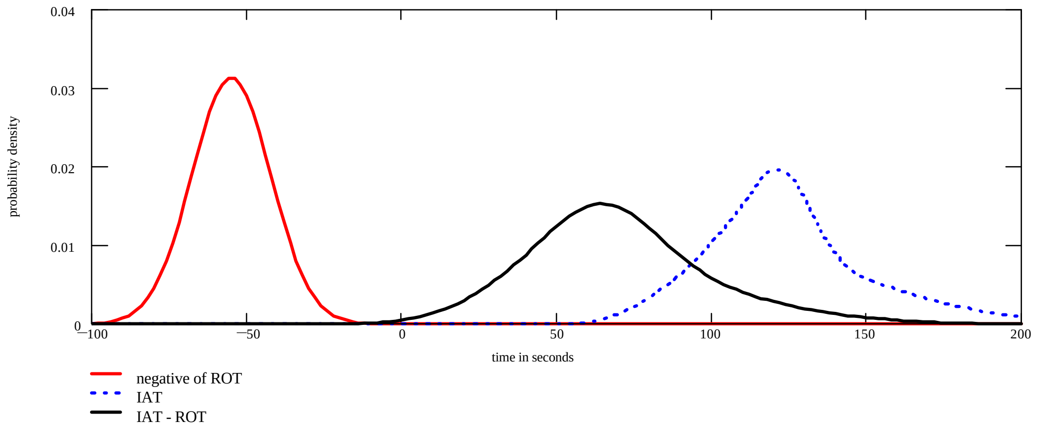

Figure 10. Computation of SIMROC (convolution of inter-arrival time and runway occupancy distributions)

It is assumed that the pilot/aircraft response would be shorter for the go-around than the breakout instruction issued in the lateral scenario, since a go-around is a standard ATC procedure. The go-around failure probability is the product of two factors: the probability that the controller will issue a go-around instruction at a time t, and the probability that an aircraft can <u>not</u> execute a go-around in the time remaining to touch-down. The probability reported is the average or *expected value* of the failure to go-around. The expected value is taken with respect to the probability function for when the controller issues the go-around instruction. This computational procedure is used in both “failure to go-around: runway occupancy” and “failure to go-around: runway incursion.” The two results differ only in the assumed distribution of the time at which the controller issues the go-around instruction.

The PDF for the issuance of the go-around instruction distribution is assumed to take one of two forms, depending on the nature of the triggering event for the go-around.

a) Go-arounds for excessive runway occupancy are assumed to be ordered more frequently when the trailing aircraft is nearer the cut off time; the controller is not expected to wait too long, creating a hazardous situation.

b) Go-arounds for runway incursions happen for reasons that have nothing to do with the position of the trailing aircraft - a uniform distribution is appropriate.

RASRAM models each of these alternatives as discrete probability distributions. The final result is the mean (or expected value) of the probability of an unsuccessful go-around, as modified by the probability distribution of the issuance time of the go-around instruction.

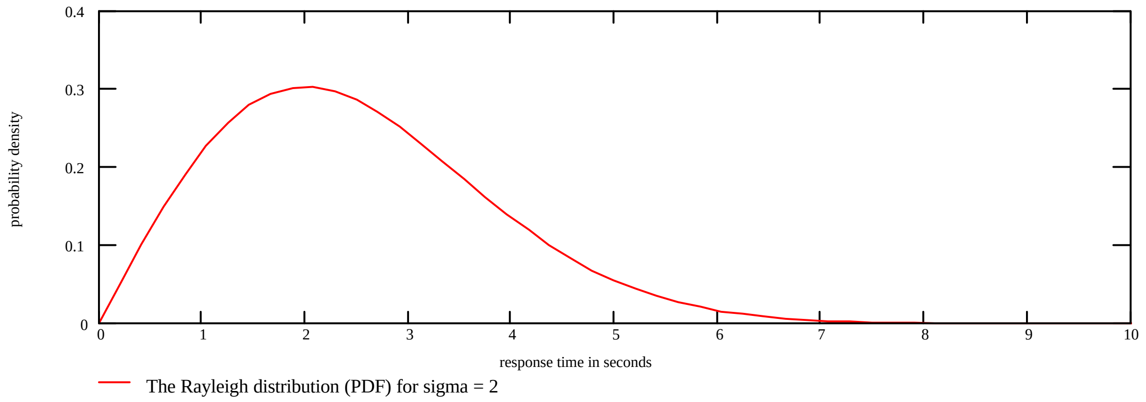

Figure 11. Pilot Response Time Distribution Used for Go-Around Execution

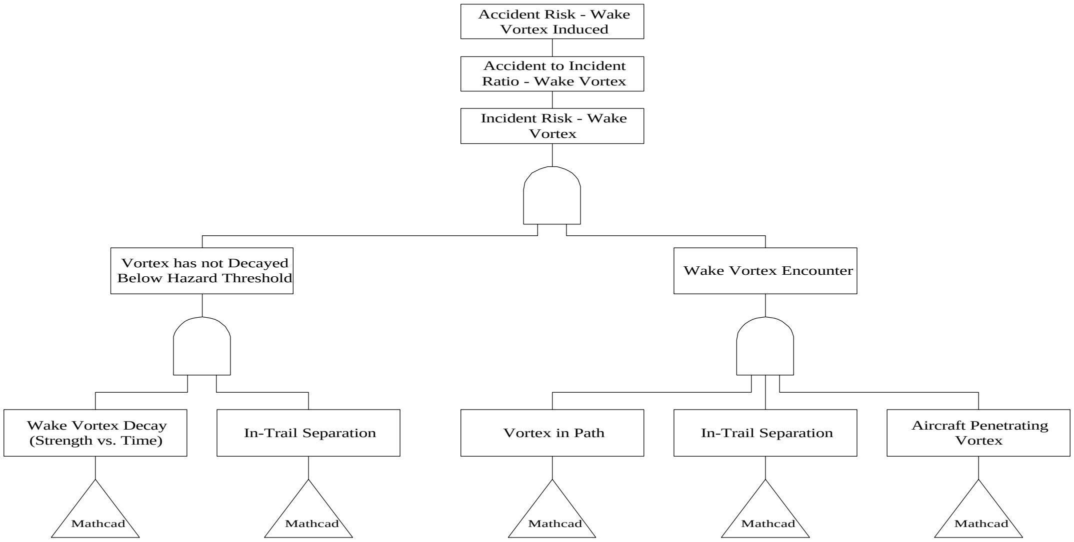

Figure 12. Wake Vortex Scenario Fault Tree

In-Trail Wake Vortex Scenario

In-trail separation refers to the distance or time between a leading aircraft and a following aircraft that are navigating along the same trajectory in space. For aircraft making an approach to a landing at an airport, two major risk elements or hazards affect in-trail separation: wake vortices and runway occupancy time. Runway occupancy time risks were treated in the previous section. This section is concerned with how wake vortices interact with in-trail separation.

The existing justifications for in-trail separation standards in IMC are based largely on empirical determinations of the strength of wake vortices. The standards reflect separation times that allow a vortex to decay until it represents only a negligible hazard to the trailing aircraft. The scientific community is making great strides in understanding the complex interactions between wake vortices, the ambient atmospheric conditions, and the aircraft at risk from encounters with wake vortices. At present, however, the scientific models do not appear ready to replace existing empirical studies in setting separation standards.

The wake vortex portion of the model is used to analyze risks associated with in-trail spacing due to potential encounters with wake vortices. Hazards associated with wake vortices drive the current in-trail IMC separation standards, which are currently pair dependent based primarily on aircraft weight classification. Various proposals are under consideration for modifying current standards, including reductions for specific categories of aircraft. RASRAM will be used to evaluate the overall safety impact of such modifications. Two tools under development by TAP, CTAS and AVOSS, are being developed for sequencing aircraft more efficiently on final approach. AVOSS is intended to optimize the wake vortex separation given the weather conditions and aircraft types.

Fault Tree

The fault tree is shown in Figure 12. The wake vortex scenario takes into account the key variables that determine whether an incident or accident will occur due to a wake vortex encounter. Key variables include time separation between aircraft, vortex decay and transport, meteorological effects, aircraft flight paths, and the probability of the encounter becoming an incident or accident. Most of the wake vortex scenario calculations take place in Mathcad$^{®}$, including the probability that the vortex has not decayed below the hazard threshold and probability of encounter.

Description of key input parameters

The model takes into account the following parameters:

Inter-Arrival Time Distribution: The inter-arrival distributions are created using surveillance radar data from Los Angeles International Airport. Inter-arrival time was based on the time difference between contiguous arriving aircraft over the threshold. The separations are based on empirical data and are dependent upon types of aircraft pairs according to weight classifications. An example of this distribution for the large/large case is shown in Figure 10 (dotted line with mean of 120 sec.).

Hazard Curve: Wake vortex encounters can be more or less hazardous depending on the characteristics of the trailing aircraft. The strength of the wake vortex, by itself, is not enough to determine whether a trailing aircraft can fly though one or more of the vortices safely. At the current time, there is little research data and little accepted theory for estimating whether a particular encounter is or is not hazardous. Figure 13 shows research that was made available to us by NASA's Langley Research Center: a hazard curve based on simulated flights of a Boeing B-737.

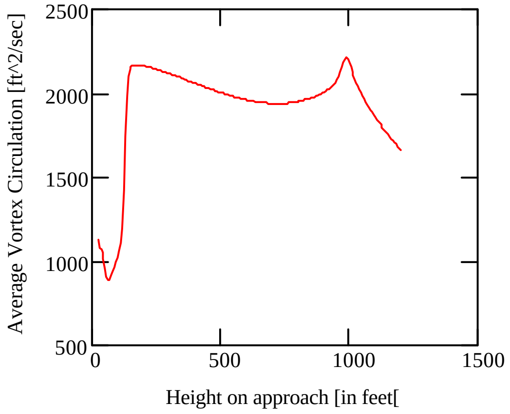

Figure 13. B-737 Vortex Critical Hazard Curve

The curve evaluated a number of potential sources of hazard such as roll-control and lateral movement. A critical curve was generated of the minimal vortex strength at which the most sensitive hazard criteria passed through its acceptable threshold. Areas below the curve represent acceptable hazard levels; areas above the curve represent unacceptable hazard levels. The critical values were strongly dependent on the height of the aircraft. Figure 13 shows that an aircraft at 80-100 feet of altitude is at risk from wake vortex strengths under 1000 feet^2/second, when at 200 feet or above the same aircraft could be flown safely through vortices of twice that strength.

Model Computations

Vortex Transport

The model for vortex transport includes effects of wind, ground effect, and initial descent velocity. The vortices start with an initial descent velocity and then are transported by the relative wind. In ground effect, the vortices tend to separate or move away from one another. An approximation to vortex transport is then computed based on the meteorological conditions.

Vortex Decay

The method for approximating the wake vortex decay utilizes equations from Greene[7]. These equations model the decay of a vortex pair based on the atmospheric effects of viscosity, turbulence, and stratification. The approach used does not take into account every aspect of wake decay such as vortex tilting, wind shear, or ground effect. The approach was chosen based on its simplicity. Using this model, a decay characteristic curve can be generated based on atmospheric conditions (turbulence, stratification, viscosity) and vortex conditions after roll up (vortex separation, initial strength, initial decent velocity). Figure 14 shows example decay characteristics for a B-767.

The decay model uses the three atmospheric parameters of viscosity, turbulence, and stratification to define the method of vortex decay. Figure 13 demonstrates the effects of these parameters when large, average, and small values are used for the atmospheric conditions. The case given for the average value can be considered a value in the standard atmosphere with moderate turbulence. This demonstrates the important impact that atmospheric conditions play in vortex decay.

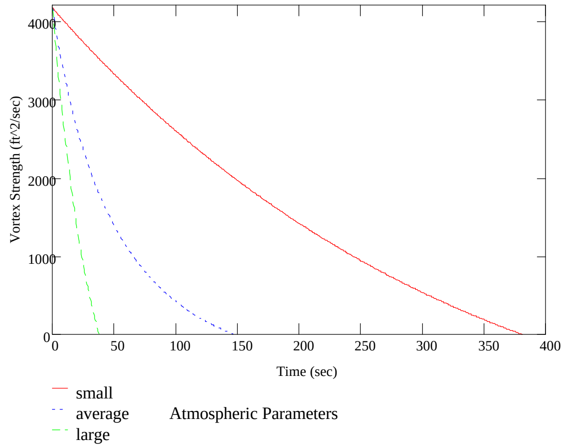

Figure 14. Vortex Decay Characteristics

Hazard Computations

In the RASRAM modeling, the hazard curve information is a strong argument for modeling wake vortex hazard as a worst case occurrence. The model therefore does assume that vortex risk should be evaluated by measuring the vortex strength and encounter probabilities when the trailing aircraft is at or near 80 feet of altitude. If this worst case encounter has acceptable risk, then it is reasonable to expect that encounters at higher altitudes will be subject to lesser risks.

It would be desirable to set separation levels equal to the distance at which the vortex strength of the leading aircraft is almost certain to have decayed below the lowest strength that might be a hazard for the trailing aircraft. This computation is not supported by the available body of wake vortex research.

The theoretical models provide useful information on the average levels of wake vortex strength and hazard levels. They do not support estimation of confidence intervals for the 99% level or higher of the vortex strength or hazard. The variability shown in Figure 14 is based on atmospheric conditions; it is not an indicator of the range of vortex strengths that might result from any one fixed set of parameters.

Conclusions

RASRAM provides a framework for evaluating the relationship between aircraft separation standards, technologies, procedures and safety. RASRAM makes use of fault trees and event trees as organization and presentation mechanisms. These appear to be good tools for communicating safety issues between the operational aviation community and the analysts working to quantify risks and safe separation minima. In this way, RASRAM can remain useful as the aviation safety community explores different alternatives for risk measures and levels of safety. Preliminary results have been obtained with the baseline safety (current separation) cases for the lateral blunder and runway occupancy scenarios. There is not sufficient data at this time to establish the safety levels for the wake vortex scenario.

The model can be used to provide a relative comparison of the safety of proposed new procedures with the safety of current operations and technologies. The safety associated with independent parallel approaches using PRM has been quantified previously. Using RASRAM, the safety of further separation reductions for parallel approaches using new technologies can be analyzed and compared with current procedures. Similarly, the safety of reductions for in-trail separation can be compared with current procedures. The RASRAM computational methodologies developed for the lateral blunder scenario can be generalized to scenarios anywhere in the terminal area or en route airspace. Evader maneuvers are directly parameterized and taken into account in the computation of when and how two aircraft will reach their point of closest approach.

In the case of in-trail separations due to wake vortices, the available scientific information on wake vortex decay is volatile and imprecise. For risk analysis, the hazard risk to a trailing aircraft would have to be based on a target level of safety. This translates into knowing the upper tail of the probability distribution of wake vortex decay and induced hazard during wake vortex encounters. The current separation standards, based on empirical evidence of safety in flight operations, appear to be the appropriate choice whenever wake vortices cannot be guaranteed to have been transported out of the entire approach path.

The most promising mechanism for reducing wake vortex separation minima is based on accurate predictions of wake vortex transport. It may be possible to analyze the risk of wake vortex in-trail separations based on a worst case. The hazard curves currently available reflect a dramatic increase in hazard risk levels as an aircraft passes through an altitude of approximately 80 ft on final approach. If an encounter with a wake vortex can be ruled out in this region of flight, closer separations can be tolerated at other points in the approach.

RASRAM offers a framework that can be used to balance a variety of risks in analyzing the safety of changing technologies and operational procedures. RASRAM organizes sufficient indicators of performance without requiring elaborate modeling of the internal processes of complex technologies or of human factors. Known physical and operational factors are suitably parameterized for the use of RASRAM with available operational data. The limitations on the use of RASRAM are generally in the accuracy of the tails of the probability functions that drive the final risk values. Future uses of RASRAM will require the careful quantification of empirical evidence of specific performance levels and scientific refinement of the tails of performance probability functions.

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