ACRP

REPORT 3

AIRPORT
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PROGRAM

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Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas

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Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas

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Richard Speir
David Pitfield
Robert Caves
Olga Selezneva
Tara Puzin
APPLIED RESEARCH ASSOCIATES, INC.
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AIRPORT COOPERATIVE RESEARCH PROGRAM

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The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), and the Air Transport Association (ATA) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

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Dr. Jim Hall, P.E., Principal Engineer at ARA, was the Principal Investigator, Dr. Derek Wong, Aviation Analyst at Ascend Worldwide Limited (formerly Research Assistant at Loughborough University) was the co-Principal Investigator, and Dr. Manuel Ayres, Senior Engineer at ARA, served as Project Manager. The other authors of this report are: Mr. Andrew Appleyard (Loughborough University), Dr. Mark Eddowes (ESR Technology), Mr. Hamid Shirazi (ARA), Mr. Richard Speir (ARA), Dr. David Pitfield (Loughborough University), Dr. Robert Caves (Loughborough University), Dr. Olga Selezneva (ARA) and Ms. Tara Puzin (ARA). The work was done under the general supervision of Dr. Manuel Ayres at ARA.

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FOREWORD

By Michael R. Salamone

Staff Officer
Transportation Research Board

Recent accidents involving aircraft overruns focused attention on improving airport runway safety areas in the United States and elsewhere. ACRP Report 3: *Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas,* the culmination of ACRP Project 04-01, examines historical data related to both overrun and undershoot occurrences. It will assist airport operators and airport planners in identifying conditions that may contribute to overruns and undershoots occurrences at airports.

ACRP Report 3: *Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas* covers four areas: (1) Research collected on accident/incident data from several notable sources; (2) inventory of the conditions relating to each; (3) assessment of risk in relation to the runway safety area; and (4) discussion on a set of alternatives to the traditional runway safety area.

Overruns and undershoots are factors in the design or improvement of runway safety areas (RSAs). The traditional approach to mitigate risk associated with accidents or incidents is to enlarge the runway safety area, but many airports do not have sufficient land to accommodate standard Federal Aviation Administration or International Civil Aviation Organization recommendations for RSAs. Airports that pursue this approach face extremely expensive and controversial land acquisition or wetlands filling projects to make sufficient land available.

This report uses a probabilistic approach—a quantitative assessment—to analyze the RSA and begins a discussion on how alternatives to a standard 1,000-foot RSA may adequately mitigate risk. The report also assesses the factors that increase the risk of such accidents occurring, helps with understanding how these incidents may happen, and suggests that aircraft overrun and undershoot risks are related to specific operational factors.

The report suggests that significant improvement to airport operations safety may be achieved by monitoring and managing these operational factors for both RSA planning and during actual aircraft operations, and it provides recommendations for collection and reporting of data in future accident and incident investigations and reporting to allow future improvements to these models.

CONTENTS

SUMMARY

Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas

The objective of this project was to develop an aircraft overrun and undershoot risk assessment approach, supported by scientific evidence and statistical theory, which provides step-by-step procedures and instructions for analysis of runway safety areas (RSA). Most aircraft accidents occur during the landing and takeoff phases of the flight and are likely to challenge the existing RSA when the aircraft overruns or undershoots the paved area of runways.

Currently, Federal Aviation Administration (FAA) standards require runways to include an RSA: a graded and clean area surrounding the runway that "should be capable, under normal (dry) conditions, of supporting airplanes without causing structural damage to airplanes or injury to their occupants" (FAA, 1989). The RSA improves the safety of airplanes that undershoot, overrun, or veer off the runway. The size of the RSA is dependent on the type and size of aircraft using each runway.

Most aircraft accidents occur during the landing and take-off phases of the flight and are likely to challenge the existing RSA when the aircraft overruns or undershoots the paved area of runways. The risks of an aircraft overrunning or undershooting a runway depend on a number of factors related to the operation conditions, like the weather, the runway surface conditions, the distance required to land or takeoff, the presence of obstacles, the available runway distance, and the existing RSA dimensions, just to name a few. The possibility of human errors or aircraft system faults during the landing or takeoff phases of the flight also may contribute to the risks.

Based on information gathered from overrun and undershoot accident and incident reports, risk models that consider relevant operational factors were developed to assess the likelihood and possible consequences for such accidents occurring on a runway subject to specific traffic and operation conditions. The approach uses historical flight data and the configuration of existing or planned RSAs to evaluate the risk for each operation and derive its probability distribution that allows for quantifying the number of high risk operations at the airport.

The major achievement of this research is to provide an innovative, rational and comprehensive probabilistic approach to evaluate the level of risk for specific airport conditions that will allow the evaluation of alternatives when FAA recommended RSA configuration for an existing airport cannot be met. In addition, based on the existing level of risk, this approach will allow prioritizing financial resources to improve safety areas, achieving target levels of safety (TLS) and helping with safety management actions when high risk conditions arise.

The results of the current study can be used by a broad range of civil aviation organizations for risk assessment and cost-benefit studies of RSA improvements. These organizations may include Federal and State agencies, the International Civil Aviation Organization (ICAO), and international civil aviation authorities, as well as airport operators, airlines, civil aviation associations and institutions, universities, and consultants.

CHAPTER 1

Background

Introduction

From 1995 to 2004, 71 percent of the world's jet aircraft accidents occurred during landing and takeoff and accounted for 41 percent of all onboard and third party fatalities (Boeing, 2005). Landing overruns, landing undershoots, takeoff overruns, and crashes after takeoff are the major types of accidents that occur during these phases of flight. Records show that while most accidents occur within the boundaries of the runway strip, most fatalities occur near but off the airport area (Caves, 1996).

Currently, Federal Aviation Administration (FAA) standards require runways to include a runway safety area (RSA)—a graded and clean area surrounding the runway that "should be capable, under normal (dry) conditions, of supporting airplanes without causing structural damage to airplanes or injury to their occupants" (FAA, 1989). Its purpose is to improve the safety of airplanes that undershoot, overrun, or veer off the runway.

The size of the RSA depends on the type and size of aircraft using the runway. RSA standard dimensions have increased over time. The predecessor to today's standard extended only 200 feet from the ends of the runway. Today, a standard RSA can be as large as 500 feet wide and extend 1,000 feet beyond each runway end. The standard dimensions have increased to address higher safety expectations of aviation users and accommodate current aircraft performance.

However, applying the new standards to existing airports can be problematic. Many runways do not meet current standards because they were constructed to an earlier standard. The problem is compounded by the fact that the airports are increasingly constrained by nearby land development and other natural features, or they face costly and controversial land acquisition, or a need for unfeasible wetlands filling projects.

The runway safety area standards are prescriptive and its rigid nature results in "averaged" degrees of protection being provided across broad ranges of risk levels, such that certain airports have much higher tolerance to risk than others. Ideally the risk associated with specific airport and operation factors should be modeled to assess the level of safety being provided by specific conditions of existing or planned RSA. Some intuitively important factors that would affect risk, such as various environmental and operational characteristics of the airport, are not considered yet.

In current risk assessment methods, factors that determine safety cannot be analyzed independently; however, a rational, systematic identification of safety influencing factors and their interrelationships has never been conducted. This situation impedes the assessment of effects of safety improvement opportunities and, consequently, risk management.

Moreover, most airfield design rules are mainly determined by a set of airfield reference codes, which only take into account the design aircraft approach speed and the aircraft dimensions (wingspan or tail height). The resulting protection is segregated in widely differing groups that do not necessarily reflect many of the actual risk exposure factors.

Project Objectives

The original objective of this project was to collect historical information related to overrun and undershoot accidents and incidents to develop a comprehensive and organized database with editing and querying capabilities, containing critical parameters, including aircraft, airport, runway, operation, and causal factor and consequence information that could assist the evaluation of runway safety areas.

The research team extended the project objective to include the development of risk models for overrun and undershoot events. The primary function of the risk models is to support risk management actions for those events by increasing the size of the RSA, removing obstacles, construction of arrestor beds or perhaps, where that is not possible, by the introduction of procedural measures or limitations for operations under high-risk conditions.

Three sets of models were developed in this study—landing overruns, landing overshoots, and takeoff overruns. Each set is comprised of three parts: probability of occurrence, location, and consequences. The models can improve the understanding of overrun and undershoot risks and help airport operators manage these risks.

Based on the information described above, the goals for this research project were extended to include:

1. Development of a comprehensive database for aircraft overrun and undershoot accidents and incidents;
2. Determination of major factors affecting the risks of such accidents and incidents;
3. Description of how these factors affect operations and associated risks, to improve understanding on how these events may occur;
4. Development of risk models for probability, location, and consequences for each type of accident: landing overruns (LDOR); landing undershoots (LDUS); and takeoff overruns (TOOR);
5. Development of a practical approach to use these models for assessing risks on existing RSA under estimated operation conditions;
6. Development of a list of relevant factors that should be reported for aircraft overrun and undershoot accidents so that availability of quality data can be improved for future studies; and
7. Development of prototype software to evaluate risks under specific operation conditions that may serve as the basis for creating analysis software that can be used to assess risks of aircraft overruns and undershoots.

Applied to any specific airport, the analysis approach for RSA risk assessment developed in this study will allow users to determine if the risk is relatively high or low and whether there is a need for risk management action. The safety benefits provided by possible mitigation measures (e.g., increased size of RSA) can be evaluated using the same approach.

In addition, three innovative techniques were incorporated to improve the development of risk models. One major improvement in the modeling of accident occurrence is the use of normal operations (i.e., nonaccident and nonincident) flight data. With normal operations data (NOD), the number of operations that experience the factor benignly, singly, and in combination can be calculated, so risk ratios can be generated and the importance of risk factors quantified.

The second improvement is the use of normalization techniques to convert information to a standard nominal airport. Using such normalization procedure allows comparing accident and NOD data for different operation conditions, thus creating a larger pool of relevant information.

Finally, the models developed were integrated in a rational probabilistic approach for risk assessment of RSA. Based on historical information for flight operations and weather conditions, and considering the configuration of the RSA and presence of obstacles located close to the runway, the probability distribution for accidents involving severe consequences may be estimated.

CHAPTER 2

Research Approach

The work for this study was planned and structured as follows:

1. Conduct a literature review and a functional hazard analysis (FHA) to improve the research team's understanding of factors causing or contributing to aircraft overrun and undershoot accidents, as well as to identify existing approaches, procedures and sources of data to support the development of risk models.
2. Collect historical accident and incident data from the sources identified and selected, and develop a comprehensive database of relevant accidents and incidents that included the causal factors, contributing factors, and operation conditions.
3. Collect historical NOD to support the development of risk models.
4. Transform the data to enable comparisons, thus increasing the pool of available information to develop risk models.
5. Develop three sets of risk models for LDOR, LDUS, and TOOR. Each set included: a frequency model for assessing the likelihood of the event, a location model to estimate the probability the aircraft wreckage is located beyond a given distance from the runway, and a consequence model that integrates the previous frequency and location model to evaluate the probability of severe consequences.
6. Develop of a probabilistic approach for the analysis of RSAs that incorporates the models developed in this study.
7. Incorporate the approach and models in prototype software to demonstrate the feasibility of the analysis approach developed.

The research plan followed the diagram depicted in Figure 1. The research team conducted a literature review followed by an FHA to identify important parameters associated with overrun and undershoot events, and collected the necessary information to potentially use as independent variables in the risk models.

After those parameters were identified, the research team screened the existing incident and accident databases to locate the events considered relevant for this study. For each event, available reports and docket documents were obtained and were analyzed in search for the relevant information included in the ACRP 4-01 database.

Data was collected and a database was created to save this information in an organized manner. When possible, gaps observed for important parameters were obtained from sources other than accident investigation agencies to complement the missing information. A statistical summary of the database was developed and is presented in this report.

Statistical tools and software were used to develop risk models for frequency and location for each type of accident. These models incorporate historical flight and weather conditions to evaluate the level of risk exposure for a specific runway. A rational probabilistic approach was developed to integrate these models and to assess the probability of severe consequences for these accidents. Finally, these models were integrated in prototype software to facilitate the analysis.

Literature Review

Risk assessments are utilized in many areas of aviation, from designing aircraft systems to establishing operational standards and air traffic control rules. However, there is little information available for assessing the risk of accidents occurring near and at airports. Previous relevant studies for airports can be broadly categorized into four areas: airport design, third-party risk, facility risk, and operational risk.

To assess risk from an airport design standpoint, the U.K. Civil Aviation Authority (CAA) Safety Regulation Group conducted a study on aircraft overrun risk, which guides airports on overrun risk assessment and provides advice on how to reduce it (CAA 1998).

Another study under this category is AEA Technology's risk assessment of airfield design rules (Eddowes et al. 2001). In this study, the authors reviewed design standards such as runway length and reference codes, the runway end safety area (RESA), separation distances between runways and taxiways,

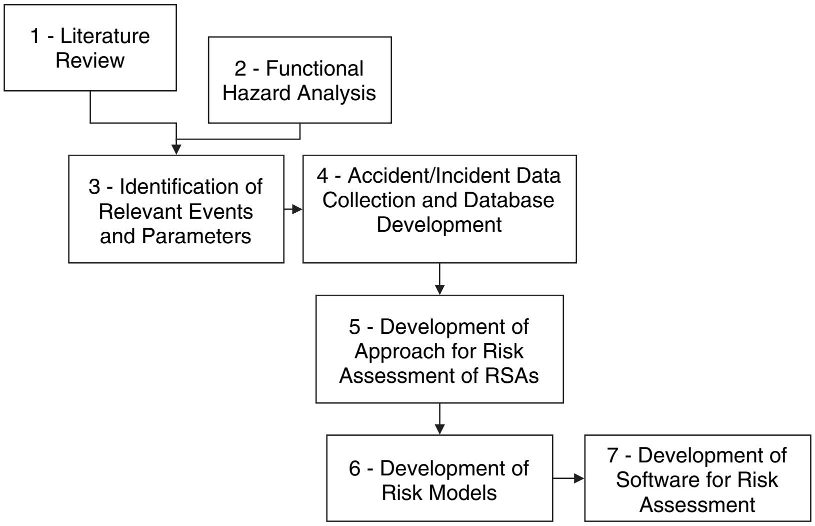


Figure 1. Research plan.

and obstacle limitation surfaces. It made concrete recommendations for amending the International Civil Aviation Organization (ICAO) Annex 14 safety areas to achieve a specific target level of safety.

In the United States, studies also have been carried out to set criteria for the design of airport safety areas, particularly in California. Garbell (1988) pioneered the accident-potential concept that led to the adoption of safety areas at a number of airports. A 1990 FAA study (David, 1990) compiled data regarding the location of commercial aircraft accidents relative to the runway involved. The database was used to validate the RSA dimensions adopted by the FAA, and it is still effective today.

There are only a limited number of general methodologies and models for assessing an airport's third party risk (Piers, 1996). They are derived principally from studies commissioned by the Dutch and British governments and their results are broadly similar (Ale and Piers, 2000).

A third family of studies seeks to assess the risk that aircraft operations pose to specific developments near airports. Examples of such studies include one for the U.S. Nuclear Regulatory Commission dealing with the safety of nuclear power plants, as well as a study for the Department of Energy for assessing the risk of an aircraft crash into its nuclear weapons and material storage facilities (Eisenhut, 1973; NRC, 1981). A study on Salt Lake City International Airport investigated the crash probability at a hospital, a school, and a shopping mall nearby (Kimura et al., 1995).

The final group of risk assessment studies concentrates on flight operational safety and is not strictly considered airport risk assessment. However, certain elements of these studies are very relevant to airport risk analysis. For example, a study on navigational aids established risk ratios for mostly airport factors that influence the risk of approach and landing accidents (Enders et al., 1996). A related piece of research by the Flight Safety Foundation measured accident risk based on, among other things, airport conditions (Khatwa and Helmreich, 1998). The ICAO's Collision Risk Model (CRM) calculates the collision probability of an operation with obstacles of known location and size during an Instrument Landing System (ILS) approach. The model is used as a decision-making tool for developing safe approach procedures and for airport planning (ICAO, 1980).

One of the core reasons for oversimplification of accident frequency modeling is the lack of data on exposure to various risk factors in normal operations. Without NOD, crash rates related to the presence of risk factors cannot be established. Closing this gap in research is a major achievement of the work conducted by Loughborough University (Wong, 2007) and ACRP 4-01.

Appendix A of this report provides information collected during the literature review on the procedures used and resources available to pilots during the landing and takeoff phases of the flight. Moreover, it describes how weather conditions, runway conditions, faults, and human errors can affect the operations and lead overruns and undershoots.

Functional Hazard Analysis

An FHA is a formal and systematic process for the identification of hazards associated with an activity. The purpose of the FHA in the context of this study was to determine relevant causal factors of overrun and undershoot accidents and hazards to aircraft associated with airport operations (e.g., landing, takeoff roll, and associated fault sequences) and the physical design of airports.

The risk analysis approach utilized in this study is based primarily on a review of operational experience, in particular, accident, incident, and normal operation data. The modeling approach adopted for the quantitative assessment of the risks associated with runway operations was based on the evaluation of:

- The likelihood of the incident occurring;
- The location where the aircraft came to stop, in case of overruns, or its point of first impact, for undershoots; and
- The consequences of such an incident (injury and cost of damage).

Overrun and undershoot incidents may be considered in terms of the deviation of the aircraft from its intended path. The definition of the deviation for each incident type is summarized as follows:

- For overrun incidents, the "longitudinal deviation" is described by the longitudinal distance traveled beyond the accelerate/stop distance available (for takeoff events), and beyond the landing distance available (for landing events).
- For undershoot incidents, the "longitudinal deviation" is described by the longitudinal distance the aircraft undershoots the intended runway threshold.
- For both overrun and undershoot events, the "lateral deviation" is the lateral distance to the extended runway centerline.

Examples of incident and accident causal factors include human error, as well as incorrect approach speed; deviation of approach height relative to desirable flight path; improper touchdown location; inappropriate runway distance availability, aircraft system faults, improper weight, and aircraft configuration; low friction runway surface conditions (wet, icy, or contaminated); adverse weather conditions, particularly tail wind, cross wind, gusting wind, low visibility, and precipitation; and unfavorable runway slopes. Results for FHA of aircraft overruns and undershoots are provided in Appendix B.

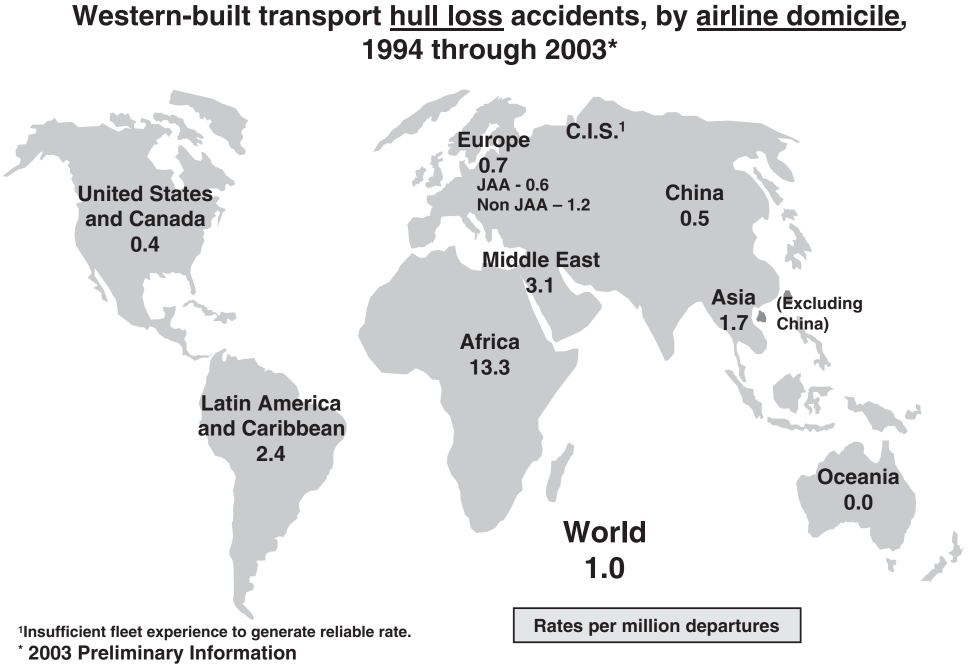
Database Development

A single database that contains a significant number of relevant accidents and incidents on and near airports was created for this study. A second database comprising normal operations data also was developed for this study. The data were organized to facilitate the assessment of each accident type in a coherent manner, rather than based on multiple databases with different inclusion criteria.

Before data were collected, some criteria were established for filtering out events available in the database sources that would not be relevant for ACRP 4-01 model development. It is important to describe the criteria used and the reasons for applying them.

Filter Applied to the Data

Some filtering criteria were used on the data so that events were comparable, as well as to ensure the models developed would represent the objectives of this study. The first filter was an attempt to use information from only specific regions of the world having accident rates comparable to the U.S. rate. Figure 2 depicts accident rates by region of the airline



Source: U.S. Department of Transportation, Federal Aviation Administration.

Figure 2. Accident rates by region of the world.

domicile. It was assumed that the information from North America (United States and Canada), Western Europe (Joint Aviation Authorities [JAA] countries), Oceania, and a few selected countries in Asia would be relevant to this study and included in the database.

Using this filter criterion, the main sources of data included the following:

- FAA Accident/Incident Data System (AIDS);
- FAA/National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS);
- NTSB Accident Database & Synopses;
- Transportation Safety Board of Canada;
- ICAO Accident/Incident Data Reporting (ADREP) system;
- Australian Transport Safety Bureau (ATSB);
- France Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) ;
- UK Air Accidents Investigation Branch (AAIB);
- New Zealand Transport Accident Investigation Commission (TAIC);
- Air Accident Investigation Bureau of Singapore;
- Ireland Air Accident Investigation Unit (AAIU); and
- Spain Comisión de Investigación de Accidentes e Incidentes de Aviación Civil (CIAIAC).

A more detailed description of each data source is available in Appendix C of this report. In addition, the filtering criteria and justification described in Table 1 were applied to the ACRP 4-01 database.

Data Limitations

There are many quantitative and qualitative limitations to reliable accident and incident data, and these limitations invariably constrain the depth, breadth, and quality of airport risk assessments (Piers et al., 1993; DfT, 1997; Roelen et al., 2000). This study is no exception. The scope and detail of the analysis are restricted by the availability and quality of the data extracted from available sources. Major data limitations found during the collection process are outlined in the following material.

Missing Data. Accident investigation records and incident reports consist of a number of standard forms and reports.

Table 1. Filtering criteria for accidents and incidents.

Filter #	Description	Justification
1	Remove non-fixed wing aircraft entries.	Study is concerned with fixed wing aircraft accidents and incidents only.
2	Remove entries for airplanes with certified max gross weight < 6,000 lbs (<12500 lbs if Part 91).	Cut off criteria for lighter aircraft utilized to develop model for overruns on unpaved areas.
3	Remove entries with unwanted Federal Aviation Regulation (FAR) parts. Kept Part 121, 125, 129, 135 and selected Part 91 operations.	Some FAR parts have significantly different safety regulations (e.g., pilot qualifications). The following cases were removed: Part 91F: Special Flt Ops. Part 103: Ultralight Part 105: Parachute Jumping Part 133: Rotorcraft Ext. Load Part 137: Agricultural Part 141: Pilot Schools Armed Forces
4	Remove occurrences for unwanted phases of flight.	Keep only undershoots and runway excursions beyond the departure end of the runway. We are also keeping veer-off occurrences that were available in the Loughborough University database, but these will not be utilized for developing the risk models.
5	Remove all single engine aircraft and all piston engine aircraft entries.	Piston engine aircraft are now used less frequently in civil aviation and therefore have been removed, to increase the validity of the modeling. Moreover, single and piston engine aircraft behave differently in accidents due to the lower energy levels involved and the fact that the major focus of this study is air carrier aircraft.
6	Remove all accidents and incidents when the point of first impact and the wreckage final location is beyond 2000ft from threshold.	It would be unfeasible to have an RSA with more than 2000ft beyond the threshold, the gain in safety may not be significant and a previous FAA study used this criterion (David 1990).

Even within these standard areas of interest, it is extremely rare that every field is complete. The NTSB docket files of minor accidents, when available, frequently contain less than a dozen pages of forms accompanied by only a brief synopsis of the occurrence. Information for incidents is very poor. As an example, prior to 1995, the narratives for AIDS reports were limited to 115 characters; reports since 1995 contain a more complete narrative prepared by the investigating inspector.

The accident wreckage site often is given only a very crude description without supporting maps or diagrams. Only a small proportion of data fields are systematically recorded for every accident. The amount of missing fields in the database is high, restricting the number of parameters that could be analyzed with confidence. In many cases the report descriptions used were coupled with the runway satellite picture obtained from Google Earth to determine the approximate location of the accident and of the wreckage.

The reports contain mostly information the accident investigators deemed relevant to an accident's occurrence. Outside of this judgment, few potential risk factors and measurements are included. This was a major obstacle to developing a database that consistently and systematically records a comprehensive set of risk exposure parameters so they could be included in the models. The data available for analysis and model-building ultimately depended on the agency accident investigation mentality and policies. There are no alternative sources of data, and this issue is particularly critical concerning unconventional or latent risk factors beyond the well established sources of risk. Parameters such as weight and runway criticality that would require additional calculation often are impossible to compute because of unavailable data.

When considering aircraft overruns, there are flights that used more than the nominal runway distance required (takeoff or landing) to complete the operation but without departing the runway due to excess runway length available. These cases usually are considered as normal operations and will never feature in accident records.

Although these cases could provide additional and valuable data to model incident location distribution, obtaining normal operations data on actual runway distance used proved difficult to obtain despite extensive efforts from the research team.

Finally, the presence of excess runway may alter pilot behavior such that more runway distance is used than otherwise. In a number of occurrences, the pilot did not apply braking to stop the aircraft as soon as possible because the pilot elected to take a specific taxiway exit or was hurried by the traffic control to quickly leave the runway.

However, it should be noted that these data limitations are not unique to the current research but are inherent to risk assessment studies that use historical accident data (Piers, 1994; ETSC, 1999).

Poor Data Quality. Previous studies using data from accident reports and docket files have reported on the poor quality of data available (Hagy and Marthinsen, 1987). Erroneous or conflicting information within the same docket is not uncommon. Some cases were identified where the provided wreckage location diagram does not match the text description given. Confusing and inconsistent use of terms and nomenclature adds to the challenges of extracting precise data points. When faced with conflicting data, the research team applied judgment to obtain a final figure according to the best information available.

Measurement Difficulties. The measurement of certain parameters suffers from inherent ambiguity in the aviation industry. A prime example is runway condition. There simply has not been an agreed industry standard on reporting runway conditions and determining its relationship with runway friction and aircraft braking performance (DeGroh 2006; FAA, 2006b). The current industry approach is to measure and report runway friction periodically using standard equipment and wet surface conditions. However, it also is common practice to rely on pilots' subjective reporting, particularly for contaminated runways. Runway surface conditions may change rapidly according to precipitation, temperature, usage and runway treatment so actual conditions may differ significantly from those reported (FAA, 2006b). Icing conditions, too, also are known to be difficult to determine even though they have an important impact on aircraft performance (Winn, 2006).

The weather measured from ground stations may vary significantly from that experienced by the accident flight (Jerris et al., 1963), particularly if the weather station is located far from the accident location, although this is common only with very remote airports. Another difficulty lies in the dynamic nature of meteorological conditions. Wind strength and direction may change constantly during the course of an approach. It may not always be clear which reading is most relevant. Some judgment was necessary to enter the most appropriate reading into the database.

Limited Data for Incidents. The importance of including data from incidents cannot be overemphasized. By excluding incident data, the project would not take into account potentially serious occurrences. However, a practical difficulty of incorporating incident data is the lack of it. The quantity and quality of incident data is in even greater doubt than for accidents.

Most agencies provide information and reports for accidents and serious accidents only. Many countries have procedures to obtain information on incidents but, except for the United States, these reports are not readily available from Internet sources. For this study, the basic sources of data for nonserious incidents were the FAA AIDS and the NASA/FAA ASRS.

One additional difficulty to incorporate the information into this project is the number of incidents reported. Some incidents are not reported because there were no consequences. To overcome this obstacle, a study was performed on the distribution of available data to assess the number of unreported incidents and to consider these cases when developing the frequency and location models. A number of missing incidents was assumed, as described in Appendix D, and a weighting factor was applied in the statistical analysis to develop the models.

Additional Issues

The database used for developing the final risk models includes only those events that may challenge the RSA beyond the runway ends. The criterion utilized is similar to that used by the FAA (David, 1990) and includes those occurrences whereby the point of first impact or the final wreckage location is within 2000 ft from the threshold. Using such criteria, 459 accidents and incidents were selected to compose the information that was used for developing the risk models. Table 2 summarizes the number and type of events by source of data.

The main reason for the criterion applied is it would not be feasible to modify an existing RSA to more than 2000 ft in length, compared to the current 1000-ft standard. Most importantly, the additional safety benefit for having an RSA longer than 2000 ft certainly would be very small and not justify the costs required for such improvements. Cases when the aircraft veered off the runway but did not challenge the area beyond the runway threshold also were removed, as these were out of the scope of this research.

Data for events investigated by the NTSB were gathered from both investigation reports and the related dockets available at the NTSB library in Washington, D.C. Before data were gathered, database rules were developed to assure uniformity for the information obtained by different researchers contributing to this project.

Table 2. Summary of events utilized in this study.

Database Source	LDOR	LDUS	TOOR
FAA AIDS (incidents)	14	29	12
FAA/NASA ASRS (incidents)	79	11	9
NTSB (accidents & incidents)	113	51	56
TSB Canada (accidents)	23	1	5
AAIB UK (accidents)	24	0	5
BEA France (accidents)	3	1	3
Other (accidents)	18	0	2
Total	274	93	92
			459

Incident information was collected from NTSB, FAA AIDS and FAA/NASA ASRS databases. Accident data were obtained from NTSB and from aviation investigation agencies from other countries.

A significant amount of aviation safety information is available worldwide, in many cases from specific websites. One of the main problems with this, however, is the fragmentation of the information. Each agency has different search engines, and data are presented in different formats. In most cases, identifying the relevant events fulfilling the criteria for this project was quite challenging.

Appendix E of this report presents the list of relevant accidents and incidents that fulfilled the criteria and filters established for the study and were utilized for developing the risk models.

Supplementary Sources of Information

Individual accident reports were evaluated to extract information. In addition, part of the data was complemented from other sources of information, particularly for aircraft, airport, and meteorological conditions. Based on the aircraft registration, we have gathered information for aircraft involved in accidents and incidents from the following websites:

- FAA REGISTRY N-Number Inquiry: http://registry.faa.gov/aircraftinquiry/NNum_inquiry.asp
- US/World – Landings.com: http://www.landings.com/evird.acgi$pass*90705575!_h-www.landings.com/_landings/pages/search.html
- Airframes.org - Passenger airliners, cargo airplanes, business jets, private aircraft, civil and military. http://www.airframes.org/
- Civil Aircraft OnLine Registers, Official Civil Aircraft Registers: http://www.airlinecodes.co.uk/reglinks.asp?type=Official

Airport information, when not included in the incident or accident investigation reports, was obtained from other sources. Basically the following web sources were utilized in this study:

- United States: AirNav provides detailed aeronautical information on airports and other information to assist pilots in gathering information for flight planning. Airport details include airport location, runway information, radio navigation aids, declared distances, and other information for pilots. http://www.airnav.com

- World: The World Aeronautical Database contains detailed, aeronautical information on nearly 10,000 airports and more than 11,000 Navigational Aids (NAVAID) worldwide. http://worldaerodata.com/

Many incident reports do not contain weather information, particularly when it is not deemed to be an important factor in the incident and was obtained from other sources. Weather for normal operations data also has been obtained from other sources, particularly from the National Oceanic & Atmospheric Administration (NOAA) database. NOAA is a federal agency focused on the condition of the oceans and the atmosphere.

In many cases, particularly for accidents that occurred outside North America, search engines available in the websites of accident investigation agencies are not very effective to filter out those events that were irrelevant to this project. Some of the events were identified using these databases and, for a few cases, some accident data has been gathered from independent accident information websites. Two of the most used during this study included:

- ASN Aviation Safety Database: The Aviation Safety Network is a private, independent initiative founded in 1996. It covers accidents and safety issues with regards to airliners, military transport planes, and corporate jets, and contained descriptions of more than 10,700 incidents, hijackings, and accidents. Most of the information are from official sources (civil aviation authorities and safety boards), including aircraft production lists, ICAO ADREPs, and country's accident investigation boards.
- World Aircraft Accident Summary: The World Aircraft Accident Summary (WAAS), produced on behalf of the British Civil Aviation Authority by Airclaims Limited, provides brief details of all known major operational accidents worldwide.

A typical example of this complementary information was the calculation of wind speed. Since the NTSB database contains wind speed and direction but not headwind and crosswind components, determination of the orientation of the runway used by the accident aircraft allowed the research team to derive the headwind and crosswind components. Wreckage location often is described in words and required translation and interpretation to obtain estimates of location coordinates relative to runway centerline and thresholds.

Accident/Incident Database Organization

The accident and incident database was organized in Microsoft Access. The system provides some software tools that facilitate the use of the database in a flexible manner. The software includes facilities to add, modify, or delete data, make queries about the data stored, and produce reports summarizing selected contents.

The database includes, for each individual event or operation, the reporting agency, the aircraft characteristics, the runway and environmental conditions, result of the operation (accident or incident), and other relevant information such as consequences (fatalities, accident costs) and causal or contributing factors and parameters required to develop the risk models. A unique identifier was assigned to each event, and the descriptions of each field and the database rules are available in Appendix F. The final database includes the categories and fields listed in Table 3.

Neither the NTSB nor the FAA routinely compiles data in this manner. Both agencies investigate accidents for aeronautical purposes to determine ways to improve the design and operation of aircraft and airports and to foster better pilot skills and techniques. If land use factors are examined at all, it is incidental to the primary purpose of the investigation.

As previously noted, it was difficult to gather information on incidents because they are rarely investigated to a level that could provide useful information for this study. Also, there are often few consequences associated with incidents.

Normal Operations Data

Another key approach in this study is the use of normal operations (nonaccident/nonincident flight) data for risk modeling. Various studies already have identified the lack of NOD as a major obstacle to the development of quantitative risk models (Department of Transport, 1979; Piers et al., 1993; Khatwa et al., 1996; Khatwa and Helmreich, 1998; Eddowes et al., 2001; Li et al., 2001). The approach and the data utilized in this project were developed by Wong (2007).

In the absence of information on risk exposure, even though the occurrence of a factor (e.g., contaminated runway) could be identified as a contributor to many accidents, it is impossible to know how critical the factor is since many other flights also may have experienced the factor without incident. With NOD, the number of operations that experience the factor benignly, singly, and in combination can be calculated, risk ratios can be generated, and the importance of risk factors quantified. This assessment may allow the prioritization of resource allocation for safety improvement (Enders et al., 1996).

A large and representative sample of disaggregate U.S. NOD covering a range of risk factors has been collected, allowing their criticality to be quantified. The basic idea was to use these data and the information on U.S. incidents and accidents as a sample to develop the frequency models only, simply because the NOD represents only events occurring in the United States. The larger dataset comprising both U.S.

Table 3. Database structure.

Category	Field Level 1	Field Level 2
Basic Info	Accident ID	
	Event ID	
	Accident Class	
	Event Type	
	Researcher	
	Source	
	Location	Country
		State
		City
	Date	
	Time	
	Basic Notes	
Aircraft Data	Make	
	Model	
	Series	
	Serial Number	
	Age	No. of hours or Years
	No. of Engines	
	Engine Type	Turboprop, Turbofan (Low or High) or Turbojet
	Max Certified Landing	
	Max Certified Takeoff	
	Max Gross Weight	
	Registration Number	
	Regulations Reference	
	ACFT Regulator	
	Owner	
	Operator	
Airport Data	Code	IATA Code
	Latitude	
	Longitude	
	Runway Number	
	Landing Distance Available	
	Takeoff Distance Available	
	Landing Elevation	
	Landing Latitude	
	Landing Longitude	
	Takeoff Elevation	
	Takeoff Latitude	
	Takeoff Longitude	
	Runway condition	
	Runway Grooved	Yes/No
	ARFF Availability	A to F
	Control Tower	Yes/No
	Temporary Construction Works	Yes/No
	Runway Width	
	Runway Slope	
	Surface Material	
	Paved Overrun Length	
	Notes	
Consequences	Aircraft Damage	Destroyed, Substantial, Minor or None
	Change of Terrain	Yes/No
	Consequence Area	
	No. of Passenger Seats	
	Total No. Of Seats	
	Difficulty in Getting to Wreckage	Yes/No
	Detailed Consequence Area	

(continued on next page)

Table 3. (Continued).

Category	Field Level 1	Field Level 2
Detailed Info	Aircraft Collision Status	Active/Passive/NA
	Visibility Min. Violation	Yes/No
	Approach Min. Violation	Yes/No
	Approach Category Required	Visual/Non-Precision/ILS Cat1, 2 or 3
	Approach Category Used	
	Other Aircraft Involved	Yes/No
	Crash Controllability	Fully/Partially/No
	Glide slope Captured	Yes/No
	Go Around	Yes/No
	GPWS	Yes/No
	GPWS type	1st or 2nd Generation
	Localizer Captured	Yes/No
	Runway Change	Yes/No
	Stabilized Approach	Yes/No
	Takeoff Aborted	Yes/No
	Takeoff Aborted Speed	
Flight Data	Actual Weight at Crash	
	Was Weight Estimated	Yes/No
	Max Weight for Operation	
	Destination Country	
	Departure Country	
	Diverted Flight	Yes/No
	ELT Fitted and Operational	Yes/No
	Flight Delayed	Yes/No
	Flight Duration	
	Fuel Load	
	Load Factor	
	Operation Type	
	Scheduled	Yes/No
	Landing Distance Required	
	Takeoff Distance Required	
	Takeoff Weight	
	Takeoff Fuel Load	
	Weight restriction Violated	Yes/No
Hit Obstacles	Obstacle Depth	
	Obstacle Height	
	Obstacle Width	
	Obstacle Location	X, Y and Z
	Notes	
Hit Terrain	Terrain Depth	
	Terrain Height	
	Terrain Width	
	Terrain Location	X, Y and Z
	Notes	
Injuries	No. Passenger Injuries	Fatal, Serious, Minor, None
	No. Flight Crew Injuries	Fatal, Serious, Minor, None
	No. Cabin Crew Injuries	Fatal, Serious, Minor, None
	No. Ground Crew Injuries	Fatal, Serious, Minor
	On Ground Injuries	Fatal, Serious, Minor
	Public Injuries	Fatal, Serious, Minor
	Total Injuries	
	Event Highest Injuries	
	Notes	

Table 3. (Continued).

Category	Field Level 1	Field Level 2
Weather	Ceiling	
	Dew Point	
	Electric Storm	Yes/No
	Fog	Yes/No
	Frozen Precipitation	Yes/No
	Wind Direction	
	Wind Velocity	
	Wind Shear	Yes/No
	Gusts	
	Icing Condition	Yes/No
	Light Level	Dawn/Day/Dusk/Night
	Rain	Heavy/Moderate/Light/None
	Snow	Yes/No
	Temperature	
	Visibility	
	RVR	
	Actual Weather Different than Reported	Yes/No
	Weather General	
	Local Variation	Yes/No
	Tailwind	
	Crosswind	
Wreckage Info	Explosion	
	Fire	
	No. Obstacles Hit	
	Runway Exit Speed	
	Total Wreckage Path Length	
	Pilot Actively Avoided	
	POFI Angle	
	POFI Velocity	
	POFI Location	X,Y and Z
	Wreckage Location	Longitude and Latitude
	Wreckage Location	X,Y and Z
	Runway Exit X	
	Runway Touchdown X	
	Touchdown Speed	
	Wreckage Site Elevation	
	Height Above Threshold	
	Approach Speed	
	Wreckage Path Length on Each Terrain	Up to 4 segments
	Wreckage Slope	Up to 4 segments
	Wreckage Surface	Up to 4 segments
Anomalies	Aircraft System Fault	Power
		Brake (wheel brakes, spoilers or reversers)
		Hydraulic
		Tire
		Other
	Weather Conditions	Low Visibility
		Rain
		Wind Shear
		Tailwind
		Crosswind
		Gusts
		Low Ceiling
		Strong Wind
		Turbulence
		Freezing Rain
		Other

(continued on next page)

Table 3. (Continued).

Category	Field Level 1	Field Level 2
	Human Errors	Incorrect Flight Planning
		Communication/Coordination
		Visual Illusion
		Fatigue
		Pressonitis
		Other
	Runway Surface Conditions	Wet
		Contaminated - Standing water
		Contaminated - Rubber
		Contaminated - Oil
		Contaminated - Ice
		Contaminated - Slush
		Contaminated - Snow
		Contaminated - Paint
		Contaminated - Other
		Construction
		Down Slope
	Wildlife Hazards	
	Approach/Takeoff Procedures	Unstabilized - Low Approach
		Unstabilized - Low Speed
		Long Touchdown
		Unstabilized - High Speed
		High Above Threshold
		Takeoff Rejected
		Other
Cost	Aircraft Body Type	Wide or Narrow
	Aircraft Cost	2007 dollar value
	Human Cost	2007 dollar value
	Total Event Cost	2007 dollar value

and world occurrences was utilized to develop the location models.

Incorporating risk exposure information into the accident frequency model enhances its predictive power and provides the basis for formulating more risk-sensitive and responsive RSA policies. Accident frequency models need no longer rely on simple crash rates based on just aircraft, engine, or operation type. As discussed below, factors previously ignored by airport risk assessments and RSA regulations are accounted for using the models developed in this study. Moreover, this normal operations database can be used for future studies.

The detailed source and sampling strategy of the NOD database is described in Appendix G. In addition, a small sample of the NOD being utilized in this study is included in that section. A list of sampled airports is shown in Appendix H and the stratified sampling strata is presented in Appendix I.

To derive the weights to be applied to each stratum, it was necessary to identify the relevant traffic from Terminal Area Forecasts (TAFs). Details on the calculation of TAF are presented in Appendix J.

Normalization of Data

The small pool of relevant data available is a fundamental problem to risk assessment in aviation (Caves and Gosling, 1999). Most studies have used data from different airports to develop risk models. However, operation conditions and levels of risk are different at different airports. In addition, only raw distances between the final wreckage location and the runway end have been used to develop current FAA RSA recommendations.

To mitigate this difficulty, information available for different airports was compared by using a normalization procedure, to transform existing data to a standard nominal airport (Kirkland et al., 2003). To normalize aircraft accident data, the "normal" airport is an airport situated at the International Standard Atmosphere (ISA) conditions, with level surrounding terrain or obstacles and an infinitely long, hard runway.

Normalization was conducted for the effects of terrain on wreckage location using the models developed by Kirkland et al. (2003) and the effects of the local atmospheric conditions on the aircraft's performance, based on standard corrections for aircraft distance required. Major factors that affect the runway distance required for the operation and used in the flight manual calculations are runway slope, runway elevation, and the air temperature; however, a correction was not applied to the slope in the RSA due to missing information for the majority of the events. The RSA slope is indeed an important factor on the wreckage distance and this information should be collected and made available in incident and accident investigation reports. Normalization procedures used in this study are presented in Appendix K.

Ideally, normalization procedures should consider the distance required relative to the runway distance available during the operation. However, the attempt to incorporate this factor proved difficult due to a lack of available information to compute the distances required, for both the accident data and NOD.

In addition, some factors cannot be normalized, such as the pilot's skill or differences in safety records between countries. Despite these difficulties the technique utilized in this study creates a larger pool of relevant and comparable data for sound model building. Results from models built with normalized accident and normal operations data then can be applied to specific airports through denormalization.

Development of Risk Models

In this study overrun and undershoot risk models were developed to allow the analysis of RSAs in the light of specific factors related to existing operation conditions. The basic concept was to model the probability distribution for wreckage location in the proximity of the runway threshold. The concept is illustrated in Figure 3 for overruns and in Figure 4 for undershoots.

The illustration for overrun incidents shows a typical probability distribution for the stopping location during a landing or rejected takeoff operation. (The illustration is not to scale and is only intended to help understanding the concept.) The great majority of aircraft will stop within the runway boundaries, represented by the lightly shaded area of the probability distribution. However, in a few cases, the aircraft may not be able to stop before the runway end and will stop on the RSA or even beyond. This probability of overrunning the runway is represented by the dark shaded area. It would be best to model the whole probability distribution for the aircraft stopping location, but this information is not available for NOD, and an alternative modeling approach was required in a two-step process: evaluating the probability an aircraft will in fact overrun the runway, and modeling the likelihood the aircraft will stop beyond any given distance from the runway threshold.

The same concept was used for the point of first impact (POFI) during landing undershoots. Figure 4 depicts the probability distribution for the touchdown location. Again, for the great majority of operations, the aircraft will touchdown within the runway boundaries, represented by the lightly shaded area of the probability distribution. The dark

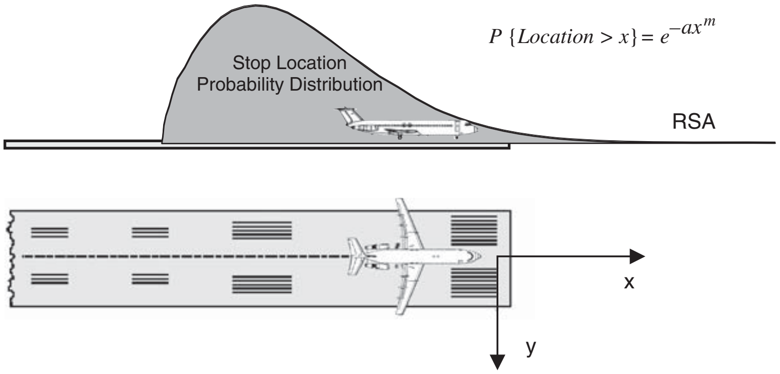


Figure 3. General concept for modeling aircraft overruns.

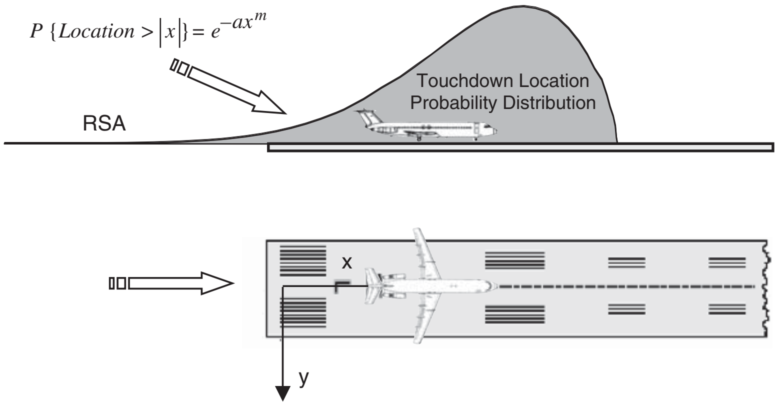


Figure 4. General concept for modeling aircraft undershoots.

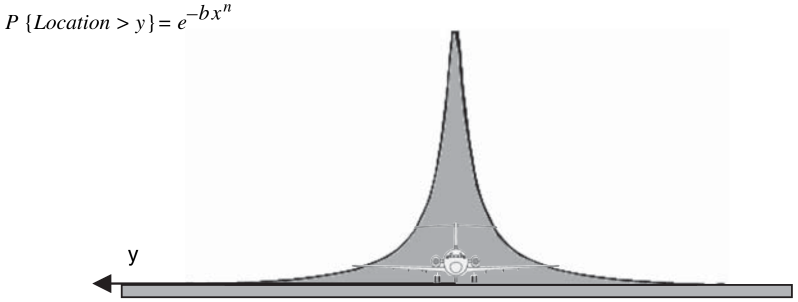


Figure 5. General concept for modeling aircraft lateral deviation.

shaded area represents the probability the aircraft will land before the approach end of the runway.

In addition, it was necessary to model the probability distribution for the aircraft wreckage location relative to the extended runway centerline. The concept is represented in Figure 5. Using the "x" and "y" models combined will allow users to evaluate RSA off standard dimensions and overall configuration. The distribution only represents the location distribution for aircrafts overrunning or undershooting the runway.

An initial analysis of the database and NOD was required to determine which risk factors were available to be built into the parametric models. The generic model and the wider insight gained from the database allowed an initial generic estimate of risk for a given situation to be made and identification of whether there were other significant risk factors that applied. The three-part modeling approach was built for each accident type, as represented in Figure 6. Before developing the final model structure, the available data were evaluated statistically, in order to develop the proper model structure and to ensure the parameters were compatible with model assumptions.

Approach Elements

Event Probability. The likelihood of an aircraft overrun or undershoot accident or incident depends on the operation conditions, including airport characteristics, weather conditions, and aircraft performance.

The probability of an accident per movement—the accident rate—is determined from historical data on numbers of movements carried out at reference airports and the number of accidents that occurred during those movements. Loughborough University has pioneered the use of NOD to include a multitude of risk factors in the assessment of accident probability. Using this approach allowed a far more discriminating analysis than relying solely on the accident rate. As a result, conclusions on RSA risks will reflect better the actual conditions and circumstances of specific airports.

Accident Location. In reality, the probability of an accident is not equal for all locations around the airport. The probability of an accident in the proximity of the runways is higher than at larger distances from the runway. This dependence is represented by the accident location model, which is the second main element of the current methodology. The accident location model is based on historical data. The distribution of accident locations relative to the runway will be modeled through statistical functions introduced by Eddowes et al. (2001). By combining the accident location model with the accident probability, the local probability of an accident can be calculated for each runway end.

Accident Consequences. The consequences of an accident are a function of the dimensions of the actual RSA, of the aircraft and impact parameters (such as aircraft size, quantity of on-board fuel, impact angle, etc.), and of the local type of terrain and obstacles. The size of the accident area is not equal for every airport or area within the airport. The influence of the aircraft and impact parameters and the type of terrain on the size of the consequence area, as well as the lethality and

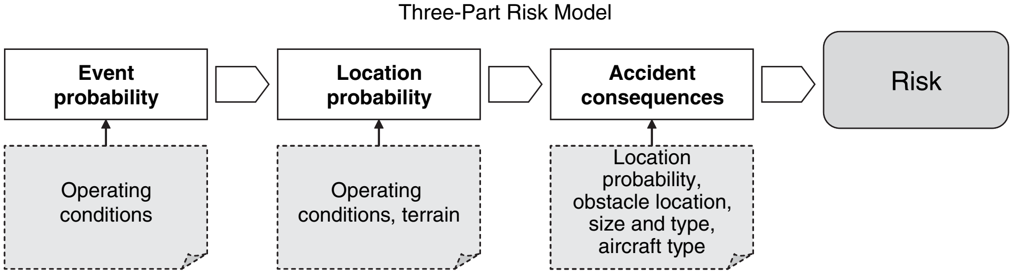


Figure 6. Modeling approach.

damage of the consequences, are defined in the consequences model, the third main element in the current methodology. For this purpose, lethality is defined as the actual probability of being killed within the consequence area. Aircraft damage is translated as the direct cost of property loss for an accident.

Accident/Incident Probability Model

To examine the accident propensity associated with different factors (e.g., environmental conditions), logistic regression was used to develop statistical models for accident/incident occurrence probability.

A number of numerical techniques could be used to carry out the multivariate analysis, but logistic regression was preferred. First, the technique is suited to models with a dichotomous outcome (incident and nonincident) with multiple predictor variables that include a mixture of continuous and categorical parameters. Logistic regression also is appropriate for case-control studies because it allows the use of samples with different sampling fractions, depending on the outcome variable without giving biased results. In this study, logistic regression allowed the sampling fractions of accident flights and of normal flights to be different. This property is not shared by most other types of regression analysis (Nagelkerke et al., 2005).

Backward stepwise logistic regression was used to calibrate the three frequency models because of the predictive nature of the research. This technique is able to identify relationships missed by forward stepwise logistic regression (Hosmer and Lemeshow, 2000; Menard, 2001). Due to the more stringent data requirements of multivariate regression, cases with missing data were replaced by their respective series means.

To avoid the negative effects of multi colinearity on the model, correlations between independent variables were tested first to eliminate highly correlated variables, particularly if they do not significantly contribute to explaining the variation of the probability of an accident.

The basic model structure selected for this study is in the following form:

$$P\{Accident\_Occurence\} = \frac{1}{1+e^{b_0+b_1X_1+b_2X_2+b_3X_3+\ldots}} \qquad (1)$$

where

P\{Accident_Occurrence\} = the probability (0-100%) of an accident type occurring given certain operational conditions;
X_i = independent variables (e.g., ceiling, visibility, crosswind, precipitation, aircraft type); and
b_i = regression coefficients.

The use of NOD in the accident frequency model provided a major improvement in the modeling of accident occurrence, as discussed previously. The analysis with NOD also adds to the understanding of cause-result relationships of the two accident types. This constitutes a causal element in the risk models, so the modeling tool developed can be used to assess risk reduction strategies and estimate future risk levels, given trends in influential factors in an airport context.

A previous Loughborough University study on overruns found that the model developed for landing overrun risk using NOD on excess landing distance available is 22 times more predictive than models based on flight type alone (Kirkland, 2001). Additional analyses using NOD have been conducted since, and they continue to show the importance of assessing the criticality of risk factors beyond the simple accident/movement rate (Wong et al., 2005b, 2006).

Accident/Incident Location Model

The model structure selected for accident location was used by Eddowes et al. (2001) and is in the following form:

$$P\{Location > x\} = e^{-ax^n} \qquad (2)$$

where

P\{Location > distance\} = the probability the overrun/undershoot distance along the runway centerline beyond the threshold is greater than x;
x = a given location or distance beyond the threshold; and
a, n = regression coefficients.

This dependence is represented by the accident location model, which is the second main element of the current methodology. The accident location model is based on historical data on accident locations. The distribution of accident locations relative to the runway was modeled through statistical functions. By combining the accident location model with accident probability, the local probability of an accident can be calculated for each runway end.

When plotting the percentage of accidents where the aircraft stopped beyond a certain distance from the threshold, in case of overruns, or first impacted the terrain, for undershoots, the probability diminishes the greater the distance is, as depicted in Figure 7.

The probability and location models will provide a quantitative assessment based on operating conditions for a specific airplane landing or taking off at a specific runway. In addition, it is necessary to relate these probabilities with the RSA conditions to provide an assessment of the probability that the consequences of an incident are severe. This is the final component of the approach, described in the following section.

Consequence Model

The consequences modeling approach should provide a qualitative assessment of the severity of an accident, based on

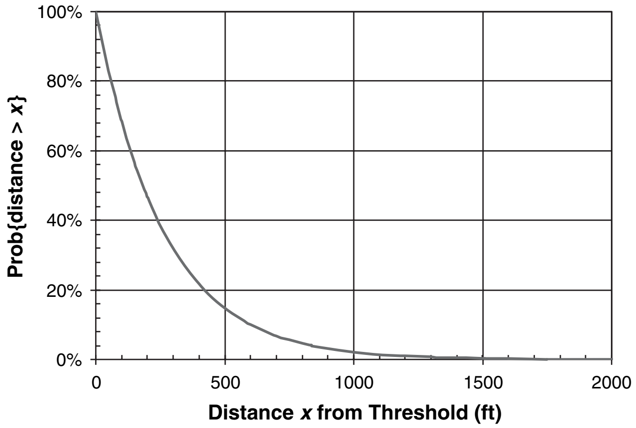


Figure 7. Typical trend for wreckage location model.

the location model and the existing runway characteristics, to include dimensions of existing RSA, airplane weight, location and type of obstacles, and topography of surrounding terrain. The approach used in this project was to model the probability of severe consequences using the frequency and location models, coupled with existing RSA configuration and obstacles.

The consequences of an accident depend on several factors that are difficult to model, such as the energy of the crash (speed, aircraft weight, and size), quantity of fuel and occurrence of fire after impact, type of obstacle (height, depth, material, size), impact angle, and the local type of terrain. Initial attempts to model consequences focused on the relationship between the raw or normalized distances and the severity of the accident, reflected by the amount of damage and cost of injuries. The overall consequences of the accidents were quantified by the total direct costs for injuries and aircraft damage.

The approach proved difficult to implement because the relationship between accident location and consequences was poor. In many situations the consequences were related to the speed that the aircraft hit an obstacle and the type of the obstacle. Information for the former was not available for the great majority of cases. Therefore, the efforts to model consequences were directed to providing a rational approach that incorporated the location model. The basic idea is simple but effective. The higher the speed, and hence the energy when an aircraft hits an obstacle, the greater the consequences. The sturdier the obstacle, the greater the consequences. The larger the obstacle, the greater the probability the aircraft will hit the obstacle.

The speed of the aircraft striking the obstacle is related to the distance the aircraft would take to stop if no obstacles were present in the area adjacent to the runway ends. Based on the location model, the terrain type, and the deceleration model developed by Kirkland (2001), the probability the aircraft moving above a certain speed when hitting the obstacle can be estimated.

The speed necessary to cause significant damage to the aircraft and potentially severe consequences should be judged based on the type of aircraft, type of terrain, and type of obstacle. For this study, only general recommendations are provided to assess the interaction between the aircraft and obstacles. Using some simple assumptions it is possible to evaluate the overall risk of severe consequence accidents.

One of the difficulties posed to evaluate consequences of accidents was to integrate the number and severity of injuries with the property loss. It was not possible or practical to evaluate indirect consequences such as lost revenue, lost work time, disruption of flight schedule, and negative customer reaction to accidents.

In this study, estimates for direct costs of accidents are provided as a means to integrate personal injury and property loss. Although it is estimated that indirect costs typically represent four times the value of direct costs, only the latter will be used in this study. The parameters that were evaluated include the cost of the accidents, and number and type of injuries. The relationships between these consequence parameters and potential independent variables include the wreckage path length, the number of obstacles hit during the accident, the location of these obstacles, and land use type for the area beyond the existing RSA.

Accident Costs

The consequences of accidents, as documented in investigation reports, are described in terms of the number of injuries and the level of damage to the aircraft. Although third-party injuries also were accounted for in this study, property loss not related to aircraft damage was not evaluated for the lack of information. Injuries are classified according to ICAO criteria into four groups: none, minor, serious and fatal. The number of passengers and crew members for each level generally is available in the accident reports. Based on the total number of passengers/crew on board the fatality rate for each accident was calculated. Damage to aircraft also is described according to four classification groups: none, minor, substantial, and destroyed.

In addition to the raw classification, direct cost of accidents was calculated based on the number and type of injuries, as well as the damage to the aircraft. The basic source for accident cost is the Guide for Economic Values for FAA Investment and Regulatory Decisions (GRA, 2004). The objective of this report is to present a set of cost items and quantify the specific values recommended that FAA use in future regulatory evaluations in the conduct of benefit-cost and other evaluations of investments, including certain Airport Improvement Program (AIP) grants, and regulations subject to FAA decision making. They also are used by others, including airports, in benefit-cost analysis of proposed investments. The basis for estimating the direct costs is presented in Appendix L.

Development of Prototype Software for Risk Analysis

As part of this research study, prototype software that incorporates and integrates the risk models was developed. Users may input raw data and obtain normalized data, run a risk assessment analysis, and obtain denormalized results. The software serves as a tool for risk assessment associated with overrun and undershoot accidents and provides a basic yet useful format for risk analysis professionals to assist airport operators in evaluating RSAs.

Input data include the airport information, target level of safety (TLS), RSA characteristics including dimensions and type of terrain, and multiple historical or planned operations that may challenge the RSA in the event of overrun or undershoot incident. Output includes frequency distribution of risks for each type of accident and the percentage of flights subject to risk above a TLS.

CHAPTER 3

Findings and Applications

Database Summary Statistics

This section provides a statistical description of the data gathered in this study and included in the ACRP 4-01 accident and incident database. The final database incorporates 459 accidents and incidents. Figure 8 depicts the distribution of events by type of accident and incident (LDOR, LDUS, or TOOR).

Proportionally, there have been more LDOR than LDUS and TOOR, as shown in Figure 9. The numbers of LDUS and TOOR are similar.

Although some events prior to 1982 were included in the study, the majority of cases date from 1982 to 2006. The distribution of incidents and accidents is variable along the period data was collected. However, in the average (from 1984 to 2004), the number of reported accidents and incidents was similar and averages 18 events per year (9 accidents and 9 incidents). Part of the reduction observed for 2005 to 2007 is due to the unavailability of the reports when the data for this study were collected. For many events during this period, either the reports had not been completed or they were not yet available in electronic format. Figure 10 summarizes the number of events per year.

Summary of Anomalies Associated with Accidents and Incidents

An FHA was conducted during the initial stages of this study to identify the relevant factors associated with aircraft overrun and undershoot events so that data on these parameters could be gathered and included in the accident database and be used for developing risk models.

The majority of investigation reports describe causal and contributing factors to accidents but in general these are not reported for incidents. In addition, certain factors not described as causal or contributing factors in the accident are relevant to the present study. For example, a runway overrun investigation report may describe high approach speed and long touchdown as causal factors, but the report described the runway surface as wet. Although the latter was not considered a relevant factor in the investigation, the anomaly was present and is included in the summary statistics that follow.

The anomalies were divided into six different categories to aid in understanding the factors leading to aircraft overrun and undershoot events:

- Aircraft System Fault (SysF);
- Wildlife Hazards (WH);
- Weather Conditions (W);
- Human Errors (H);
- Runway Surface Conditions (R); and
- Approach/Takeoff Procedures (AT).

Several anomalies within each of these categories may be present during accidents and incidents. The majority of these anomalies were taken from the list of causal and contributing factors described in the investigation reports. In a few cases, even when not listed in the report, if an additional anomaly was identified, it was included in this analysis. For example, some investigation reports did not describe the wet runway as a causal or contributing factor to the accident, but rain during touch down on the runway was listed, and wet runway was included in the analysis.

The complete list of anomalies within each of the above categories and used in this study is shown in Table 4.

Figure 11 depicts the distribution by category for landing overruns. In this case, anomalies are mostly related to weather, human error, runway conditions, and approach procedures.

Figure 12 shows the frequency of anomalies by the category for undershoots. Similarly to landing overruns, the anomalies are mostly related to weather, human error, runway conditions, and approach procedures. Except for runway conditions, the incidence of anomalies was higher for the accidents under the predominant categories.

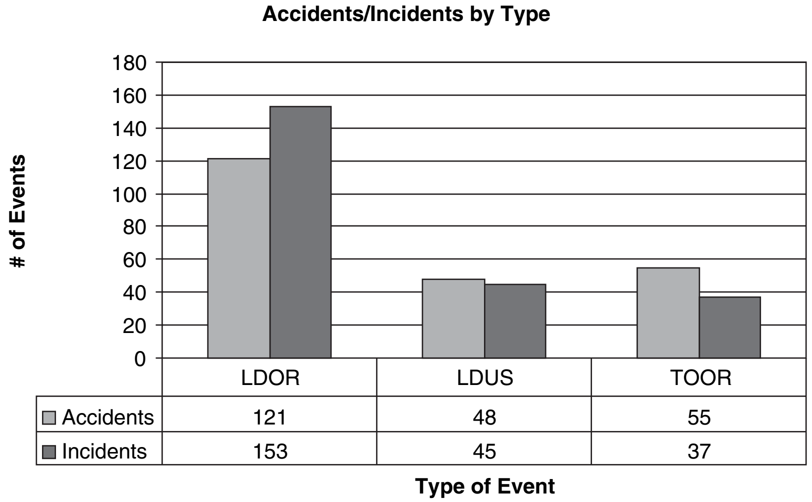


Figure 8. Distribution of events by type.

A summary of anomalies by category for takeoff overrun events is presented in Figure 13. For most of the events there were anomalies in the takeoff procedures. When there were anomalies related to weather conditions there were significantly more events in the accident category than incidents. The same conclusion is generally true for human errors, while system faults are mostly related to incidents.

Anomalies reported or identified were included within each of these categories, as shown in Figure 14 for LDOR events. Only the anomalies having more than 10 percent incidence are reported here, but a comprehensive list of anomalies is available in the accident/incident database.

The highest incidence anomalies for landing overrun are contaminated and wet runways. Sometimes these anomalies occur in combination (e.g., a wet runway contaminated with rubber). For contaminated runways, ice was the most predominant contaminant in the accidents and incidents evaluated. Three additional factors with high incidence for landing overruns are long touchdown, high speed during the approach, and the presence of rain.

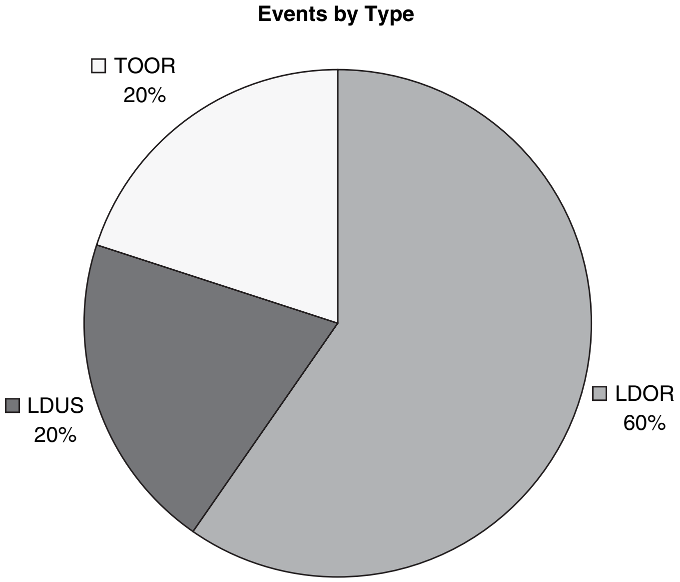


Figure 9. Distribution by type of event.

According to the numbers presented in Figure 15 for LDUS, the most frequent anomaly was low visibility, followed by rain, particularly for the accidents. Gusting conditions had high incidence for these accidents. As expected, approaches below the glide path are an important anomaly for this type of event. Visual illusion was a significant factor only for landing undershoots.

The presence of rain, gusting, crosswind, and low ceiling conditions were most predominant for these accidents when compared to incidents.

Figure 16 depicts the most frequent anomalies for TOOR events. As expected, rejecting the takeoff operation at high speeds led to the majority of accidents and incidents. The second most important anomaly was incorrect planning, such as: aircraft overweight, short takeoff distance available, and incorrect load distribution in the aircraft. Basically, the factors are equally frequent for accidents and incidents, except for the presence of rain, gusting, and crosswind conditions. These were more important for accidents when compared to incidents.

A summary of the most frequent anomalies for all events by accident type is shown in Table 5. The "X" represents the anomaly was present in more than 10 percent of the cases for the specific event type: LDOR, LDUS, or TOOR.

Unreported Events

When using U.S. accidents and incidents as a sample, the number of reported incidents (53 percent) is close to the number of accidents (47 percent), when it was expected to see

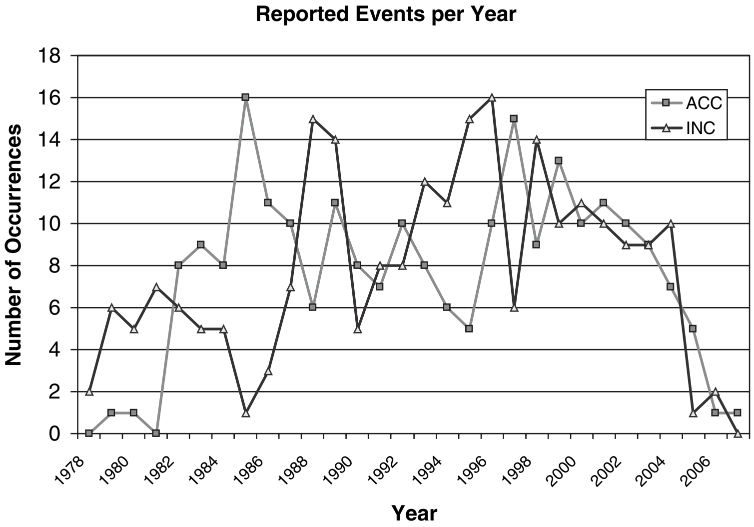


Figure 10. Events per year.

a much higher number of incidents compared to accidents. One possible explanation for this phenomenon would be that some incidents are unreported. Therefore, an analysis of the number of unreported incidents was carried out.

The methodology for evaluation of under reporting incidents is based on the assumption that there is a progressive decrease in the probability of travel to any given distance from the runway end with increasing distance. Such behavior is evident from the empirical accident and incident data set and is consistent with theoretical considerations of the nature of the event. The same basis considerations apply to LDOR, TOOR, and LDUS. Behavior of this type can be represented by a cumulative probability distribution function of the following form:

$$PROB\{d > x\} = e^{-ax^n} \qquad (3)$$

where PROB{d > x} is the probability of traveling a distance *d* greater than *x*.

Where there is full reporting of events it is expected that the available empirical data should fit a function consistent with this basic form. Where there is under-reporting, some distortion in the apparent behavior can be expected. Failure to report is expected to be more likely for events where the distance traveled off the runway is relatively low. The reported cumulative probability distribution (CPD) will be depressed at lower values of *x* but co-incident with the full distribution at higher values, as shown schematically in Figure 17.

There may be other factors that distort the form of the CPD. A data set of incidents is expected to lack a disproportionate number of events at greater distances, since these would be expected to more likely result in more serious consequences and be classified as accidents. On that basis, it is likely to be most appropriate to apply the analysis method proposed to a data set of incidents and accidents combined.

Another factor that might distort the form of the curve is the obstacle environment beyond the runway end. An obstacle might cause the aircraft to come to a stop earlier than it might otherwise. Generally, there is an increased probability of an aircraft encountering an obstacle the farther it has traveled, and particularly when it has traveled farther than the RSA, this effect will lead to a reduced probability of aircraft traveling to greater distances than would otherwise be the case. The implications of this phenomenon required further consideration as part of this analysis.

The analysis of unreported incidents is presented in Appendix D, and the results are summarized in Table 6. Based on these numbers, different weights for statistical modeling were used to reflect the expected rate of incidents relative to accidents.

Probability of Incident–Frequency Models

The chance of an aircraft overrunning or undershooting a runway depends on the probability of accident per aircraft movement and the number of movements (landings and takeoffs) carried out per year.

Logistic regression, discriminant analysis, and probit analysis were evaluated for modeling the probability of aircraft overrun and undershoot events. Discriminant analysis was not used because it involves numerous assumptions, including requirements of the independent variables to be normally distributed, linearly related, and to have equal variance within each group (Tabachnick and Fidell, 1996). Logistic regression was chosen over probit analysis because

Table 4. Anomalies during aircraft overrun and undershoot events.

Category	Anomaly	Type
Aircraft System Fault	Tire	
	Hydraulic	
	Power	
	Brake	
	Other	
Wildlife Hazards	Bird strike	
	Other	
Weather	Low Visibility	
	Wind Shear	
	Tailwind	
	Crosswind	
	Gusts	
	Low Ceiling	
	Strong Winds	
	Turbulence	
	Freezing Rain	
	Rain	
	Other	
Human Error	Fatigue	
	Communication/Coordination/ Planning	
	Pressonitis	
	Visual Illusion	
	Other	
Runway Surface	Wet	
	Contamination / Low friction	Standing Water
		Rubber
		Oil
		Slush
		Snow
		Ice
		Paint
	Construction	
	Downslope	
	Other	
Approach/Takeoff Procedures	Unstabilized Approach	Approach Below Flight Path
		Approach Above Flight Path
		High Speed
		Low Speed
	Long Touchdown	
	Takeoff rejected at high speed	
	Other	

the latter does not give the equivalent of the odds ratio and changes in probability are harder to quantify (Pampel, 2000).

Logistic regression is suited to models with a dichotomous outcome (incident and nonincident) with multiple predictor variables that include a mixture of continuous and categorical parameters. Logistic regression also is appropriate for case-control studies because it allows the use of samples with different sampling fractions depending on the outcome variable without giving biased results. In this study, it allowed the sampling fractions of accident flights and normal flights to be different. This property is not shared by most other types of regression analysis (Nagelkerke et al., 2005).

Backward stepwise logistic regression was used to calibrate the three frequency models because of the predictive nature of the research. The selected technique is able to identify relationships missed by forward stepwise logistic regression (Hosmer and Lemeshow, 2000; Menard, 2001). Due to the more stringent data requirements of multivariate regression, cases with missing data were replaced by their respective series means.

Every risk factor available in both Accident/Incident database and NOD were used to build each model. Table 7 shows the final parameters retained by the backward stepwise logistic regression as relevant independent variables for each of the frequency models.

It should be noted that it was not possible to include some risk factors in the frequency models, for example, the ratio between the landing distance available and the landing distance required. Although a possible important factor to assess runway criticality, the lack of information for landing

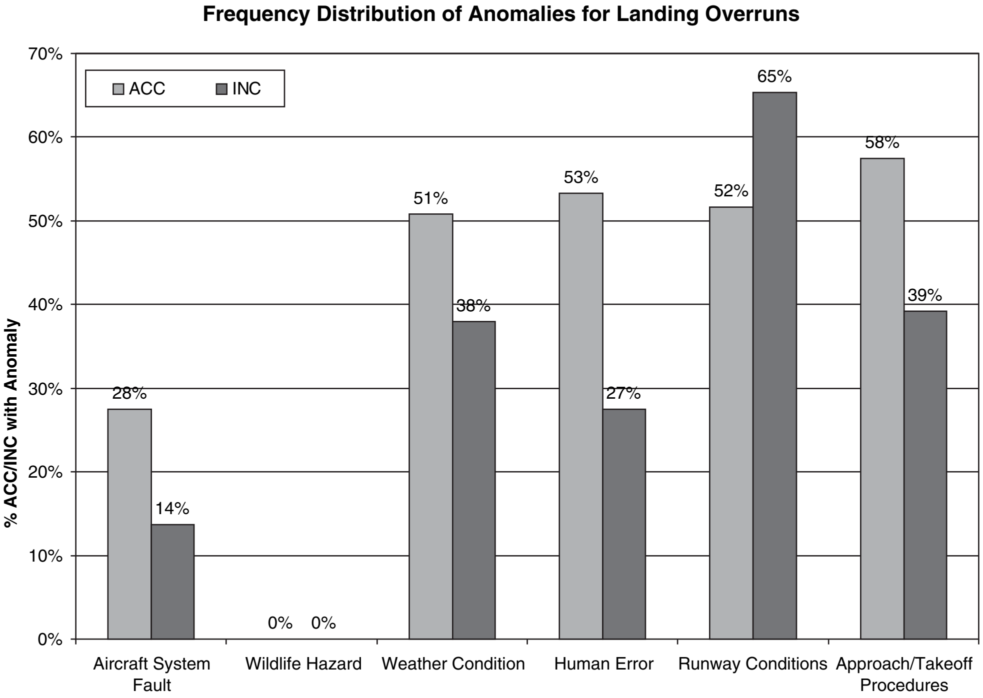


Figure 11. Frequency of anomalies by category (LDOR).

distance required in the normal operations data precluded the use of such variables in the frequency models. However it is difficult to evaluate how much improvement such a factor would bring to the model accuracy. Theoretically the runway length always should be compatible with the distances required by the aircraft under certain conditions. In this sense the new factor may bring little benefit to the model but, on the other hand, a larger safety factor for distances required also should be expected for most flights operating in longer runways.

The goal was to develop risk models based on actual accidents/incidents and normal operation conditions so that the probability of occurrence for certain conditions may be estimated. The use of such models will help evaluate the

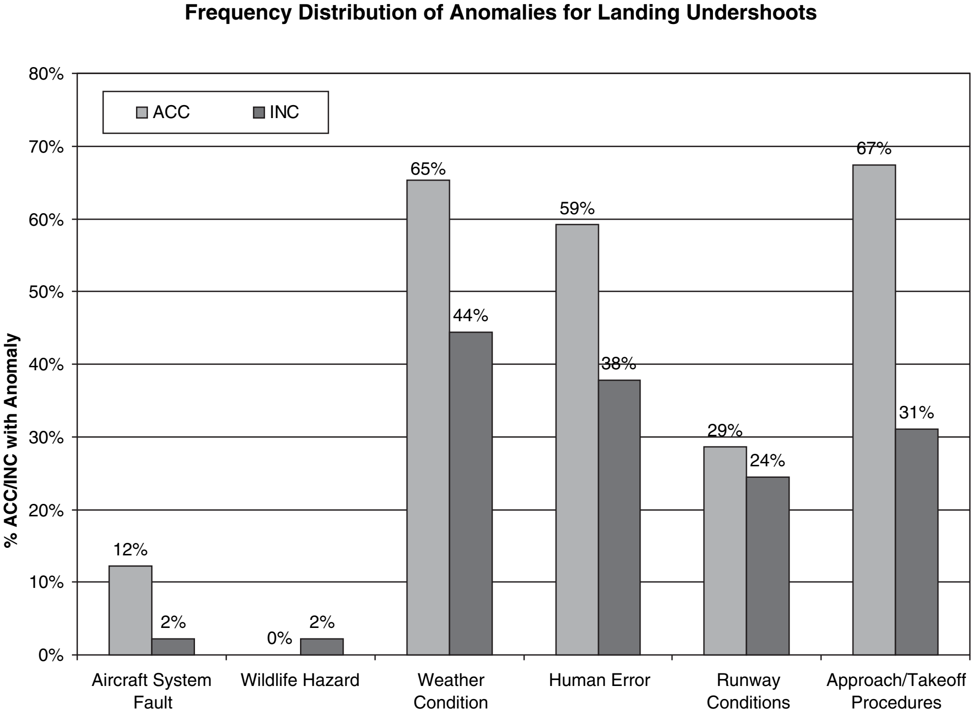


Figure 12. Frequency of anomalies by category (LDUS).

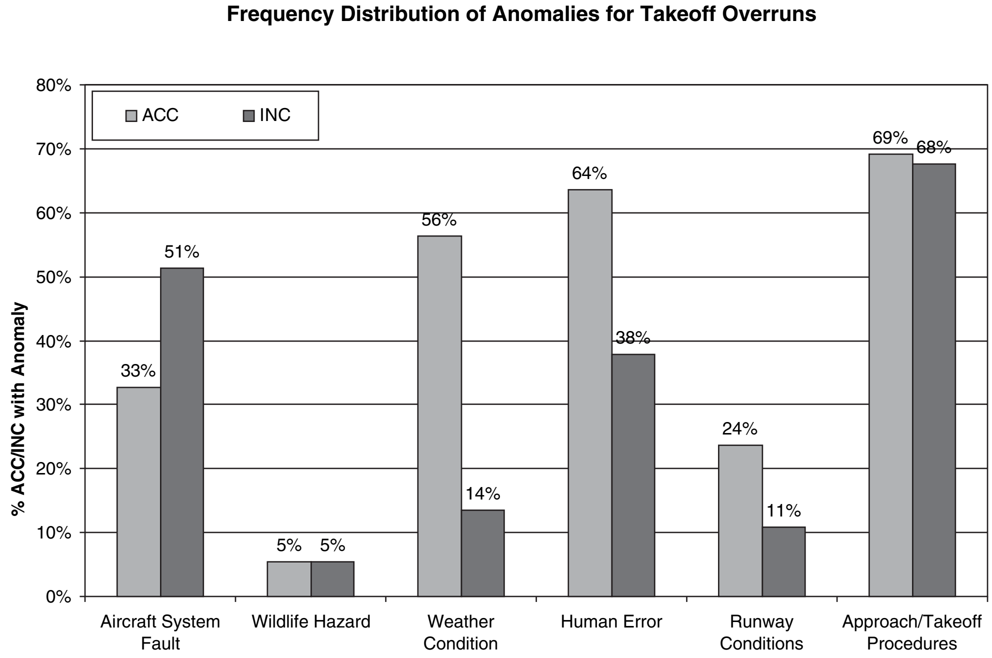


Figure 13. Frequency of anomalies by category (TOOR).

likelihood of incident occurrence for a runway that is subject to certain environmental and traffic conditions over the year.

The frequency model is in the following form:

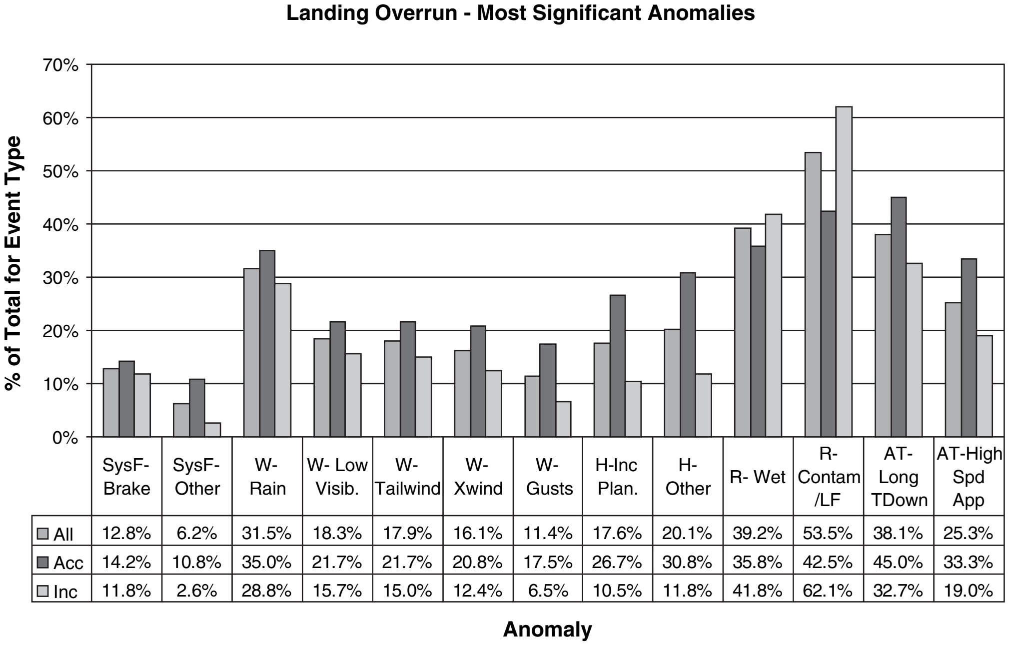
$$P\{Accident\_Occurrence\} = \frac{1}{1+e^{-(b_0+b_1X_1+b_2X_2+b_3X_3+\ldots)}} \quad (4)$$

where

$P\{Accident\_Occurrence\}$ = s the probability (0-100%) of an accident type occurring given certain operational conditions;

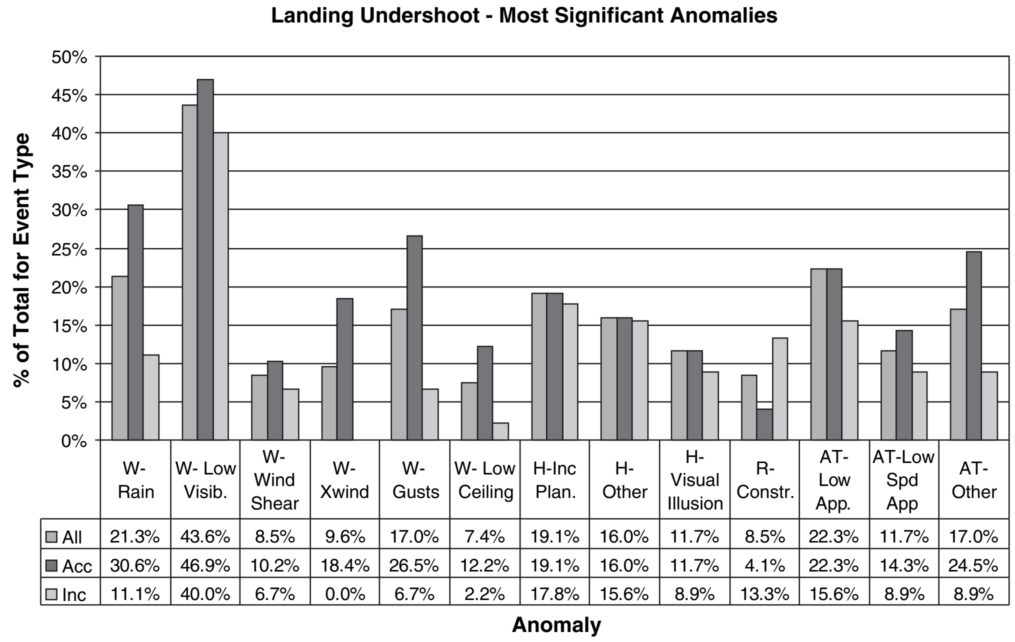
X_i = independent variables (e.g. ceiling, visibility, crosswind, tailwind, aircraft weight, runway condition, etc.); and

b_i = regression coefficients.



	SysF-Brake	SysF-Other	W-Rain	W- Low Visib.	W-Tailwind	W-Xwind	W-Gusts	H-Inc Plan.	H-Other	R- Wet	R-Contam /LF	AT-Long TDown	AT-High Spd App
▨ All	12.8%	6.2%	31.5%	18.3%	17.9%	16.1%	11.4%	17.6%	20.1%	39.2%	53.5%	38.1%	25.3%
■ Acc	14.2%	10.8%	35.0%	21.7%	21.7%	20.8%	17.5%	26.7%	30.8%	35.8%	42.5%	45.0%	33.3%
□ Inc	11.8%	2.6%	28.8%	15.7%	15.0%	12.4%	6.5%	10.5%	11.8%	41.8%	62.1%	32.7%	19.0%

Figure 14. Most frequent anomalies (LDOR).

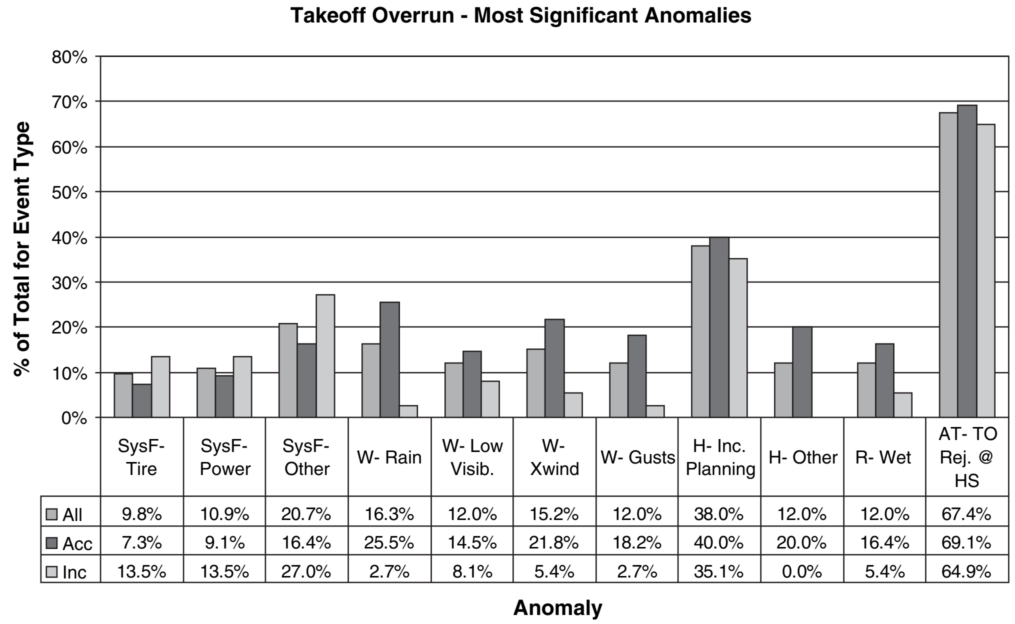


	W- Rain	W- Low Visib.	W- Wind Shear	W- Xwind	W- Gusts	W- Low Ceiling	H-Inc Plan.	H- Other	H- Visual Illusion	R- Constr.	AT- Low App.	AT-Low Spd App	AT- Other
▨ All	21.3%	43.6%	8.5%	9.6%	17.0%	7.4%	19.1%	16.0%	11.7%	8.5%	22.3%	11.7%	17.0%
■ Acc	30.6%	46.9%	10.2%	18.4%	26.5%	12.2%	19.1%	16.0%	11.7%	4.1%	22.3%	14.3%	24.5%
□ Inc	11.1%	40.0%	6.7%	0.0%	6.7%	2.2%	17.8%	15.6%	8.9%	13.3%	15.6%	8.9%	8.9%

Figure 15. Most frequent anomalies (LDUS).

Before logistic regressions were performed, it was ensured that all assumptions for the statistical procedure were met. Logistic regression is relatively free from assumptions, especially compared to ordinary least squares regression. However, a number of assumptions still apply. One of these is a linear relationship between the independents and the log odds (logit) of the dependent.

The Box-Tidwell transformation test was used to check whether all continuous variables met this assumption (Garson, 1998). This involved adding to the model interaction terms that are the cross-product of each independent variable times its natural logarithm [(X)ln(X)]. The logit linearity assumption is violated if these terms are significant. In the current analysis, the continuous variables were found to have non-linear logits. As a solution, these variables were divided into different categories according to standard equal intervals using landing NOD and accident data. The variables then were converted into categorical ones with these different levels, each being a separate logit independent variable.



	SysF- Tire	SysF- Power	SysF- Other	W- Rain	W- Low Visib.	W- Xwind	W- Gusts	H- Inc. Planning	H- Other	R- Wet	AT- TO Rej. @ HS
▨ All	9.8%	10.9%	20.7%	16.3%	12.0%	15.2%	12.0%	38.0%	12.0%	12.0%	67.4%
■ Acc	7.3%	9.1%	16.4%	25.5%	14.5%	21.8%	18.2%	40.0%	20.0%	16.4%	69.1%
□ Inc	13.5%	13.5%	27.0%	2.7%	8.1%	5.4%	2.7%	35.1%	0.0%	5.4%	64.9%

Figure 16. Most frequent anomalies (TOOR).

Table 5. Summary of anomalies for aircraft overruns and undershoots.

Anomaly	LDOR		LDUS		TOOR	
	ACC	INC	ACC	INC	ACC	INC
Brake system failure	X	X				
Power failure						X
Tire failure						X
Other aircraft system fault	X				X	X
Rain	X	X	X	X	X	
Low Visibility	X	X	X	X	X	
Low Ceiling			X			
Tailwind	X	X				
Crosswind	X	X	X		X	
Wind shear			X			
Gusts	X		X		X	
Improper flight planning	X	X	X	X	X	X
Visual illusion			X			
Other human errors	X	X	X		X	
Wet runway	X	X			X	
Contaminated runway	X	X				
Long touchdown	X	X				
High speed during approach	X	X				
Low speed during approach			X			
Approach too low			X	X		
Other approach anomalies			X			
Runway construction				X		
Rejected takeoff at high speed					X	X

A test for multicollinearity is required for multivariate logistic regression. Collinearity among the predictor variables was assessed by conducting linear regression analyses to obtain the relevant tolerance and Variance Inflation Factor (VIF) values. None of the tolerance values were smaller than 1, and no VIF value was greater than 10, suggesting that collinearity among the variables is not serious (Myers, 1990; Menard, 2001). Kendall's Tau also was used to assess potential correlations between predictor variables that are likely to be related.

Two pairs of variables had Kendall's Tau correlation coefficient between 0.51 and 0.60, indicating moderate correlation: equipment class with airport hub size and icing conditions with frozen precipitation. Since none of the correlations were serious, all variables were kept in the multivariate model, and caution was applied in interpreting the results. This is preferred to the alternative solution of removing variables, which would lead to model misspecification.

Although the R^2 for the models ranged between 0.148 and 0.245, as shown in Table 8, relatively low values are the norm in logistic regression (Ash and Schwartz, 1999), and they should not be compared with the R^2 of linear regressions (Hosmer and Lemeshow, 2000). The analysis of models using Receiver Operating Characteristic (ROC) curves to classify flights as "accident" or "normal" suggests good to excellent classification accuracy for such models (C-Statistic from 0.819 to 0.872).

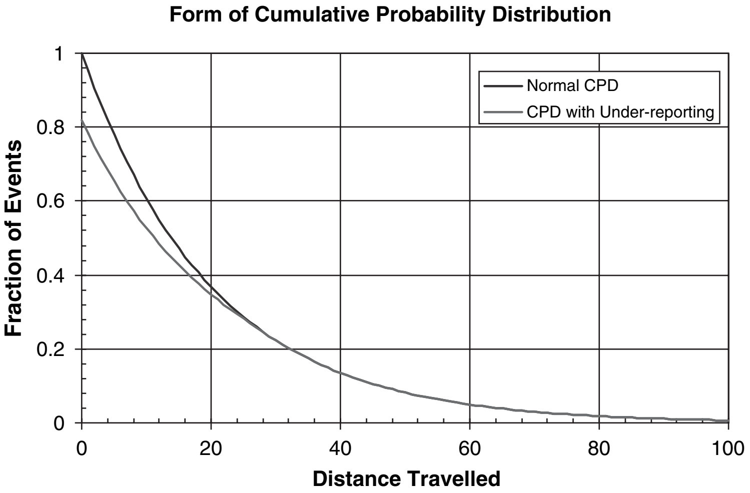


Figure 17. Schematic form of cumulative distribution functions.

Table 6. Summary results for under-reported incidents.

	Total # of Accidents and Incidents	Total # of Incidents	% Unreported Incidents **	Estimated # Unreported Incidents
LDOR	240	121	28.8%	17
LDUS	81	38	9.6%	7
TOOR	75	28	28.8% *	1

Note: * value assumed based on comparisons with LDOR
** based on incidents occurring at small distances from threshold

Due to the case-control set-up of the study, the constant (intercept) term b_0 of the final formula must be adjusted to account for the different sampling fractions between the cases and the controls. The following formula was used for this purpose (Hosmer and Lemeshow, 2000):

$$b^*_0 = \ln(t_1/t_0) + b_0 \tag{5}$$

where

b^*_0 = the original intercept,
t_1 = the sampling fraction of cases,
t_0 = the sampling fraction of controls, and
b_0 = s the adjusted intercept.

Although parameter t_1 is normally one when relevant information is available for all events, it was necessary to adjust these values to reflect under-reporting of incidents.

From the NOD sampling exercise, it was calculated that the total number of relevant normal operations from 2000 to 2005 inclusive is 191,902,290. That is 44.78 percent of the period's total itinerant operations excluding military operations. From the TAF, the total number of itinerant operations from 1982 to 2002 inclusive (the accident sampling period) excluding military operations was computed to be 1,408,495,828 movements. Of the latter, 44.78 percent equates 630,792,133 movements. A detailed description on the calculation of relevant terminal area forecast traffic is presented in Appendix J. Since the total sampled normal operation population is 242,420 flights,

$$t_0 = 242420/630792133 = 3.843 \times 10^{-4}$$

With t_1 and t_0, the adjusted intercepts of each of the risk model formula can be calculated:

$$b^*_0 = \ln(t_1/t_0) + b_0 = \ln(t_1/3.843 \times 10^{-4}) + b_0 = 7.864 + b_0 \tag{6}$$

Where b^*_0 is the original intercept, t_1 is the sampling fraction of cases, t_0 is the sampling fraction of controls, and b_0 is the adjusted intercept. The calculated parameters for each model are shown on Table 9.

Using the adjusted intercepts, the final frequency models are the following:

Landing Overrun (7)

$$\begin{aligned} b = {} & -15.456 + 0.551(\text{Heavy}Acft) - 2.113(CommuterAcft) \\ & -1.064(MediumAcft) - 0.876(SmallAcft) \\ & +0.445(TurbopropAcft) - 0.857(ForeignOD) \\ & +1.832(CeilingHeight < 1000\,ft) \\ & +1.639(CeilingHeight1001 - 2500\,ft) \\ & +2.428(Visibility < 2SM) + 1.186(Visibility2 - 4SM) \\ & +1.741(Visibility4 - 6SM) + 0.322(Visibility6 - 8SM) \\ & -0.532(Crosswind2 - 5knts) + 1.566(Crosswind5 - 12knts) \\ & +1.518(Crosswind > 12knts) + 0.986(ElectStorm) \\ & +1.926(IcingConditions) + 1.499(Snow) - 1.009(Temp < 5C) \\ & -0.631(Temp5 - 15C) + 0.265(Temp > 25C) \\ & +1.006(NonhubApt) + 0.924(SignificantTerrain) \end{aligned}$$

Table 7. Independent variables used for frequency models.

Variable	LDOR	LDUS	TOOR
Aircraft Weight/Size	X	X	X
Aircraft user class		X	X
Ceiling	X	X	X
Visibility	X	X	X
Fog		X	X
Crosswind	X		X
Gusts			
Icing Conditions	X	X	X
Snow	X	X	X
Rain		X	
Temperature	X	X	X
Electrical Storm	X		
Turboprop/Jet	X		
Foreign Origin/Destination	X	X	
Hub/Non-hub airport	X		

Table 8. Summary statistics for frequency models.

Model	R^2	C
LDOR	0.245	0.872
LDUS	0.199	0.819
TOOR	0.148	0.861

Table 9. Calculated model intercepts.

Type of Event	Sampling Fraction (t_1)	Original Intercept (b^*_0)	Adjusted Intercept (b_0)
LDOR	0.938274	-7.656	-15.45637
LDUS	0.943765	-7.158	-14.96421
TOOR	0.997447	-8.790	-16.65153

Landing Undershoot (8)

$$\begin{aligned}
b = & -14.9642 + 0.036(\text{Heavy}Acft) - 1.699(CommuterAcft)\\
& -0.427(MediumAcft) + 1.760(SmallAcft)\\
& +0.288(UserClass1) + 0.908(UserClass2) - 1.042(ForeignOD)\\
& +0.199(CeilingHeight < 1000\,ft)\\
& +1.463(CeilingHeight1001 - 2500\,ft)\\
& +2.074(Visibility < 2SM) + 0.069(Visibility2 - 4SM)\\
& -0.185(Visibility4 - 6SM) - 0.295(Visibility6 - 8SM)\\
& +1.830(Fog) - 1.705(Rain) - 0.505(Temp < 5C)\\
& -0.874(Temp5 - 15C) - 0.446(Temp > 25C)\\
& +2.815(Icing) + 2.412(Snow)
\end{aligned}$$

Takeoff Overrun (9)

$$\begin{aligned}
b = & -16.6515 + 0.721(\text{Heavy}Acft) - 0.619(CommuterAcft)\\
& -0.009(MediumAcft) + 1.669(SmallAcft) + 1.336(UserClass1)\\
& +1.052(UserClass2) + 1.225(CeilingHeight < 1000\,ft)\\
& +1.497(CeilingHeight1001 - 2500\,ft)\\
& +0.201(Visibility < 2SM) - 1.941(Visibility2 - 4SM)\\
& -0.366(Visibility4 - 6SM) + 0.317(Visibility6 - 8SM)\\
& +1.660(Fog) - 0.292(Xwind2 - 5knts)\\
& +1.598(Xwind5 - 12knts) + 1.781(Xwind > 12)\\
& -0.536(Temp < 5C) - 0.507(Temp5 - 15C)\\
& +0.502(Temp > 25C) + 1.805(Icing) + 2.567(Snow)
\end{aligned}$$

Where:

Equipment Class	Ref: C	Large jet of MTOW 41k-255k lb (B737, A320 etc.)
HeavyAcft	AB	Heavy jets of MTOW 255k lb+
CommuterAcft	D	Large commuter of MTOW 41k-255k lb (small RJs, ATR42 etc.)
MediumAcft	E	Medium aircraft of MTOW 12.5k-41k lb (biz jets, Embraer 120 Learjet 35 etc.)
SmallAcft	F	Small aircraft of MTOW 12.5k or less (small, single or twin engine Beech90, Cessna Caravan etc.)
User Class	Ref: C = Commercial	
UserClass1	F = Cargo	
UserClass2	G = GA	
ForeignOD	Foreign origin/destination (yes/no) - Ref: domestic	
CeilingHeight	Ref: >2500ft	
CeilingHeight<1000ft	<1000	
CeilingHeight1001-2500ft	1001-2500	
Visibility	Ref: 8-10 statute miles (SM)	
Visibility<2SM	< 2 SM	
Visibility2-4SM	2-4 SM	
Visibility4-6SM	4-6 SM	
Visibility6-8SM	6-8 SM	
Crosswind	Ref:< 2 knots	
Xwind2-5knts	2-5 knots	
Xwind5-12knts	5-12 knots	
Xwind>12knts	>12	
ElectStorm	Electrical storm (yes/no) – Ref: no	
IcingConditions	Icing conditions (yes/no) – Ref: no	
Snow	Snow (yes/no) – Ref: no	
Air Temperature	Ref: 15 – 25 deg.C	
Temp<5C	< 5 deg.C	
Temp5-15C	5 – 15 deg.C	
Temp>25C	> 25 deg.C	
NonhubApt	Non-hub airport (yes/no) – Ref: hub airport	
SignificantTerrain	Significant terrain (yes/no) – Ref: no	

Notes:

Ref: indicates the reference category against which the odds ratios should be interpreted.

Non-hub airport: airport having less than 0.05% of annual passenger boardings

Significant terrain: terrain within the plan view of airport exceeds 4,000 feet above the airport elevation, or if the terrain within a 6.0 nautical mile radius of the Airport Reference Point rises to at least 2,000 feet above the airport elevation.

Appendix M provides the results for multivariate logistic regression analysis used to obtain the model coefficients described earlier.

Accident Location Models

Based on the accident/incident data for wreckage locations, three sets of complementary cumulative probability distribution (CCPD) models were developed in this study. With CCPDs, the fraction of accidents involving locations exceeding a given distance from the runway end or threshold can be estimated. When the CCPD is multiplied by the frequency of accident occurrence, a complementary cumulative frequency distribution (CCFD) is obtained. The latter quantifies the overall frequency of accidents involving locations exceeding a given distance from the runway end or threshold.

The CCPD model structure selected was used by Eddowes et al. (2001) and is in the following form:

For the longitudinal distribution, the basic model is:

$$P\{Location > x\} = e^{-ax^{n}} \qquad (10)$$

where

P{Location > x} = the probability the overrun/undershoot distance along the runway centerline beyond the threshold is greater than x;
x = a given location or distance beyond the threshold; and
a, n = regression coefficients.

For the transverse distribution, the same model structure was selected. However, given the accidents transverse location is not reported, in general, if the wreckage location is within the extended runway lateral limits, it was necessary to use weight factors to reduce model bias, particularly for modeling the tail of the probability distribution. Therefore the model can be represented by the following equation:

$$P\{Location > y\} = e^{-by^{m}} \qquad (11)$$

where

P{Location>y} = the probability the overrun/undershoot distance from the runway centerline is greater than y (P{Location<=0} = c);
y = a given location or distance beyond the threshold; and
b, m = regression coefficients.

The correlations between the overrun and undershoot distances to the lateral distance relative to the runway axis also were evaluated for assessing the correlation between x and y locations. A high correlation would suggest the best geometry for RSAs is not a rectangle.

When plotting the percent of accidents beyond a certain distance from the threshold, shown in Figure 18, it can be noted that an RSA with 1000 ft in length will encompass close to 95 percent of all landing overruns. It should be noted that the raw data includes reported accidents and incidents, but incidents were weighted to account for unreported cases.

Figure 19 depicts the distribution of raw lateral distances from the extended runway centerline. For many events the distance was very close to the runway centerline and the actual distance was not reported. For such cases when possible, the y-distance was assumed to be 0.0. As mentioned earlier, weighting factors were used to obtain unbiased estimates at the tails of the distribution. In this case, weighting was applied to the events having y-distances above 400 ft.

The LDOR CCPD for normalized distances is shown in Figures 20 and 21. Using transformed distances, a 1000 ft-long

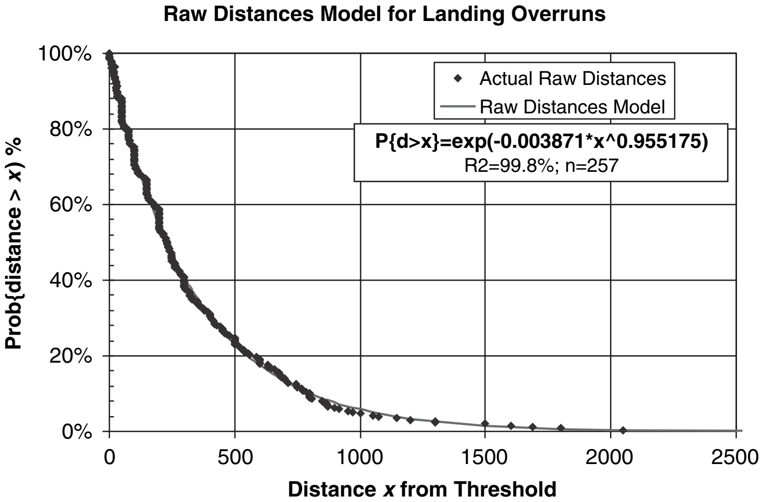


Figure 18. LDOR location model using raw (nonnormalized) distances.

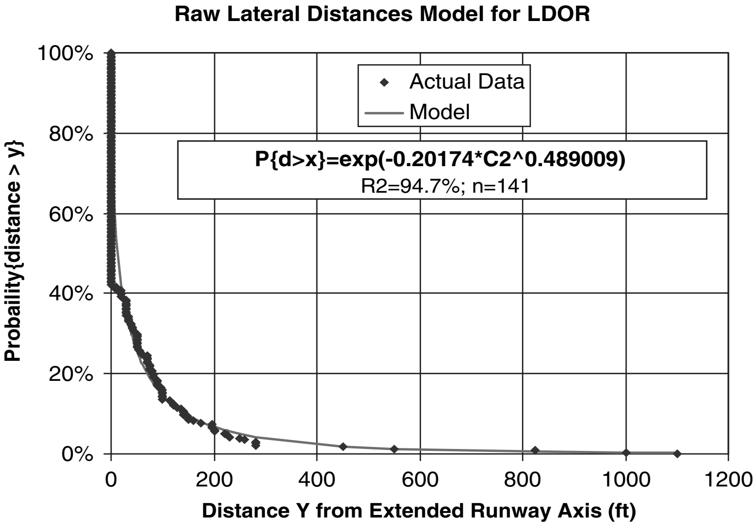


Figure 19. LDOR lateral location model using raw (nonnormalized) distances.

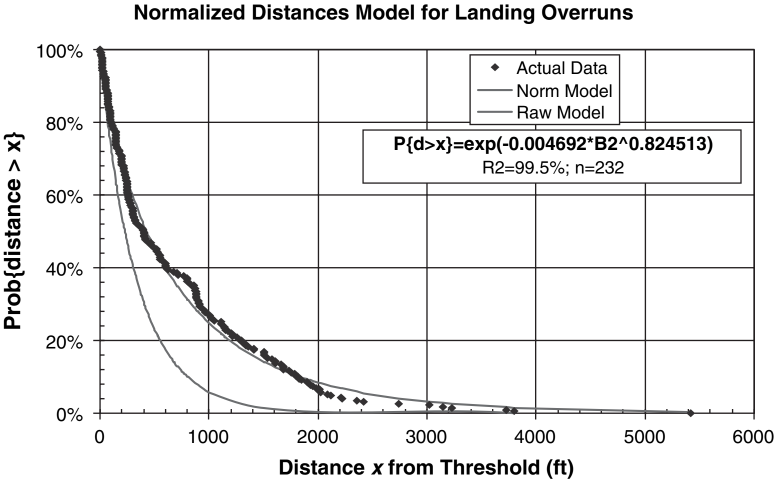


Figure 20. LDOR location model using normalized distances.

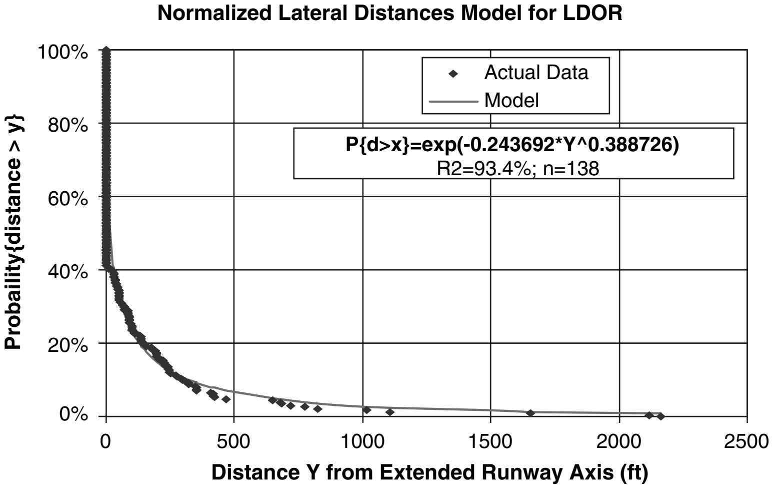


Figure 21. LDOR lateral location model using normalized distances.

RSA will encompass approximately 80 percent of all landing overruns.

The probability that the point of first impact is beyond a certain distance for landing undershoots is depicted in Figures 22 and 23, for raw distances, and in Figures 24 and 25, for normalized distances. For nearly 13 percent of landing undershoots, the aircraft point of first impact will occur at distances greater than 1000 ft from the runway threshold.

The raw location probability trend for takeoff overruns is depicted in Figures 26 and 27. From the raw, unweighted accident and incident data, close to 20 percent of takeoff overruns will occur beyond a 1000 ft distance from the threshold. The normalized distance models for takeoff overruns is presented in Figures 28 and 29.

For each set of location models, one model was developed with the raw distance locations and one model used normalized distances relative to terrain type, runway elevation, and the air temperature during the accident/incident. Tables 10 and 11 show the location models developed in this study.

The sample sizes available to develop the models shown in Table 11 were smaller than those used for the models shown in Table 10. A number of investigation reports provide only the distance from the threshold, but not the lateral distance. Sample sizes for normalized models also are smaller than those developed with raw data. For a few cases in each accident group there was no information on the terrain type used to normalize the distance.

Analysis of RSA Geometry

The correlation between the overrun and undershoot distances to the lateral distance relative to the runway axis was evaluated to define the geometry of the safety areas. RSA are normally rectangular-shaped areas, but it was possible that a strong correlation between longitudinal and lateral could exist. In other words, a statistical analysis was necessary to evaluate if greater longitudinal distances for wreckage location can lead to greater transverse distances.

The correlation between the longitudinal and lateral distance for each type of event is shown in Table 12.

Although the correlation between x and y locations is not zero for LDOR and LDUS ($P < 0.05$), the level is relatively low; it was assumed that the correlation is not important. This leads to the assumption that the transverse location distribution of accidents is fairly constant along the longitudinal locations from the threshold.

Consequences

As described earlier, accident costs were used to integrate consequences related to injuries and property loss into a single parameter. The initial intent was to relate the consequences, represented by the accident cost, with the wreckage distance for the accident. The relationship could be used to estimate the consequences of accidents based on the wreckage location, providing a link between the location and consequences models. Unfortunately these relationships were found to be quite poor, as consequences depend not only on the speed when the aircraft departs the runway, but also the nature and location of existing obstacles, as well as the type and size of aircraft.

Additional analysis attempted to relate accident location with aircraft damage. Four categories of damage—none, minor, substantial, and hull loss—were correlated to accident location. The use of raw distances proved to hold very low correlations between wreckage path distance and the aircraft damage. However, there was an improvement when normalized distances relative to terrain, elevation, and temperature were used. The correlations are quite reasonable, as shown in Table 13.

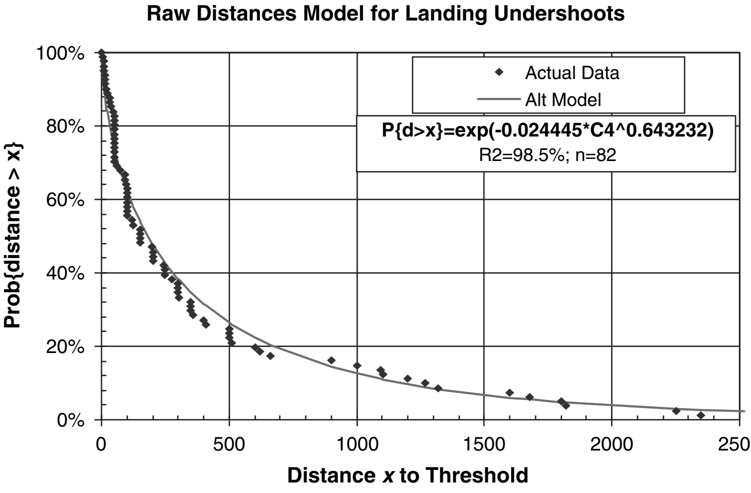


Figure 22. LDUS location model using raw (nonnormalized) distances.

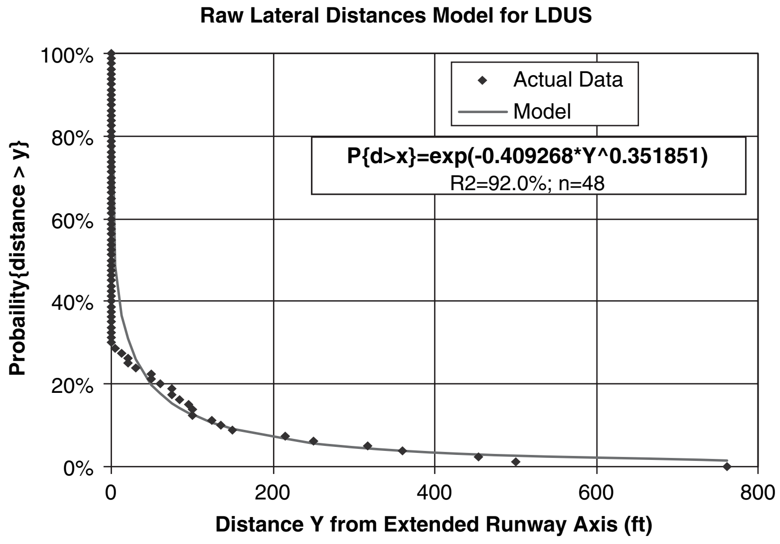


Figure 23. LDUS lateral location model using raw (non-normalized) distances.

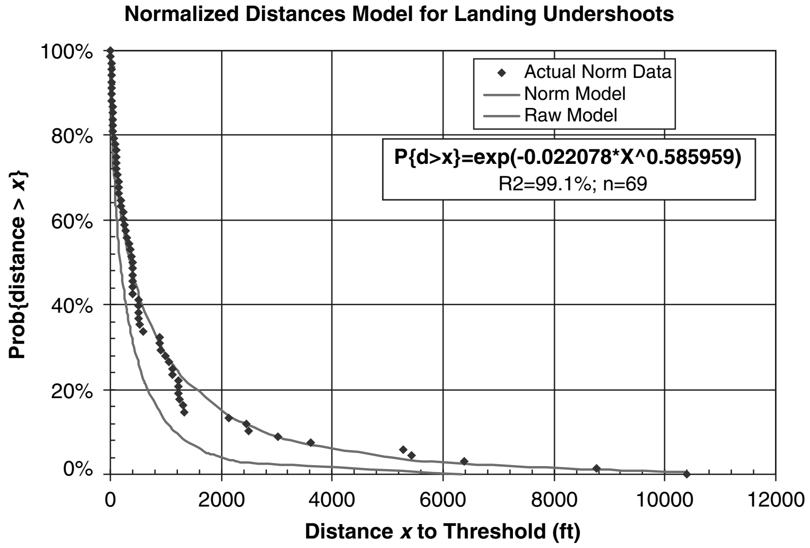


Figure 24. LDUS location model using normalized distances.

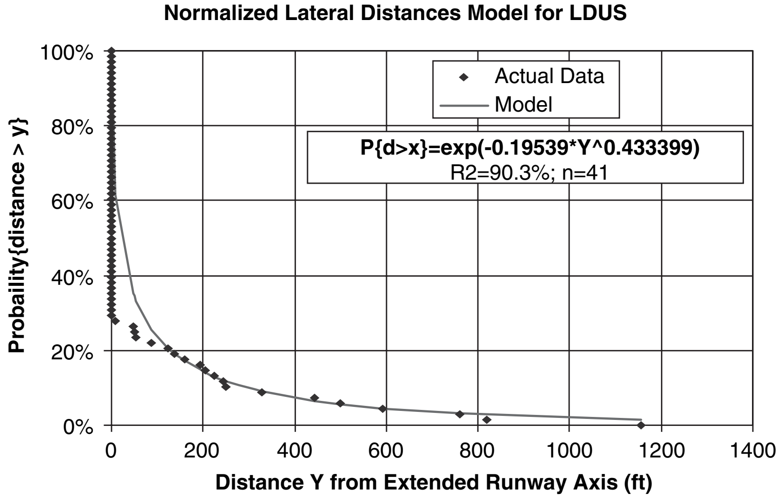


Figure 25. LDUS lateral location model using normalized distances.

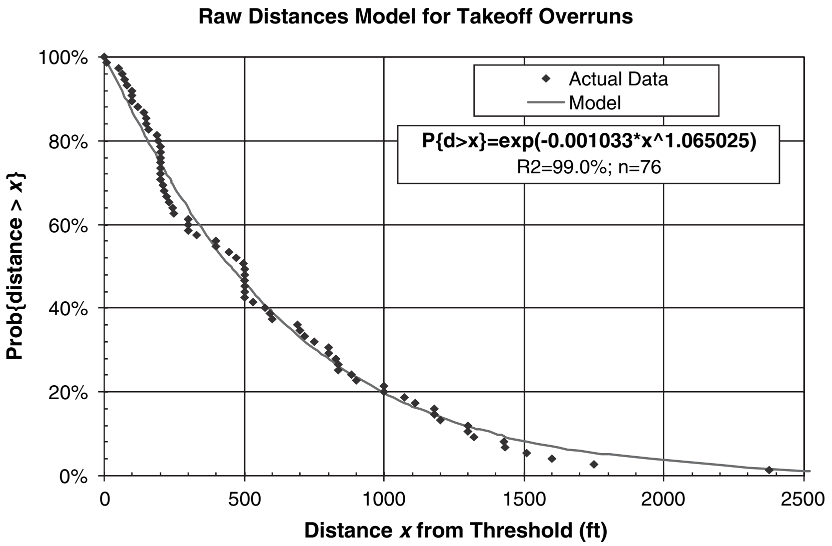


Figure 26. TOOR location model using raw (nonnormalized) distances.

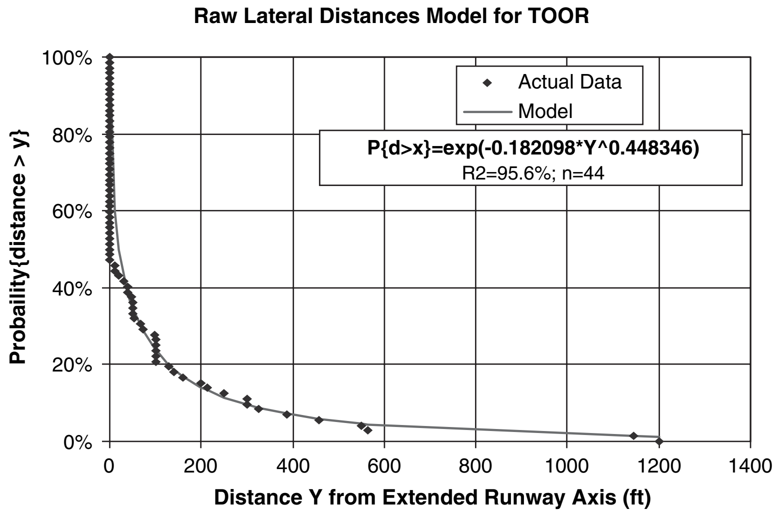


Figure 27. TOOR lateral location model using raw (nonnormalized) distances.

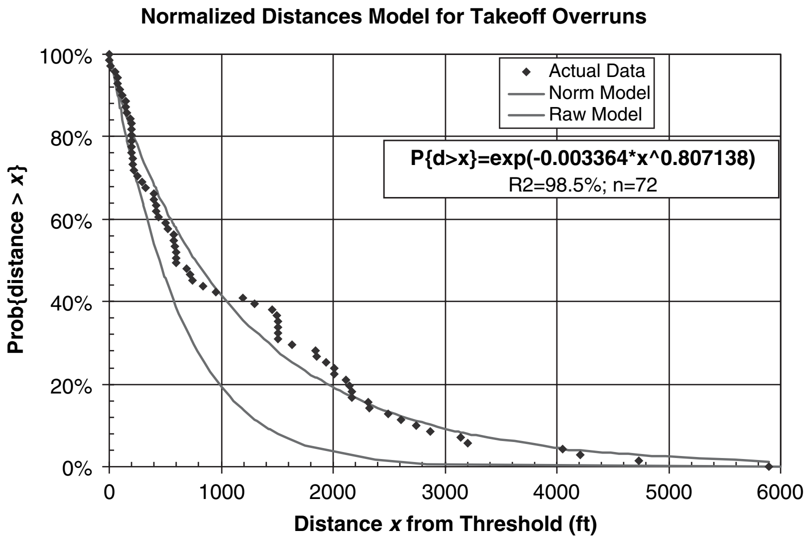


Figure 28. TOOR location model using normalized distances.

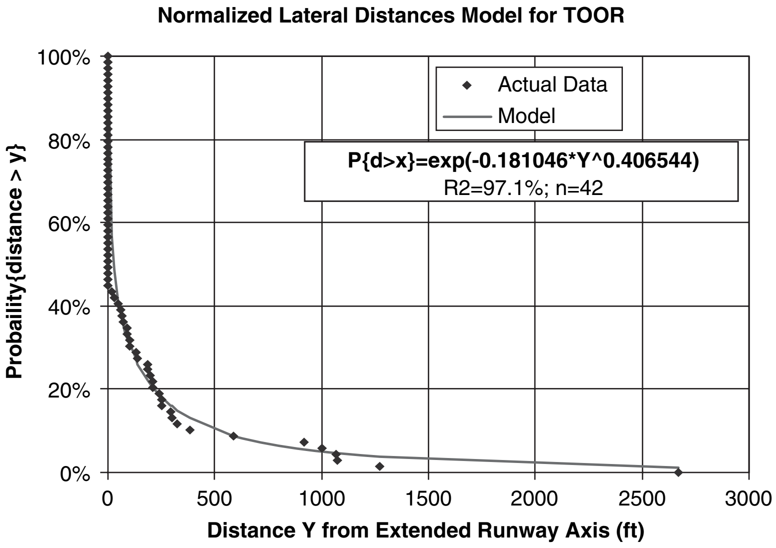


Figure 29. TOOR lateral location model using normalized distances.

Both Spearman R and Kendal Tau correlation coefficients provide an indicator of the degree of co-variation in the variables. Both tests require that variables are represented at least in ordinal scale (rank), which is the case for aircraft damage. While Spearman R has an approach similar to the regular Pearson product-moment correlation coefficient, Kendall Tau rather represents a probability.

Despite these reasonable correlations, a more rational approach to model consequences was preferred to assess the effect of different obstacles at various locations in the vicinity of the RSA. Examples of such obstacles include fences, drops and elevations in the terrain, existing facilities, culverts, ALS, and ILS structures, trees, etc.

Modeling Approach

The main purpose for modeling consequences of aircraft accidents is to quantify the risk based on the probability of occurrence and the results in term of injuries and property loss. It was not possible to develop one model for each type of accident, as previously done to model frequency and location. However, a rational probabilistic approach is suggested to evaluate the probability of accidents or serious accidents.

The basic idea is to use the location model to estimate the incident occurrences when the aircraft will have high energy resulting in serious consequences. Figure 30 can be used to illustrate and help understand this approach.

The x-axis represents the longitudinal location of the wreckage relative to the threshold. The y-axis is the probability that the wreckage location exceeds a given distance "x." The location distance can be normalized or not, according to the criteria selected.

In this example, an obstacle is located at a distance "D" from the threshold and the example scenario being analyzed is an aircraft landing overrun incident. The figure shows an exponential location model developed for the specific accident scenario, in this case, landing overrun.

There are three distinct regions in this plot. The first region (medium shaded area) represents those occurrences that the aircraft departed the runway, but the exit speed was relatively

Table 10. Summary of X-location models.

Type of Accident	Type of Data	Model	Eq.#	R^2	# of Points
LDOR	Raw	$P\{d > x\} = e^{-0.003871x^{0.955175}}$	(12)	99.8%	257
	Normalized	$P\{d > x\} = e^{-0.004692x^{0.824513}}$	(13)	99.5%	232
LDUS	Raw	$P\{d > x\} = e^{-0.024445x^{0.643232}}$	(14)	98.52%	82
	Normalized	$P\{d > x\} = e^{-0.022078x^{0.585959}}$	(15)	99.1%	69
TOOR	Raw	$P\{d > x\} = e^{-0.001033x^{1.065025}}$	(16)	99.0%	76
	Normalized	$P\{d > x\} = e^{-0.003364x^{0.807138}}$	(17)	98.5	72

where $P\{d > x\}$ is the probability the wreckage location exceeds distance x from the threshold, and x is the longitudinal distance from the threshold.

Table 11. Summary of Y-location models.

Type of Accident	Type of Data	Model	Eq.#	R^2	# of Points
LDOR	Raw	$P\{d > y\} = e^{-0.20174\,y^{0.489009}}$	(18)	94.7%	141
	Normalized	$P\{d > y\} = e^{-0.243692\,y^{0.388726}}$	(19)	93.4%	138
LDUS	Raw	$P\{d > y\} = e^{-0.409268\,y^{0.351851}}$	(20)	92.0%	48
	Normalized	$P\{d > y\} = e^{-0.19539\,y^{0.433399}}$	(21)	90.3%	41
TOOR	Raw	$P\{d > y\} = e^{-0.182098\,y^{0.448346}}$	(22)	95.6%	44
	Normalized	$P\{d > y\} = e^{-0.181046\,y^{0.406544}}$	(23)	97.1%	42

low, and the aircraft came to a stop before reaching the existing obstacle. The consequences for such incidents are expected to be none to minor as the aircraft may hit only frangible objects (e.g., threshold lights) within these small distances.

The rest of the curve represents events that the aircraft exited the runway at speeds high enough for the wreckage path to extend beyond an existing obstacle. However, a portion of these accidents will have relatively higher energy and should result in more severe consequences, while for some cases the aircraft will be slow when hitting the obstacle so that catastrophic consequences are less likely to happen.

Using this approach, it is possible to assign three scenarios: the probability that the aircraft will not hit the obstacle (resulting in none or minor consequences); the probability that the aircraft will hit the obstacle with low speed and energy (with substantial damage to aircraft but minor injuries); and the probability that the aircraft will hit the obstacle with high energy (with substantial damage and injuries).

For events with low energy when impacting the obstacle, it is possible to assume that if no obstacle was present the aircraft would stop within a distance Δ from the location of the obstacle. The problem is to evaluate the rate of these accidents having low speeds at the obstacle location and this is possible based on the same location model. This probability can be estimated by excluding the cases when the speed is high and the final wreckage location is significantly beyond the obstacle location.

A similar approach was developed to combine the longitudinal and transverse location distribution with the presence, type, and dimensions of existing obstacles. The basic approach is represented in Figure 31 for a single and simple obstacle.

A few simplifying assumptions were necessary when developing this approach. One simplification is to assume the lateral distribution is random and does not depend on the presence of obstacles. This is a conservative assumption because there are events when the pilot will avoid some obstacles if he has some control of the aircraft. The database contains a number of cases when the pilot avoided ILS and Approach Lighting System (ALS) structures in the RSA.

Table 12. Correlation between lateral and longitudinal overrun/undershoot distances.

Type of Event	R	R^2	CI 95%	p	n
LDOR	0.320	10.2%	0.20 - 0.43	< 0.0001	235
LDUS	0.316	10.0%	0.11 - 0.50	0.0040	81
TOOR	0.113	1.3%	-0.12 a 0.33	0.3430	73

A second assumption is that the aircraft follows a path near parallel to the extended runway axis. Again, this assumption will lead to calculations of higher than actual risk and is conservative. The aircraft may hit or avoid obstacles in paths that are nonparallel to the runway axis.

The shaded area in Figure 31 represents the area of analysis. Accident data was considered relevant when wreckage location challenged an area of 2000 × 2000 ft beyond the threshold. The example shown in the figure depicts an overrun example.

Obstacle 1 is located at a distance x_o, y_o from the threshold and has dimensions $W_1 \times L_1$. When evaluating the possibility of severe consequences it is possible to assume this will be the case if the aircraft fuselage or a section of the wing close to the fuselage hits the obstacle. Thus, it is possible to assume the accident will have severe consequences if the y location is between Y_c and Y_f, as shown in the figure. Based on Equation 11 for transverse distance, the probability the aircraft axis is within this range can be calculated as follows:

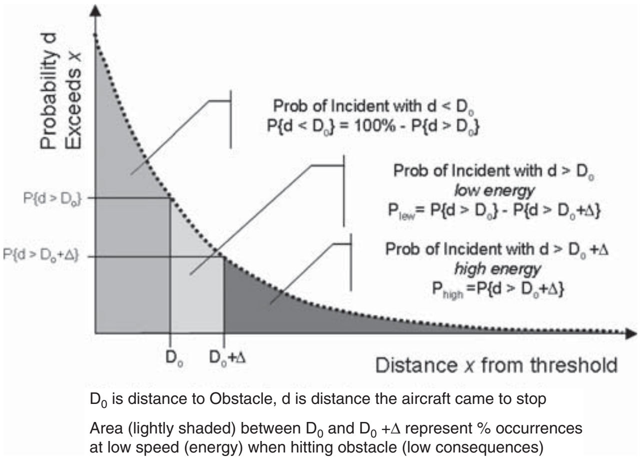
$$P_{sc} = \frac{e^{-by_c^m} - e^{-by_f^m}}{2} \tag{24}$$

where

P_{sc} = the probability of high consequences;
b, m = regression coefficients for y-location model;
Y_c = the critical aircraft location, relative to the obstacle, closest to the extended runway axis; and

Table 13. Correlation between normalized wreckage location and aircraft damage.

Type of Event	Sample Size	Spearman R	Kendall Tau
LDOR	224	0.62	0.49
LDUS	68	0.30	0.23
TOOR	67	0.55	0.44
All	359	0.56	0.44



D_0 is distance to Obstacle, d is distance the aircraft came to stop

Area (lightly shaded) between D_0 and $D_0 + \Delta$ represent % occurrences at low speed (energy) when hitting obstacle (low consequences)

Figure 30. Approach to model consequences of overrun/undershoot accidents.

Y_f = the critical aircraft location, relative to the obstacle, farther from the extended runway axis.

The same example is depicted in Figure 32 showing the probability of severe consequences can be represented by the lightly shaded area in the probability distribution.

Combining this approach with the longitudinal distribution approach and the possibility of multiple obstacles, the risk for accidents with severe consequences can be estimated using the following model:

$$P_{sc} = \sum_{i=1}^{N} \frac{\left(e^{-by_{ci}^{m}} - e^{-by_{fi}^{m}}\right)}{2} e^{-a(x_i+\Delta_i)^n} \qquad (25)$$

where

N = the number of existing obstacles;

a, n = regression coefficients for the x-model; and

Δ_i = the location parameter for obstacle i.

The value of Δ may be estimated based on Kirkland's model for aircraft deceleration over different types of terrain (Kirkland et al., 2004) and crashworthiness speed criteria for aircraft. It should be noted that Δ depends on the type of terrain, type and size of aircraft, and type of obstacle. Frangible objects in the RSA are less prone to causing severe consequences. Lighter aircraft may stop faster and the landing gear configuration also may have an effect on the aircraft deceleration in soft terrain, but these factors are not accounted for in Kirkland's model.

The probability and location models should provide a quantitative assessment based on operating conditions for a specific airplane landing or takeoff at a specific runway. The consequences model should provide a qualitative assessment of the severity of an accident, based on the location model and the existing runway characteristics, to include dimensions of existing RSA, airplane weight, type, location and size of obstacles, and the topography of the surrounding terrain.

The procedure will allow modeling overrun and undershoot risks for the conditions of the airport being evaluated. The probability of the accident occurring, as well as stopping location distances, will be compared to existing geometry of safety areas and existing obstacles to assess the possible consequences of the accident, at least qualitatively.

Cost of Accidents

As described in the previous chapter, the direct costs of accidents and incidents were estimated for each event having sufficient information for the computation. This section presents a summary of these costs.

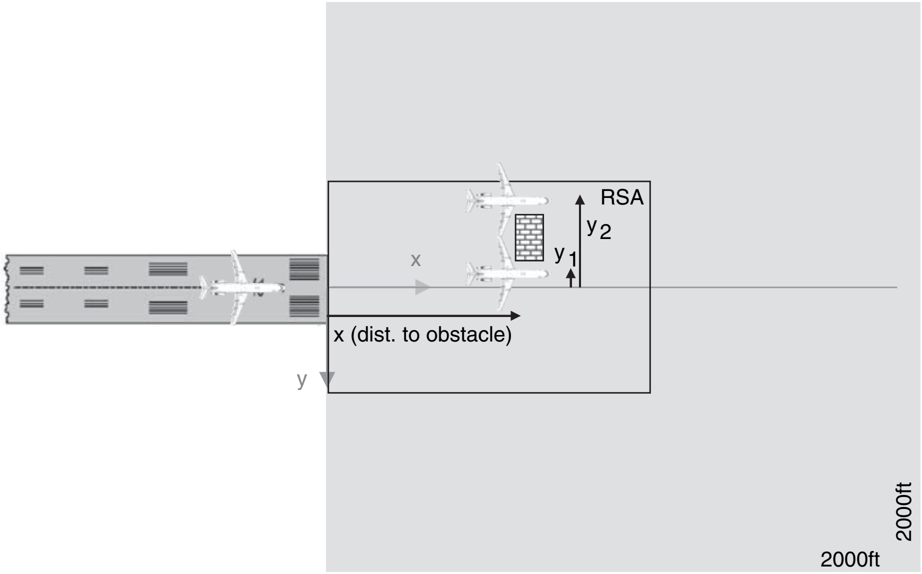


Figure 31. Modeling consequences.

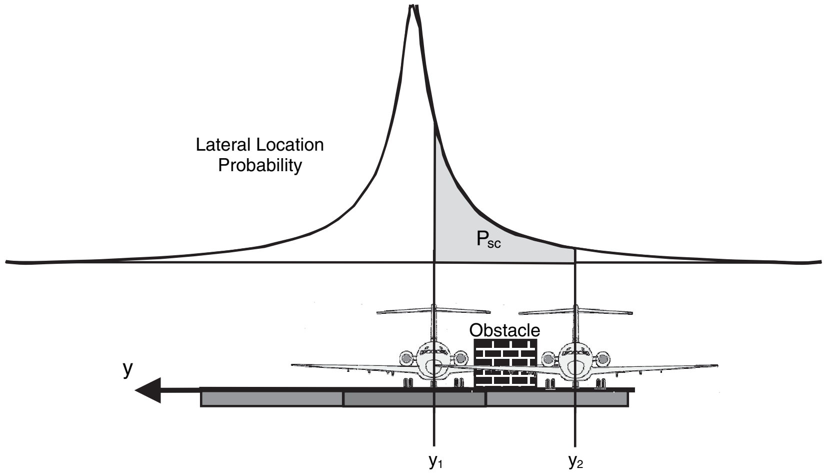
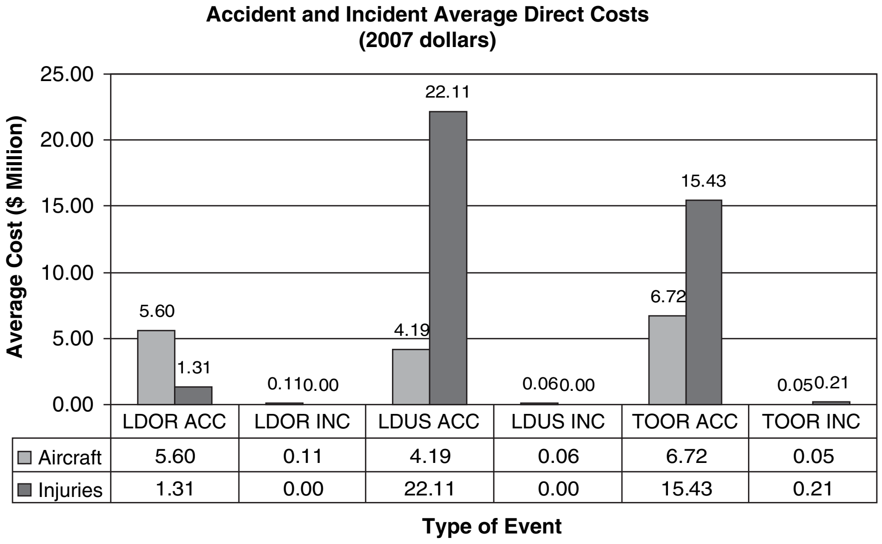


Figure 32. Modeling likelihood of striking an obstacle.



	LDOR ACC	LDOR INC	LDUS ACC	LDUS INC	TOOR ACC	TOOR INC
▨ Aircraft	5.60	0.11	4.19	0.06	6.72	0.05
■ Injuries	1.31	0.00	22.11	0.00	15.43	0.21

Figure 33. Direct cost of accidents and incidents.

As mentioned earlier, the intent was to use the data and find relationships between certain parameters of the accident (e.g., wreckage path distance) and the number and level of injuries, as well as damage to aircraft. The total consequences were estimated in terms of total direct costs for injuries, aircraft damage, and accident investigation.

Figure 33 depicts the average cost by type of accident and by severity. Most of the cost for LDORs is attributed to loss of property or aircraft damage. On the other hand, loss of dollars due to injuries is significantly higher for LDUSs, most likely due to the high speed and energy during these accidents.

The average loss of property among the three types of accidents was fairly similar. As expected, the cost of incidents was significantly lower for all three types of events. The cost of investigation is not represented in the figure, but rather is shown in Table 14.

Table 14. Total and investigation costs (2007 dollars, millions).

Type of Event	Total Cost	Investigation Cost
LDOR ACC	7.08	0.17
LDOR INC	0.11	0.00
LDUS ACC	26.75	0.45
LDUS INC	0.06	0.00
TOOR ACC	22.60	0.46
TOOR INC	0.26	0.00

The costs for injuries, aircraft damage, and accident/incident investigation are available in the accident database for each event included in this study. Appendix L provides more details on the calculation of accident costs.

CHAPTER 4

Practical Application of Models

Upon developing the risk models, it is necessary to integrate them to allow risk assessment of RSAs under specific conditions. A practical application of such models for examining a specific RSA will involve estimating the risk that an aircraft operating under specific airport conditions will challenge the existing RSA and stop beyond the available RSA limits or crash into existing obstacles.

This chapter includes a step-by-step procedure to evaluate an RSA using the models and the approach developed in this study. The example presented is for a hypothetical Runway 07/25, but actual NOD for an existing airport was collected from 2002 to 2004 and is used to illustrate the practical application of the approach developed. The procedure represented in Figure 34 will allow assessing the probability that an incident will occur during the aircraft operation and that as a result, the consequences are likely to be severe. The initial process will involve the following steps:

The initial process will involve the following steps:

1. Select the specific RSA to analyze and gather information to include dimensions, type of terrain, and existing obstacles adjacent to the RSA.
2. Collect (or estimate) a representative traffic sample for the three crash scenarios (LDOR, LDUS, and TOOR) challenging the RSA being evaluated.
3. Divide the RSA into sections comprising specific crash scenarios. Each scenario should include the distance from the threshold and two lateral distances relative to the extended runway axis.
4. Using the frequency models and location models, estimate for every operation the probability for each crash scenario and type of operation. Based on these data, develop the frequency distribution for each crash scenario and for each type of incident (LDOR, LDUS, and TOOR).
5. For each type of operation, determine the percentage of occurrences having a risk higher than a selected level or TLS.
6. Determine the weighted frequency distribution for all types of incidents together.
7. Repeat the analysis for the remaining runway ends of the airport.
8. Account for the risk exposure and estimate the probability, in terms of accidents per year, for each type of incident and for each RSA of the airport.
9. Classify the RSA according to the percentage of high-risk operations.

Step 1—RSA Details

The RSA to be evaluated should be characterized by type of terrain, dimensions, and type, size, and location of obstacles. The analysis is for the approach end of Runway 25 and is a simple example because the obstacles that can cause severe consequences are well defined; the RSA is rectangular and symmetric, and it is surrounded by a body of water, as depicted in Figure 35.

Step 2—Collect Representative Traffic Sample

This step will involve gathering normal operations data for the airport. A second alternative for this step is to estimate the expected operations based on the planned flight schedule for the facility. When using historical data, two possible sources are: the Aviation System Performance Metrics (ASPM) data, which identify the takeoff and landing runways in hourly segments, the runway, and direction for each flight; and the Enhanced Traffic Management System Counts (ETMSC), which provides information on traffic counts by airport or by city pair for various data groupings. These same sources were used to obtain NOD for this study. The sample flight data are for operations that may challenge the RSA being evaluated in the event of an aircraft overrun or undershoot.

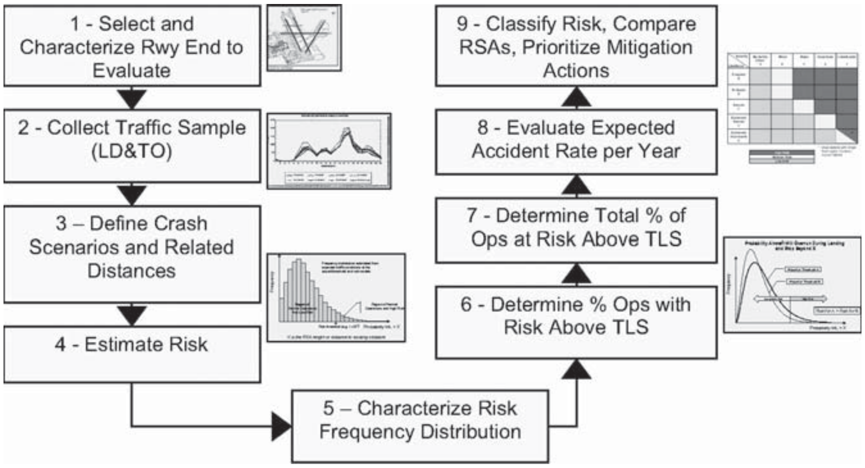


Figure 34. RSA risk assessment.

The information on flights should be coupled with weather conditions obtained from the airport weather station. The representative sample (e.g., 1 year) should contain the information on the parameters used in the frequency models (Table 7).

Aircraft operations challenging the RSA at the runway end shown in Figure 35 are those arriving on Runway 25 (LDUSs) or arriving and departing from Runway 07 (LDORs and TOORs). To run the analysis, a sample of the traffic landing and taking off on Runway 07 and landing on Runway 25 is necessary. The sample must be representative of the existing or planned conditions for Runway 07/25. Preferably, the sample should cover at least 1 year of operations, but it may not be necessary to obtain data for each month. A sample comprising at least 4 months of operations, but characterizing the whole year should suffice (e.g., January, April, July, and October), such that different seasons, environmental conditions, and seasonal variations of traffic are represented.

Between 2002 and 2004, a sample of historical data from an existing airport was gathered for this example. Data include landing operations for Runway 25, landing operations for Runway 07, and takeoff operations for Runway 07. In the event of an incident, these flights may challenge the RSA for this example.

Step 3—Define Crash Scenarios

This step still requires some judgment from the analyst. In the example shown in Figure 35, the RSA adjacent to the Runway 25 approach end is only 100 ft long by 500 ft wide.

When applying the risk assessment procedure to a particular RSA, it is important to recognize that not every RSA has a standard or rectangular shape. In many cases, a combination of the shapes and sizes as well as obstacles may exist. Other factors, such as the type of obstacle, will often need a

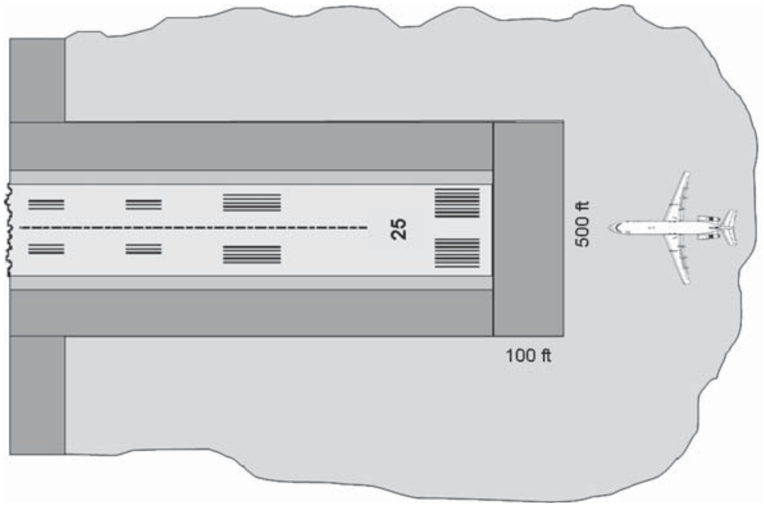


Figure 35. RSA on approach end of Runway 25.

subjective assessment and the use of some simplification to run the risk analysis.

For the RSA configuration in the example, there are only four crash scenarios that may lead the aircraft to fall into the water if overrunning or undershooting the runway:

Crash Scenario 1. During a landing or takeoff operation on Runway 07, the aircraft will overrun the RSA within its 500 ft wide boundaries and fall after running 100 ft.

Crash Scenario 2. During a landing on Runway 25, the aircraft will undershoot the RSA within 500 ft wide boundaries and before the RSA end, 100 ft from the threshold.

Crash Scenario 3. Same as Crash Scenario 1, but the aircraft will fall into the water outside the 500 ft wide boundaries of the RSA.

Crash Scenario 4. Same as Crash Scenario 3, but the aircraft will undershoot before the runway end and outside the 500 ft wide boundaries of the RSA.

It should be noted that the small number of crash scenarios identified is for this simple example only. The presence of obstacles or the asymmetry of the RSA would lead to additional possible crash scenarios. For example, if the RSA had an ILS structure, two additional crash scenarios should be considered:

Crash Scenario 5. During a landing or takeoff operation on Runway 07, the aircraft will overrun the RSA within the center area of the RSA and hit the ILS structure with enough energy for severe consequences.

Crash Scenario 6. Same as Crash Scenario 5, but the aircraft will undershoot in the RSA, before the ILS structure and strike it.

In this case, Crash Scenario 1 should be modified so that the aircraft would overrun or undershoot the runways between the RSA 500ft boundaries in a path that avoids the ILS structure and the aircraft falls into the water. No modification would be required for Crash Scenario 2, when the aircraft undershoots the runway before the beginning of the RSA.

Step 4—Estimate the Risk

For each operation in the NOD sample, it is necessary to calculate the risk. An example calculation for one landing operation will be described to help understanding of the process.

Suppose one of the landing operations on Runway 07 is characterized by the parameters depicted in Table 15.

The information is used in Equation 7 to compute the probability the aircraft will overrun Runway 07 during a landing operation under these conditions, thus challenging the RSA being evaluated. The computation is the following:

Table 15. Example normal operation on Runway 07, hypothetical airport.

Parameter	Value	Note
Aircraft	B738	Boeing 737-800
Equipment Class	N	Large jet
User Class	C	Commercial
Equipment Type	J	Jet
Wind Direction	340	
Wind Speed Knts	13	
Ceiling ft	500	
Visibility Sm	1.0	
Temperature C	30	
Fog	1	Fog present
Icing	0	No icing
Elec. Storm	0	No elect. Storm
Frozen Precipitation	0	No frozen precip.
Snow	0	No snow
XWind Knts	13	calculated
Rain	0	No rain
Foreign Origin/Dest.	0	Domestic
Significant Terrain	0	No significant terrain

$$\begin{aligned} b = {} & -15.456+0.551(0)-2.113(0)-1.064(0)-0.876(0) \\ & +0.445(0)-0.857(0)+1.832(1)+1.639(0)+2.428(1) \\ & +1.186(0)+1.741(0)+0.322(0)-0.532(0)+1.566(0) \\ & +1.518(1)+0.986(0)+1.926(0)+1.499(0)-1.009(0) \\ & -0.631(0)+0.265(1)+1.006(0)+0.924(0)=-9.413 \end{aligned}$$

The probability that an aircraft will not be able to stop during a landing operation and overrun the runway under these conditions is therefore computed as follows:

$$P\{LDOR\}=\frac{1}{1+e^{9.413}}=8.165\times 10^{-5}$$

As expected, the risk of an incident is high for such unfavorable conditions: strong cross wind, low visibility, and low ceiling. After calculating the likelihood of an overrun, the next step in the process is to estimate probability the aircraft will stop beyond the RSA or hit an existing obstacle.

The area surrounding the RSA is a body of water. In this case, it is possible to assume the aircraft will be lost if it overruns the RSA and falls into the water. Distance x from the runway end is simply the length of RSA measuring 100 ft, and this is the value to be entered in the normalized x-location model given by Equation 13. It should be noted that the parameter "Δ" from general Equation 25 in this case should be set to 0 because the aircraft will fall into the water if its stop location simply exceeds 100 ft beyond the threshold.

The calculation is given by:

$$P\{d>x\}=e^{-0.004692x^{0.824513}}$$

$$P\{d>x\}=e^{-0.004692\times 100^{0.824513}}=81\%$$

The probability an aircraft will end in the water if overrunning the runway during landing is high because the RSA is very short.

As previously described, it is assumed the aircraft will overrun in a path that is nearly parallel to the runway axis. The probability that the aircraft will overrun the RSA under Crash Scenario 1 is given by a product of three probabilities: the probability of occurring the event (overrun); the probability the aircraft will stop beyond 100 ft from the threshold; and the probability the aircraft will remain within the RSA lateral limits during the overrun. Mathematically:

$$\text{Prob}\{\text{CS } 1\} = \text{Prob}\{\text{LDOR}) \times \text{Prob}\{x > 100\text{ft}\} \times (1 - \text{Prob}\{|y| > 250 \text{ ft})$$

And $\text{Prob}\{|y| > 250 \text{ ft}\}$ is that given by:

$$P\{d > y\} = e^{-0.20174 \times 250^{0.489009}} = 5.0\%$$

Probability for crash scenario 1 is: $8.165 \times 10^{-5} \times 0.81 \times (1-0.050) = 6.28 \times 10^{-5}$

Similarly, the probability for crash scenario 2 is simply given by:

$$\text{Prob}\{\text{CS } 3) = \text{Prob}\{\text{LDOR}) \times \text{Prob}\{|y| > 250 \text{ ft}$$

In this situation the aircraft only needs to overrun the runway by a small margin; as long as the transverse deviation is greater than 250 ft, the aircraft will end up in the water. The probability for crash scenario 3 is calculated as follows:

$$P\{\text{CS } 3\} = 8.165 \times 10^{-5} \times 0.050 = 4.083 \times 10^{-6}$$

The last step is to compute the total probability the aircraft will overrun the runway during landing and fall into the water with severe consequences:

$$P\{\text{LDOR Severe}\} = P\{\text{CS } 1\} + P\{\text{CS } 3\} = 6.28 \times 10^{-5} + 4.08 \times 10^{-6} = 6.69 \times 10^{-5}$$

According to the FAA criteria described in Table B1-2 from Attachment 1 to Appendix B, the event is probable and such probability is unacceptable, as shown in the FAA Risk Matrix depicted in the same Attachment (Figure B1-1), even when there are major consequences. Considering the criteria set by FAA, the risk is considered high and suggests the operation is not safe enough under such conditions. However, the risk estimated for such conditions at any airport should be considered for planning and risk mitigation strategies only as it represents an "average" risk level for such conditions.

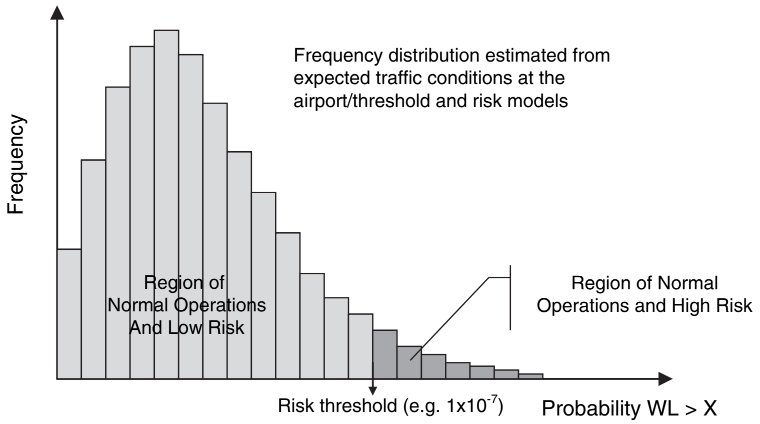
Step 5—Characterize Risk Frequency Distribution

The same procedure described for Step 3 can be used to compute the probability of severe consequences for every landing operation for Runway 07 that is part of the NOD sample. Each operation has a different risk associated with it. If all these risks are estimated, it is possible to build a histogram depicting the distribution of risk, as illustrated in Figure 36.

Step 6—Determine Percentage of Operations with Risk Above TLS

An example of the probability distribution generated by the prototype software developed under this project is shown in Figure 37. Each bar represents the percentage of operations having a specific risk level. The line represents the percentage of operations having risk higher then the level selected. In this example, if a TLS of 1:10000000 is selected, approximately 9 percent of the operations will be subject to undesirable levels of risk. This is useful, as it evaluates the percentage of operations with risk above a selected TLS. The area in dark bars represents such flights.

The same process is used to estimate the percentage of operations having a risk level above the selected TLS for LDUSs on Runway 25 and for TOORs on Runway 07, using the models associated with these types of events. The probability distribution of risks then can be characterized for each type of accident in the vicinity of that RSA.



X is the RSA length or distance to existing obstacle

Figure 36. Frequency distribution of risk.

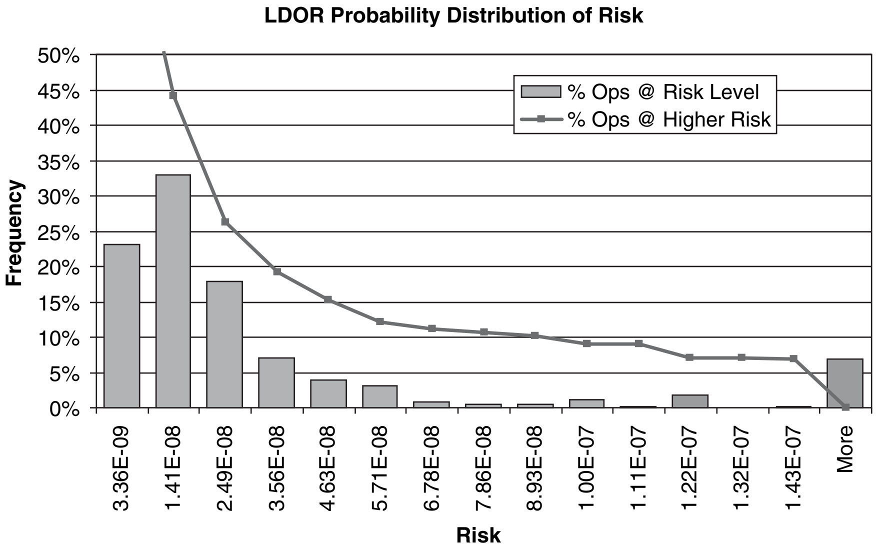


Figure 37. Typical frequency distribution of risk from prototype software.

Step 7—Total Percentage of Operations with Risk Above TLS

The three probability distributions (LDOR RWY 07, LDUS RWY 25, and TOOR RWY 07) can be combined to provide an overall probability distribution that a serious accident will occur in the specific RSA. The percentages for each cell should be weighted relative to the traffic for each type of operation. A hypothetical example is presented to help understanding of the process.

Assuming these are the conditions for the airport being evaluated if the TLS is set to 1×10^{-6}, results for the approach end of Runway 25 are summarized on Table 16.

There are significant differences to risk levels for each operation, particularly noting that 34 percent of landings on Runway 07 have risk above the threshold level selected for this analysis. But there also are notable discrepancies in terms of exposure to visibility, ceiling height, and fog between landings on Runway 07 and those on Runway 25.

Over 30 percent of landings on Runway 07 take place in visibility under 2 statute miles, compared to 1.67 percent on Runway 25. In a related measure, almost 40 percent of landings on Runway 07 experienced fog versus less than 7 percent for Runway 25. Moreover, 39 percent of landings on Runway 07 took place in ceiling height under 1000 ft, while the equivalent for Runway 25 is only 3.9 percent.

These differences are most likely related to the airport's runway use policy. In fact, data on the airport's runway usage patterns revealed that landings on Runway 07 are relatively rare. It is reasonable to assume this runway is used for landings only for exceptional circumstances, such as adverse wind conditions, and this also would explain the discrepancy in risk exposure for landings on Runway 07 and Runway 25.

Using these numbers, the percentage operations with risk above the TLS and challenging the RSA being evaluated can be estimated as follows:

$$\% > TLS = \frac{(0.073 \times 0.34 + 0.09 \times 0.01 + 0.3 \times 0.02)}{(0.073 + 0.09 + 0.3)} = 6.9\%$$

Based on the annual number of operations at the airport, the analysis also can be used to estimate the annual rate of accidents or the number of years likely to take for a severe accident to occur. These are useful parameters as they allow comparing different RSAs of the same or different airports to identify and prioritize the RSAs requiring risk management actions or improvements.

Steps 8 and 9—Repeat the Analysis for Other Runway Ends

In repeating the analysis for the remaining runway ends of the same airport, it is possible to evaluate which RSA poses

Table 16. Summary results for hypothetical airport.

Operation	% of Movements	Ops @ High Risk	Sample Size
Landing on RWY 07	7.3%	34%	487
Takeoff on RWY 07	9.0%	1%	606
Landing on RWY 25	30.0%	2%	2020

Table 17. Summary risk for hypothetical airport.

RSA	Annual Ops Challenging RSA	%Ops>TLS	Annual Ops w/ Risk Above TLS
Approach End RWY 11	300,000	6%	18,000
Approach End RWY 29	160,000	7%	11,200
Approach End RWY 03	410,000	1%	4,100
Approach End RWY 21	40,000	14%	5,600

higher risk during the year. The assessment may help improve runway use so that risk is minimized for the airport. To compare different RSAs, it is preferred to use a parameter that can provide a direct comparison. One possibility is to transform the percentage of operations above TLS into a volume of annual operations above TLS by multiplying the percentage by the volume of flights challenging the specific runway end. Using such a parameter, it is possible to compare multiple RSAs of the same airport, or even for different facilities, to determine and prioritize which RSAs may require risk mitigation actions.

Using another hypothetical example, the following parameters can characterize the conditions for an existing airport having two runways: 11/29, and 03/21.

In Table 17, the approach end for Runway 11 has a higher number of annual operations with risk above the selected TLS. A number of risk mitigation measures may be prioritized to improve safety for such area. Some safety management alternatives may include modifying runway use for the airport, installing new NAVAIDS, or improving the RSA, among other procedures.

CHAPTER 5

Conclusions and Recommendations

Current standards for RSAs are fairly rigid as they depend only on the type and size of aircraft using the runway. However, numerous factors affect the operations that may lead to aircraft overruns and undershoots. In reality, operations are carried out under varying levels of safety.

This study introduces a more comprehensive approach to evaluate the degree of protection offered by a specific RSA and provides a risk-based assessment procedure that is rational and accounts for the variability of several risk factors associated with aircraft overruns and undershoots. In addition this study provides risk models that are based on comprehensive evidence gathered from aircraft accidents and incidents in the United States and other countries. Information gathered from these events has been organized into a database that may be used for future studies on airport risk assessment. Moreover, the basic approach utilized in this research can be used to model other types of accidents occurring near airports, particularly for veer-off and takeoff and crash accidents.

Existing and new techniques were integrated into a practical approach that uses NOD and normalization procedures. Incorporating NOD allows the user to account for different aircraft flight risk exposure to assess the criticality of risk factors. Although with some limitations, the normalization procedures increased the pool of comparable data for model development.

Despite some limitations on availability of information to develop the models presented in this report, the models provide useful information and are integrated in a practical approach that will be useful for RSA planning and airport safety management. Prototype software also was developed as part of this effort and serves to verify how the several models interact and determine risk probability distributions for an RSA subject to specific conditions.

Major Achievements

Development of Accident and Incident Database

One of the accomplishments of this study was the development of a comprehensive and organized database of accidents and incidents. It includes the information gathered for events involving aircraft LDORs, LDUSs, and TOORs. The database has editing and querying capabilities, and includes most parameters associated with the events, including aircraft, airport, runway, operation, causal factors, and consequence information used in the modeling process and can be used for future studies on airport safety. The database overcame the lack of depth of many accident databases developed in previous studies.

Analysis of the database revealed which anomalies are more frequent for each type of incident and the factors contributing to these events that would be desirable to incorporate in the modeling process.

Frequent Anomalies in Aircraft Overruns and Undershoots

When possible, the anomalies present during the occurrences were listed for each accident and incident included in the database. Most of these anomalies were taken from accident investigation report lists of causal and contributing factors; however, other anomalies were listed, even when not included in the report if they were present during the occurrence.

These anomalies were summarized by type of event and by severity of the event. The summary provided is useful to help airport operators understand how these factors may lead to accidents, and it helped to identify those factors more frequently associated with aircraft overrun and undershoot events. Whenever possible, these factors were incorporated in the modeling approach.

Normal Operations Database

Another achievement in this research is the availability of a normal operations database for U.S. flight operations. The NOD sample comprising 242,420 flights is a representative sample of 95.8 percent of flights in the United States and covers the great majority of airport types, geographical regions, and operational and meteorological parameters. The development of this database was crucial in quantifying and characterizing accident risk factors, as well as the development of accident frequency models. In addition, the NOD provides an assessment of flight risk exposure and may be used for future studies on airport and runway safety.

Development of Risk Models for RSA

Each set of models includes one model for frequency and two models for location: one developed from raw distance data and one based on normalized distance data. A rational approach was developed to model severe consequences and serves for any of the model sets.

These models incorporate several risk factors identified for each type of accident. These include a range of meteorological conditions, operational parameters, and existing features and obstacles present in the RSA and its surroundings. In addition the approach allows consideration of multiple risk factors in a single model that accounts for their joint influences on accident likelihood. Consequently, the models developed have substantially improved predictive power, with enhanced sensitivity and specificity, versus existing regulations based on a small number of risk factors.

Integrated Practical Approach

This study also brings a new rational and probabilistic approach to integrate the frequency and location models for evaluation of the likelihood of an accident with severe consequences. The approach accounts for the variability and risk exposure relative to various factors and provides a probabilistic assessment of risks.

The output of the risk assessment is a probability distribution of risks for an existing RSA subject to specific meteorological and operation conditions. As a result, it is possible to evaluate quantitatively the overall risk of accidents for a particular runway and associated RSA.

Prototype Software

Running a risk assessment for a specific RSA using the approach developed in this study requires extensive calculations. A sample of NOD for the runway must be representative of the traffic occurring in the airport during at least one year so that it covers different meteorological conditions for the airport. In addition, depending on judgment by the analyst, there may be multiple crash scenarios and these will require modeling for each of these situations.

To facilitate these computations, software that incorporates models developed in this study was developed. The software allows one to enter existing RSA conditions and a sample NOD for each type of operation that may challenge the RSA to run the analysis for an existing obstacle. Appendix O describes the prototype software developed for this project and shows some screens, and input and output parameters.

Model Limitations

Modeling aviation risks always has been a challenge. Accident and incident reports often lack quantitative information for causal factors of overrun and undershoot accidents. The large quantity of causal factors and the scarceness of reliable data limits the accuracy of models developed. Modeling consequences still depend on some judgment from the analyst. In this study it was not possible to make more solid recommendations on how to treat the obstacle/aircraft interaction and how much energy is required to cause severe consequences during the impact.

Most likely, airport operators may need expert help to make correct use of the models developed in this study, but they should be able to use them effectively with the help of a risk assessment professional. The modeling approach on its own is not enough to allow anyone to perform a risk analysis for RSAs. The assessment of risk associated with overrun and undershoot events has to be placed in some context, a process to be followed by airport operators that will support their risk management decision making.

A review of existing databases has shown that deviation data for air operations are generally sparse, particularly for reporting of relevant details on incidents (more detailed data generally are available for accidents). Collection of NOD was a challenge, particularly to counteract the impossibility of accessing the flight operation quality assurance (FOQA) database from the airlines.

The models and approach developed in this study can be helpful for airport planning and safety management RSA improvement actions. However, under no circumstances should the models developed in this research be used to assess real-time operational risks. There are several factors not accounted for in the models and their accuracy is not appropriate for decision making during actual operations or emergency situations.

Recommendations for Future Work

Improved Normal Operations Data

Collecting normal operations data for parameters not covered in this study would greatly help to improve the approach developed in this study. Some of the factors, although considered important to modeling aircraft overrun and undershoot events, were not available from the NOD sources used in this study. Of particular importance are: the runway criticality, the presence of tailwind and the runway friction during the operation. Information on these factors could not be obtained from the ETMSC and ASPM databases.

Incorporation of these factors would certainly improve the predictive performance of the models and enhance the overall accuracy of the risk assessment. Airline flight data recorder (FDR) information is especially relevant to obtain information on runway criticality but access to such data will require the cooperation of airlines and industry organizations.

Even if data from FDRs are not available, the runway criticality factor may be incorporated in the models using the basic distances required for operation of each aircraft type. Although this improvement was identified in the course of this research, time and financial resources constraints did not allow the incorporation of such factors in the present models.

Availability of Information for Accidents and Incidents

Accident investigation and incident reports seldom contain the comprehensive information required to improve modeling. Even when there are standard forms and reports, many of the existing fields are not filled by the reporter. In addition, some important parameters associated with events relevant to this study are not available in the standard forms, or the investigator is not aware of their importance for modeling risks. Of particular interest is the runway distance required for landing or takeoff. Without such information or the parameters (e.g., actual weight at crash) required to compute the distances of interest, it becomes difficult to assess the runway criticality.

Precise wreckage path, location exiting the runway, and final wreckage location are rarely reported, even for accidents. Details on the type of obstacle, its dimensions and location are seldom reported. Therefore, it is important to develop more comprehensive guidance related to the parameters required to improve risk modeling in the future. A list of suggested parameters to report is presented in Appendix N.

It should be noted that the availability of information on accidents and incidents will only be helpful if these parameters also are available in NOD.

Development of Comprehensive Software

The prototype software developed for this project is fairly simple and allows risk assessment of RSA using sample NOD for different types of operation challenging a specific RSA. However, there are limitations, as resources constrained the development of more comprehensive software. The risk assessment is performed for each type of accident separately and does not integrate the results to obtain the overall risk. Moreover, the analysis system is capable of evaluating one simple and rectangular-shaped RSA or one existing obstacle. Although the analysis of other shapes and multiple obstacles is possible, each comprises one single analysis that will require integration to be performed manually.

Data normalization is still limited to one type of terrain. Ideally, the analysis should include multiple sections with different terrain conditions and possibly the capability to evaluate risks when Engineered Material Arresting Systems are available in the RSA.

Development of Onboard Real-Time Models

One of the products of this research is a summary of factors or anomalies frequently present during aircraft overruns and undershoot. Some of these factors may greatly help pilots making good decisions about attempts to go around if the information and risk processing capabilities are provided in real-time. If onboard computers could process real-time information, like approach speed, height above threshold, touchdown location, wind, and braking capability based on actual aircraft deceleration to estimate remaining distance required compared to distance available, an effective warning system could be provided by aircraft manufacturers to advise pilots on the best emergency procedure (e.g., go around) to prevent many undesirable events.

References

AEA Technology. *London City Airport: Runway End Safety Area (RESA) Studies*. London City Airport, February 2002.

AEA Technology. *Runway End Safety Area (RESA) Risk Assessment at Southampton International Airport*.UK Airport Operator BAA, March 1999.

Airbus. *Takeoff and Departure Operations—Understanding Takeoff Speeds, Flight Operations Briefing Notes*. August 2004.

Aircraft Bluebook Price Digest. Overland Park, KS: Primedia, Summer 2003.

Aircraft Hazards. Section 3.5.1.6, Standard Review Plan, Report No. NUREG-0800. Nuclear Regulatory Commission, Washington, D.C., 1981.

Airport Design. AC 150/5300-13. Federal Aviation Administration, September 1989.

Air Traffic Organization Safety Management System Manual, Version 2.0 (Draft). Federal Aviation Administration, March 2006.

Ale, B. and Piers, M. The Use of Risk Information for the Development of a Safety Policy Around Airports. Safety Engineering and Risk Analysis (SERA) technical sessions. ASME, Vol. 10, 2000, pp.51–58.

Ale, B., Smith, E. and Pitblado, R. Safety Around Airports—Developments in the 1990s and Future Directions. Presented at IBC Conference.

Annex 14 to the Convention on International Civil Aviation–Airfields–International Standards and Recommended Practices, 3rd edition ed. Vol. I Aerodrome Design and Operations. International Civil Aviation Organization, Montreal, Canada, 1999.

Appleyard, A., Caves, R., Pitfield, D., and Wong, K. Normalization of Aircraft Accident Data. Presented at Air Transport Research Society World Conference, Nagoya, Japan, May 2006.

Ash, A. and Schwartz, M. R2: A Useful Measure of Model Performance When Predicting a Dichotomous Outcome. *Statistics in Medicine*, 18(4), 1999, pp. 375–384.

Boeing Commercial Airplanes. *Statistical Summary of Commercial Jet Airplane Accidents—Worldwide Operations 1959-2004.* May 2005.

California Airport Land Use Planning Handbook. Division of Aeronautics, California Department of Transportation, January, 2002.

Caves, R. Control of Risk Near Airports. *Built Environment*, Vol. 22, No. 3, 1996, pp. 223.

Caves, R. and Gosling, G.D. *Strategic Airport Planning*. Pergamon, Oxford, England, 1999.

Cowell, P., Foot, P., Gerrard, R., Kent, D., Mason, S., and Rivoire, A. A Method for Calculating Individual Risk Due to Aircraft Accidents Near Airports. R&D Report 0007. National Air Traffic Services, London, 2000.

Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries. FAA Publication No. FHWA-HRT-05-051. Federal Aviation Administration, October 2005.

David, R. *Location of Aircraft Accidents/Incidents Relative to Runways*. DOT/FAA/AOV 90-1. Office of Safety Oversight, Federal Aviation Administration, 1990.

DeGroh, B. Rink or Runway? *Air Line Pilot,* November/December, 2006, pp.14–19.

Development of a Systems Risk Methodology for Single and Multi-Modal Transportation System. U.S. Department of Transportation, Washington, D.C., 1979.

Eddowes, M., Hancox, J., and MacInnes, A. Final Report on the Risk Analysis in Support of Aerodrome Design Rules. AEAT/RAIR/RD02325/R/002, Issue 1, Dec. 2001.

Eisenhut, D.G. Reactor Siting in the Vicinity of Airfields. *Transaction of the American Nuclear Society*. Vol. 16, 1973, pp. 210–211.

Enders, J., Dodd, R., Tarrel, R., Khatwa, R., Roelen, A., and Karwal, A. Airport Safety: A Study of Accidents and Available Approach-and-Landing Aids. *Flight Safety Digest*, Vol. 15, No. 3, 1996.

Flight Safety Foundation. ALAR Tool Kit. *Flight Safety Digest*, Vol. 19, No. 8–11, Aug-Nov 2000.

Flight Safety Foundation. Controlled Flight into Terrain Takes Highest Toll in Business Jet Operations. *Flight Safety Digest*, Vol. 23, No. 5, May 2004.

Flight Safety Foundation. Special FSF Report: Killers in Aviation: FSF Task Force Presents Facts About Approach-and-Landing and Controlled-Flight-into-Terrain Accidents. *Flight Safety Digest*, Vol. 17, No. 11–12, Nov.–Dec. 1998, Vol. 18, No. 1–2, Jan.–Feb. 1999.

GAIN Working Group B. Analytical Methods and Tools, Guide to Methods & Tools for Airline Flight Safety Analysis, June 2003.

Garbell, M. *Airport Accident Potential and Safety Areas*. M.G.G. Consultants, Inc., Society of Automotive Engineers, Inc., 1988.

Garson, G. *Logistic Regression: Statistical Notes from Quantitative Research in Public Administration*. North Carolina State University, Raleigh, 1998. www2.chass.ncsu.edu/garson/pa765/logistic.htm, accessed 22/01/07.

Giesman, P. Wet Runway, Physics, Certification, Application, Boeing Flight Operations Engineering. Presentation, 2005.

GRA Inc. *Economic Values for FAA Investment and Regulatory Decisions: A Guide*. Office of Aviation Policy and Plans, Federal Aviation Administration, Dec 2004.

Hagy, H. and Marthinsen, H. *Compilations of Accidents/Incidents Involving Runway Overruns/Undershoots/Veeroffs*. ALPA Accident

Investigation Department. Air Line Pilot Association, Washington D.C., 1987.

Hosmer, D. and Lemeshow, S. *Applied Logistic Regression*. John Wiley & Sons, Hoboken, New Jersey, 2000.

INECO. Informe de Riesgos Potenciales Aeropuerto de la Gomera, Spanish Airport Operator (AENA), AEA Technology, March 2006.

INECO. Informe de Riesgos Potenciales Aeropuerto de los Rodeos (Tenerife Norte), Spanish Airport Operator (AENA), AEA Technology, July 2005.

INECO. Informe final de riesgos Aeropuerto de La Palma, Spanish Airport Operator (AENA), AEA Technology, March 2004.

Jerris, E., Gerafola, J., Dagen, H., and Brady, F. *Analysis of Safety Aspects of Aircraft Landing Operations*. Final Report 238-01-3-392. ARINC Research Corporation, Annapolis, Maryland, 1963.

Khatwa, R. and Helmreich, R. Analysis of Critical Factors During Approach and Landing in Accidents and Normal Flight. *Flight Safety Digest*. Vol. 17, No. 11–12, November 1998, Vol. 18, No. 1–2, February 1999, pp. 1–77.

Khatwa, R., Roelen, A.L., Karwal, A.K., Enders, J.H., Dodd, R., and Tarrel, R. *An Evaluation of Approach Landing Factors Influencing Airport Safety*. NLR-TP-96221U. Dutch National Aerospace Laboratory NLR, Amsterdam, Netherlands,1996.

Kimura, C., Bennett, C., Sandquist, G., and Smith, S. Aircraft Accident Data Development for Aircraft Risk Evaluation to Ground Facilities Through the Use of G.I.S. *Proc., ASME Joint Pressure Vessels & Piping Conference*, Honolulu, Hawaii, Vol. 256, 1994, pp. 493–513.

Kirkland, I. *The Risk Assessment of Aircraft Runway Overrun Accidents and Incidents*. PhD thesis. Loughborough University, United Kingdom, 2001.

Kirkland, I., Caves, R.E., Hirst, M., and Pitfield, D.E. The Normalization of Aircraft Overrun Accident Data. *Journal of Air Transport Management*, Vol. 9, No. 6, 2003, pp. 333–341.

Kirkland, I.D., Caves, R.E., Humphreys, I.M. and Pitfield, D.E. An Improved Methodology for Assessing Risk in Aircraft Operations at Airports, Applied to Runway Overruns. *Safety Science*, Vol. 42, No. 10, 2004, pp. 891–905.

Landing Performance Assessments at Time of Arrival (Turbojets). *Safety Alert for Operators*. Flight Standards Service, Federal Aviation Administration, 2006.

Li, G.I., Baker, S.P., Grabowski, J.G., and Rebok, G.W. Factors Associated with Pilot Error in Aviation Crashes. *Aviation, Space, and Environmental Medicine*, Vol. 72, No. 1, 2001, pp.52–58.

Manchester Airport Runway End Safety Assessment. Engineering, Safety & Risk (ESR) Technology, January 2007.

Manual on the Use of the Collision Risk Model (CRM) for ILS Operations, 1st edition. Doc 9274-AN/904. International Civil Aviation Organization, Montreal, Canada, 1980.

Menard, S.W. *Applied Logistic Regression Analysis*, 2nd edition. Sage University Papers Series on Quantitative Applications in the Social Sciences, 07-103. Sage, Thousand Oaks, Calif., 2001.

Myers, R. *Classical and Modern Regression with Applications*, 2nd edition. Duxbury, Boston, 1990.

Nagelkerke, N., Smits, J., Le Cessie, S., and van Houwelingen, H. Testing the Goodness-of-Fit of the Logistic Regression Model in Case-Control Studies Using Sample Reweighting. *Statistics in Medicine*, Vol. 24, 2005, pp.121–130.

Pampel, F. *Logistic Regression: A Primer*. Sage University Papers Series on Quantitative Applications in the Social Sciences, 07-132. Sage, Thousand Oaks, Calif., 2000.

Piers, M. The Development and Application of a Method for the Assessment of Third Party Risk Due to Aircraft Accidents in the Vicinity of Airports. *Proc., 19th International Council of Aeronautical Sciences Congress*, Anaheim, Calif., Vol. 19, 1994, pp.507–518.

Piers, M. Methods and Models for the Assessment of Third Party Risk Due to Aircraft Accidents in the Vicinity of Airports and Their Implication for Societal Risk. Presentation at a Workshop on Societal Risk, Utrecht, Netherlands, May 22-23, 1996.

Piers, M., Loog, M., Giesberts, M., Moek, G., Couwenberg, M., and Smeets, M. The Development of a Method for the Analysis of Societal and Individual Risk Due to Aircraft Accidents in the Vicinity of Airports. NLR-CR-93372L. Dutch National Aerospace Laboratory NLR, Amsterdam, Netherlands, 1993.

Pikaar, A.J., Piers, M.A., and Ale, B. External Risk Around Airports: A Model Update. NLR-TP-2000-400. Dutch National Aerospace Laboratory NLR, Amsterdam, Netherlands, 2000.

Risks from Aeroplanes Overrunning Aerodrome Runways. United Kingdom Civil Aviation Authority Edition 1., London, 1998.

Roelen, A., Bellamy, L., Hale, A. Molemaker, R., and van Paassen, M. A. Causal Model for the Assessment of Third Party Risk Around Airports. Ministerie van Verkeer en Waterstaat, Programmadirectie Ontwikkeling Nationale Luchthaven, April, 2000.

Safety In and Around Airports. European Transport Safety Council, Brussels, Belgium, 1999.

System Design and Analysis. AC 25.1309-1A. Federal Aviation Administration, June 1988.

Tabachnick, B. and Fidell, L. *Using Multivariate Statistics*. Harper Collins, New York, 1996.

Third Party Risk Near Airports and Public Safety Zone Policy. Department for Transport, London, 1997.

Winn, R. Probing the Causes of Aircraft Accidents. *Aerospace America*. American Institute of Aeronautics and Astronautics, September, 2006.

Wong, D. *The Modeling of Accident Frequency Using Risk Exposure Data for the Assessment of Airport Safety Areas*. PhD thesis. Loughborough University, United Kingdom, 2007.

Wong, D., Appleyard, A., Caves, R., and Pitfield, D. An Approach to Airport Risk Assessment Using Normal Operations Data with Bootstrapped Logistic Regression. Presented at 44th Annual Meeting of the Western Regional Science Association, San Diego, Calif., Feb 2005.

Wong, D., Appleyard, A., Caves, R., and Pitfield, D. The Development of Models of the Frequency of Aircraft Accidents Near Airports. Presented at 9th ATRS World Conference, Rio de Janeiro, Brazil, July 2005.

Wong, D., Pitfield, D., Caves, R., and Appleyard, A. Identifying and Quantifying the Criticality of Aviation Accident Risk Factors. Presented at Air Transport Research Society World Conference, Nagoya, Japan, May 2006.

APPENDICES

Appendices to the contractor's final report for ACRP Project 04-01, "Aircraft Overrun and Undershoot Analysis for Runway Safety Areas," are available on the TRB website at http://trb.org/news/blurb_details.asp?id=8928. The appendices are the following:

Appendix A: Understanding Aircraft Overruns and Undershoots
Appendix B: Functional Hazard Analysis
Appendix C: Key Accident/Incident Database Sources
Appendix D: Analysis of Unreported Incidents
Appendix E: List of Accidents for Model Development
Appendix F: Database Rules
Appendix G: Normal Operations Data
Appendix H: Sampled Airports
Appendix I: Stratified Sampling Strata and Weights
Appendix J: Calculation of Relevant Terminal Area Forecast Traffic
Appendix K: Normalization Procedures
Appendix L: Direct Costs of Accidents
Appendix M: Results for Multivariate Logistic Regression
Appendix N: Recommended Reported Information
Appendix O: Prototype Software for RSA Risk Assessment

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation