The Modelling of Accident Frequency Using Risk Exposure Data for the Assessment of Airport Safety Areas

By

Ka Yick WONG

A Doctoral Thesis
Submitted in partial fulfilment of the requirements
for the award of

The Degree of Doctor of Philosophy
of Loughborough University

March 2007

ABSTRACT

This thesis makes significant contributions to improving the use of Airport Safety Areas (ASAs) as aviation accident risk mitigation measures by developing improved accident frequency models and risk assessment methodologies. In recent years, the adequacy of ASAs such as the Runway End Safety Area and Runway Safety Area has come under increasing scrutiny. The current research found flaws in the existing ASA regulations and airport risk assessment techniques that lead to the provision of inconsistent safety margins at airports and runways.

The research was based on a comprehensive database of ASA-related accidents, which was matched by a representative sample of normal operations data, such that the exposure to a range of operational and meteorological risk factors between accident and normal flights could be compared. On this basis, the criticality of individual risk factors was quantified and accident frequency models were developed using logistic regression. These models have considerably better predictive power compared to models used by previous airport risk assessments.

An improved risk assessment technique was developed coupling the accident frequency models with accident location data, yielding distributions that describe the frequency of accidents that reach specific distances beyond the runway end or centreline given the risk exposure profile of the particular runway. The application of the proposed methodology was demonstrated in two case studies. Specific recommendations on ASA dimensions were made for achieving consistent levels of safety on each side of the runway. Advances made in this study have implications on the overall assessment and management of risks at airports.

Key words: Airport risk assessment, aerodrome design, airport land-use planning, aircraft accidents, third party risk, risk exposure, accident frequency model, logistic regression

ACKNOWLEDGEMENTS

The completion of this research is a personal milestone marked by the support, patience and inspiration of many others. Some accompanied me throughout the journey, others just sections of the way. For others still, the project was only a short leg of a grand voyage together. All played their part.

My gratitude goes first to my supervisors Dr. David Pitfield and Dr. Bob Caves, without whose expert advice and guidance this research would never come to be. Their readiness to provide direction and encouragement never waned for the past three and a half years. They made the project possible, successful and enjoyable. I also thank David for his enthusiasm for result dissemination, which took me to exotic locations from Tijuana to Niteroi. Those were special times and will be treasured. I am also grateful to Bob for supervising my PhD, which was beyond his duty.

I would also like to thank Andrew Appleyard for helping with the accident database and any computer problems. My appreciation extends to Dr. Ian Humphreys and Mike Hirst, who helped in the early stages of the study. Thanks are also due to the EPSRC for funding the project.

A number of friends and former colleagues in the United States also went beyond their obligations in support of this work. I would like to thank Dick Marchi at ACI-NA for backing this project as well as providing me with contacts and the opportunity to present at his meetings. Steve Cornell at San Diego International Airport and Bonnie Wilson at Jackson-Evers International Airport must also be thanked for assisting me in my quest for aircraft weight data. Thanks must equally be expressed to individuals at JetBlue, ExpressJet, General Microfilms Inc., NTSB, GAIN, FAA, NOAA and NASA for providing me with valuable information. Back in Loughborough University, I would like to thank Dr. Richard Gadsden and Prof. Paul Chung for answering my many questions on statistics, logistic regression and artificial intelligence.

My gratefulness also goes to the brothers and sisters of LCCF who treated me like a true sibling. Their friendship, care and concern spurred me on countless times and they brought so much laughter and fun to my numerous years in Loughborough.

In addition, I would like to thank Tina for cheering "add oil!" during the write-up and above all for her companionship despite my weaknesses and flaws. Finally, my utmost gratitude belongs to my parents, who never cease to unconditionally support me, without question or pressure. They help me cut through waves of the grand voyage.

"...FOR HE WENT OUT, NOT KNOWING WHITHER HE WENT,
BUT KNOWING WHOM HE FOLLOWED
AND UNDER WHOSE DIRECTION HE WENT."
Matthew Henry Bible Commentary for Genesis 12:4-5

CHAPTER 1 INTRODUCTION

1.1 Research Background & Justification

The airlines are estimated to carry 2.2 billion passengers and almost 40 million tonnes of freight in 2006 (IATA 2006). Meanwhile, air travel has preserved its title as the safest form of mass transport (Muir & Thomas 2004). The hull loss rate of 2005 is a remarkable 0.76 per million sectors flown (IATA 2006). There was less than one fatal accident per five million flights between 2002 and 2005 in US commercial aviation (GAO 2005a).

Growth in the aviation sector is expected to continue for the years to come. By 2015, commercial aviation in the United States alone is projected to carry one billion passengers (FAA 2006a). International passenger traffic is estimated to grow 5.6 percent annually between 2005 and 2009 (IATA 2005). If the industry is to sustain its expansion, one of the challenges that must be met is maintaining its excellent safety record.

The majority of accidents occur at or near airports (Cowell et al. 1997). Hale (2002) reports that some 70 percent of crashes take place close to airports while Ashford (1998) found 90 percent of aviation accidents occur during phases of flight related to take-off and landing. For the worldwide commercial jet fleet, 69 percent of accidents and 42 percent of fatalities between 1996 and 2005 occurred during the take-off, initial climb, final approach and landing phases of flight (Boeing 2005). The European Transport Safety Council also highlighted the concentration of aircraft accidents in climb and approach (ETSC 1999a). Appropriate protection and mitigation measures for these types of accidents and their consequences would translate into a significant improvement in aviation safety as a whole. Chapter 2 provides more detailed descriptions and statistics on each of the accident types concerned.

1.2 Growing Pressures

With the industry-wide implementation of Safety Management Systems, there is a growing need to improve the management of safety at airports. The following developments add to the pressure to examine current risk mitigation policies.

1.2.1 Traffic growth vs. safety improvement

Aviation worldwide expects robust growth in the years to come (IATA 2005). The US air transport system is expected to carry one billion passengers by 2015 (FAA 2006a). If the accident rate does not improve, traffic growth alone will increase the absolute number of accidents to an extent unacceptable to the public and regulators within the foreseeable future (Roelen et al. 2004, Simmons & Forrest 2005, ICAO 2006, Lee 2006). Because of the increase in flights, it is projected that there will be 23 fatal approach and landing accidents worldwide annually by 2010 (CAST 1999). The US has a goal of reducing the commercial fatal accident rate to 0.010 per 100,000 departures by 2007. If applied to the forecast traffic of 2025, there would still be ten accidents per year (Fiorino 2005).

Despite the very low accident rate, it is nonetheless the frequency of accident occurrence and their absolute number which the public uses as the yardstick for safety (Hayes 2003). The average person rarely considers the increase in exposure due to the growing number of flights (FAA 1997). In order to maintain public confidence, the accident rate must improve in line with traffic growth (CAA 1998, Hayes 2003). Unfortunately, there are signs of slowing safety improvement in aviation. The reduction of accident occurrences and the decline in accident rate appear to be slowing and stabilising (Raghavan & Rhoades 2005).

1.2.2 Capacity needs

With rising traffic levels, many airports have plans to increase capacity. Extra capacity at the busiest airports in Europe and America is likely to have significant impacts on the level and distribution of risk near airports. In the past, demand for more capacity has already led to more over-flights of residential areas, increasing third party risk (Eurocontrol 2005). New aerodrome designs, such as the End-Around Taxiway which runs around runway ends now installed at Atlanta-Hartsfield International Airport and Dallas-Fort Worth International Airport in the US, introduce new risks to the system.

1.2.3 Development encroachment

As airports expand in size, communities are also spreading out towards them. Van Nuys Airport, California was in the middle of orange groves in the 1940s and 1950s but urban development now fills the seven mile radius of the airport (Esler 2006). With no more room for expansion and thousands of homes and businesses surrounding it, airport and community now sit cheek by jowl. Other airports, such as Lowell Airport in Michigan, tell of developers overpowering town planners to build in close proximity to runways (Avweb 2005). Airports tend to attract corporate real estate too. From East Midlands Airport, UK to Hong Kong International Airport, business parks are increasingly located near runways. These developments have consequences on risks (ETSC 1999b, Ale & Piers 2000a, State of California 2002). Third party risk exposure mounts as communities and airports draw closer to one another.

In the Netherlands, the policy of capping third party risk at 1990 levels at Amsterdam Schiphol Airport has already failed because of the growth in traffic and employees in the area (Post et al. 2006). Instead, societal risk – one of the measures of third party risk – has almost doubled between 1990 and 2006. It is expected that large airports will have increasing difficulty in meeting standards on third party risk (Caves 1996).

1.3 Research Aims

The provision of airport safety areas (ASAs), such as the Runway End Safety Area (RESA) and Public Safety Zone (PSZ), is a crucial element of risk mitigation against near-airport aviation accidents. However, the development of some of these areas lacks substantial research and defendable analysis, relying more on historical precedent and qualitative expert judgement (Kirkland et al. 2003a). The aim of this thesis is to improve the effectiveness of ASAs as a means of managing risks related to aircraft accidents near airports. The overall concern of this work, then, centres on developing a more risk-based, flexible and effective strategy of risk mitigation by airport safety areas.

The primary objective of this study is to build a predictive model of the occurrence of landing and take-off accidents at or near airports. The model would be capable of discriminating between airports of different risk levels to the extent that is significant for the formulation of ASA policies. This contributes to the development of an improved tool for airport risk assessment. The focus of the study has been placed on the probability of accident occurrence, rather than the accident location or consequence, because understanding accident frequency is not only essential to risk management (GASR undated) but it is also the first and prerequisite step to a full risk assessment exercise.

Another key objective of this study is the development of a comprehensive database of all accidents associated with ASAs. For its depth and breadth, it would be the definitive resource for current and future ASA risk analyses.

A representative database of normal operations' risk exposure is also to be generated to provide unprecedented insight into non-incident flights' exposure to a multitude of meteorological and operational risk factors.

Combining the strengths of the accident and normal operations databases, this thesis aims to quantify the criticality of a range of risk factors as well as the risk of accident occurrence at particular airports according to their exposure to specific risks.

Additionally, this study reviews the current approach to risk management in aerodrome design and ASA policies in light of the industry's adoption of risk-based safety management. Then, in view of the risk assessment technique developed, it suggests policy options that would assist the industry to conform with the prevailing philosophy of safety management.

1.4 Thesis Structure

The next chapter provides a more detailed account of the risks related to the take-off and landing phases of flight.

Chapter 3 reviews the existing risk mitigation measures and gives an account of the issues surrounding regulatory compliance and the intrinsic deficiencies of the present risk mitigation regime.

Chapter 4 presents the fundamental characteristics of the Safety Management System, which is gaining industry acceptance as the standard framework for safety oversight. This chapter highlights the role of risk assessment and explains the need for improved methodologies of assessing risks.

Chapter 5 considers former airport risk assessment studies, including their main concerns, analytical approaches and key shortfalls. This provides the context in which the current research is carried out.

Chapter 6 presents the proposed risk assessment methodology, justifies the chosen approach and highlights the advances made. The chapter also sets out the structure of the subsequent analysis and modelling work.

Chapter 7 describes the development of a comprehensive database of ASA-related accidents while Chapter 8 presents the analysis of this database, highlighting accident trends as well as differences between accident types.

Chapter 9 explains the development of the normal operations database, including the data sources, sampling strategy as well as the extensive efforts spent on ensuring that it is compatible with the accident database.

Chapter 10 details the bivariate analysis using accident and normal operations data to quantify and characterise the criticality of individual risk factors. The differences in risk exposure between accident and normal flights were extensively compared using a number of statistical techniques.

Chapter 11 presents the development of accident frequency models using logistic regression. The choice of the statistical procedure, the form and coefficients of the four risk models and their respective goodness-of-fit and predictive performance are discussed.

Chapter 12 considers the distribution of accident wreckage locations based on the comprehensive database described in Chapter 7. This is an essential step before the application of the accident frequency models for risk assessment.

Based on two case study airports, Chapter 13 demonstrates how the accident frequency models could be used for practical airport risk assessment along with the accident location distributions. Recommendations on ASA needs for each of the runways in the case studies are included.

The thesis concludes with Chapter 14, which reviews the major breakthroughs of the study including their significance and implications. The limitations of the work and avenues of further research are also discussed.

1.5 EPSRC Project & Responsibilities

The research of this thesis was carried out within the context of a broader project funded by the UK Engineering and Physical Sciences Research Council (EPSRC). While a research team was responsible for completing the EPSRC project, the work described in this thesis was undertaken solely by the author, with the exception of the development of the accident database, which was a joint-effort as described in Chapter 7. The present author had sole responsibility over the literature review, collection of normal operations data, all data analysis, subsequent modelling, model application and the reporting of the research.

1.6 Prior Publications and Presentations

Parts of this thesis have been previously published in preliminary form (Wong et al., 2006a, 2006b). Presentations have also been made at academic as well as industry conferences (Wong et al. 2005a, 2005b, 2005c, 2006c, 2006d, 2006e, 2006f).

CHAPTER 2 THE RISKS

2.1 Safety vs. Risk

Safety is more a construct or concept than a quantifiable entity (Rose 2005). One considers relative safety rather than absolute safety (State of California 2002, ICAO 2006). Research in safety, then, relies on the notion of risk, which could be measured (Lowrance 1976). The US Federal Aviation Administration (FAA) defines "safety risk" as a measure of probability and impact (Rose 2005). This thesis focuses on the probability of occurrence of accidents at airports and their vicinity, which are described in more detail in the remainder of this chapter.

2.2 Accidents at and near airports

A commercial aircraft spends only about six percent of its flight time in the take-off, initial climb, final approach and landing phases of flight. Nonetheless, approximately 70 percent of hull loss accidents occur during these stages of operation (FAA 1997).

Approach and landing accidents have come under the industry's scrutiny for some years. The Flight Safety Foundation (FSF) identified approach and landing accidents (ALAs) as the primary cause of fatalities in aviation along with controlled-flight-into-terrain (Khatwa et al. 1998). The approach and landing phase of flight begins at descent and continues though the landing or missed approach procedure (CAST 1999). From 1980 to 1996 there were 287 ALAs involving jet and turboprop aircraft (MTOW>12500 lbs), resulting in 7185 fatalities (Ashford 1998). It is understood that approach and landing is the most unforgiving and stressful phase of flight for pilots because of the high information load and the numerous tasks that must be handled simultaneously (Fitzgerald 1998, Van Es et al. 2001).

Take-off accidents deserve much attention too. Although they occur less frequently than ALAs, their consequences in terms of fatalities and aircraft damage tend to be more serious. Research comparing landing and take-off incidents confirms this (David 1990, CAA 1998, Eddowes et al. 2001, Kirkland 2001a).

Take-off and landing accidents comprise of several sub-categories of occurrences – overruns, veer-offs, undershoots, crashes after take-off and third-party accidents. These are now considered in turn.

2.2.1 Overruns

According to the FAA, an overrun occurs when an aircraft passes beyond the end of a runway during an aborted take-off or while landing (FAA 1989). The United Kingdom's Civil Aviation Authority (CAA) similarly considers an aircraft to have overrun a runway if its ground run on take-off or landing extends beyond the distance that has been declared by the aerodrome as suitable for that purpose (CAA 1998). In a FAA study, aircraft that veer-off the side of the runway but come to rest beyond the departure end of the runway are also included as overruns (David 1990).

There are an average of ten aborted take-off or landing overruns at US airports every year (Croft 2004). During thirty years of jet transport service up to 1992, 46 accidents and 28 potentially serious incidents have occurred due to overruns during rejected take-offs alone, resulting in over 400 fatalities (Boeing 1992). In the UK, there were 26 overruns involving civilian, fixed-wing aircraft over 5700kg MTWA between 1976 and 1996 (CAA 1998). Even though the overall accident rate of aircraft operations have fallen significantly in the past three decades, the rate of overruns has not improved over the same period (Kirkland et al. 2003b).

There are a number of prominent examples of aircraft overruns in 2005 alone. In February, a Challenger CL-600 business jet aborted its take-off at Teterboro Airport, New Jersey. It overran the end of the runway, crossed a six-lane highway, struck a vehicle and smashed into a warehouse, injuring twenty (Parry 2005, Rosero 2005). In August, Air France flight 358 overran the runway upon landing with 309 people on board at Toronto Pearson International Airport. The Airbus 340 aircraft stopped metres from Etobicoke Creek and burst into flames (Simmie et al. 2005).

2.2.2 Veer-offs

The FAA defines a veer-off as an aircraft running off the side of the runway during take-off or landing roll (David 1990). Veer-off accidents are closely related to overruns. In this study, the two are distinguished only by the aircraft's path of deviation. Instead of passing beyond the runway end as in an overrun, the veer-off aircraft leaves either side of the paved runway onto the surrounding runway strip. It involves greater lateral deviation from the runway centreline before reaching the end of the runway.

The combined frequency with which veer-off incidents occur during commercial flight landings and take-offs is estimated at 4.4×10^{-7} per movement (Eddowes et al. 2001).

Better known veer-off accidents include the case at Los Angeles International Airport, California in February 1991. USAir Flight 1493 was cleared to land on a runway which another aircraft occupied. The USAir Boeing 737 collided with the Southwest Metroliner and veered off the runway hitting an airport building, killing 22 (NTSB 1991).

2.2.3 Undershoots

An undershoot occurs when a landing aircraft contacts the ground or an obstruction prior to reaching the runway (Ashford & Wright 1992). However, there is no industry-wide agreement on how near the crash or wreckage site must be from the runway threshold to constitute an undershoot. A FAA study uses 2000ft as the cut-off point (David 1990).

The 1978 - 2000 average occurrence rate for commercial carriers is roughly 10^{-7} incidents per landing while the combined figure for commercial operations and air taxis is 2.5×10^{-7} (Eddowes et al. 2001). The fatality rate of undershoots has been found to be about twice as high as overruns (Ashford 1998).

Notable undershoot accidents include the British Midland Boeing 737, which crashed onto a highway embankment approximately 900m short of runway 27 of East Midlands Airport UK in 1989 with 46 fatalities (AAIB 1990).

2.2.4 Crashes after take-off

Crashes after take-off can be broadly defined as accidents that take place between an aircraft achieving lift-off and levelling off. Occuring after the take-off roll and during climb, crashes after take-off are usually high energy, high consequence events.

A recent example of crash after take-off occurred in August 2006. Comair Flight 5191 used the wrong runway for take-off at Lexington Blue Grass Airport, Kentucky. The CRJ-100 subsequently crashed about a mile from the airport with 49 fatalities (BBC 2006a).

2.2.5 Third party accidents

Third party accidents are those that cause injury or death to persons not involved in operating or taking that specific flight. Third parties of aviation accidents have little or no control over their exposure to risk (Brady & Hillestad 1995), which originate principally from living or working near airports. Since a large proportion of aircraft accidents occur near airports, areas in the vicinity of busy runways are subject to above average risk (Cowell et al. 1997). While not all accidents near airports result in third party injuries or deaths, all occurrences outside the airport boundaries have the potential of causing third party casualties.

European studies have found that, on average, every accident involves one third party death (Monk 1981, Caves 1996). In the UK, there was an average of 3.5 cases of "Falling Aircraft" per year between 1990 and 1999 (CAA 2000). These include all cases where an aircraft struck or ended up on third party property.

One of the most notorious accidents involving third party deaths is El Al Flight 1862 of October 1992. The Boeing 747 crashed in the suburban district of Bijlmer, Amsterdam, resulting in 43 third party deaths (Smith 1995). Earlier in December 1985, a Beechcraft Baron crashed into Sun Valley Mall in Concord, California, killing 84 shoppers (Kimura & Bennett 1993). More recently in December 2005, Southwest Flight 1248 overran the runway at Chicago Midway Airport, Illinois. The Boeing 737 crossed a fence onto a road, impacted a car and killed one of its passengers (BBC 2006b).

Awareness of aviation third party risk has increased throughout the 1990s, with growing concern in many European countries (Piers et al. 1993, ETSC 1999a). There is evidence emerging that the risk to people living near busy runways is comparable to the risk of living near chemical plants (ETSC 1999a, Hale 2001) or participating in road traffic accidents (Piers 1998a). If airports were governed by laws applied to industrial sites, substantial demolition of homes or other measures to reduce activity in airports' vicinity may be necessary (Ale & Piers 2000a). It is expected that this issue will continue to grow in importance to airports as well as nearby communities (Eurocontrol 2005).

CHAPTER 3 CURRENT RISK MITIGATION MEASURES

Given the prevalence of accidents occurring at and near airports, appropriate protection for these incidents and their consequences would translate into a significant improvement in aviation safety as a whole. This chapter gives an overview of current mitigation measures, issues surrounding regulatory compliance and intrinsic deficiencies of the present risk mitigation regime.

3.1 Risk Mitigation Measures

Aviation authorities, airlines and airports alike often cite safety as their primary concern (ICAO 2006). Indeed, safety features are incorporated at multiple levels from the manufacture of an aircraft to its operation, maintenance as well as related infrastructure design. Aircraft certification and operational measures, aerodrome design and land-use regulations around runways, inter alia, contribute to the mitigation of risks resulting from accidents upon landing and take-off. While this thesis focuses on land-based physical safety measures, the primary components of this safety system are briefly described below. Regulatory details of these measures can be found in the relevant official documents and so are not covered here.

3.1.1 Aircraft certification & operational regulations

The protection of safety standards plays an important role in the interaction between aircraft performance, operational regulations and infrastructure design. Field length requirements are published in flight manuals as part of the aircraft certification process. Airports are respectively required to publish for each of its runways critical distances, namely the take-off run available (TORA), take-off distance available (TODA) and landing distance available (LDA) (Ashford & Wright 1992). Operational regulations, such as the Procedures for Air Navigation Services, Operations (PANS-OPS), require sufficient runway length for each take-off and landing. The difference between an aircraft's gross runway length requirement and the actual length available represent a margin of safety, which increases with the amount of excess runway length available.

Although the above regulations are well established, regulators sometimes issue additional rules governing the operation of aircraft with the intention of increasing the safety margin available. For example, the FAA published a Safety Alert for Operators (SAFO) in August 2006 in response to the landing overrun at Chicago Midway Airport eight months earlier (FAA 2006b). The document recommends jet operators to consider landing performance based on conditions at the time of arrival further to the assessment at dispatch. Once the runway requirement is determined, an extra safety margin of at least 15 percent is to be applied (Thurber 2006).

3.1.2 Aerodrome design

Airports are also designed with safety in mind. There is an internationally agreed framework on airport design set out in Annex 14 to the Convention on International Civil Aviation (ICAO 1999). National aviation authorities, however, may deviate from Annex 14 or develop different standards. For instance, the FAA's Advisory Circular 150/5300-13 on Airport Design is a parallel framework to Annex 14 (FAA 2004a), as is the UK's CAP 168. This section summarises the safety areas relevant to take-off and landing accidents under ICAO Annex 14 and FAA AC150/5300-13.

3.1.2.1 ICAO Annex 14

Dimensional requirements under Annex 14 have been described as necessary to provide adequate clearance between aircraft and obstacles or other hazards so as to avoid collision and damage (Eddowes et al. 2001). The most relevant ASAs under Annex 14 concerning the accident types of interest are the Runway Strip and the Runway End Safety Area (RESA).

The Runway Strip technically refers to the physical paved runway, the runway shoulders as well as the area surrounding these, up to 60m beyond runway ends and 150m from the runway centreline for runways used by large aircraft. Of particular interest to this study is the area surrounding the physical runway and shoulders since it is designed to reduce the risk of damage to aircraft running off the runway by having adequate load bearing strength to support the aircraft and emergency vehicles, meeting slope requirements and by being clear of obstacle or ditches (Kirkland 2001a). The dimensions of the area are intended to contain the large majority of incidents where an aircraft fails to remain on the paved runway (Caves 1996).

In 1999, the former recommended RESA length of 90m was adopted as the standard with a recommendation of 240m for longer runways (Kirkland et al. 2003a). RESA width should be no less than twice as wide as the associated runway. Graded, cleared of obstacles and meeting slope requirements, the area is expected to contain 50 percent of all off-runway accidents (Caves 1996). The UK's CAP 168 RESA standards are aimed at capturing a statistical majority of overruns and minimising their impact (CAA 1998).

The ICAO Annex 14 RESA requirements have been challenged by the International Federation of Air Line Pilots' Associations (IFALPA) and others for more than two decades. The association contends that RESAs at air transport category airports should be at least 300m in length (Airports World 2005). Countries with no legislative requirements for RESAs, such as Canada and New Zealand (NZAPLA 2004), also face critics. After the August 2005 Air France overrun in Toronto, IFALPA pointed to the paved overrun area of only 60m as a safety defect (Airports World 2005).

ICAO Annex 14 also stipulates three-dimensional obstacle limitation surfaces to be provided above and around airports. These are slices of airspace which must be clear of obstructions. They are beyond the scope of the current thesis, which focuses on ground-based ASAs.

3.1.2.2 FAA AC150/5300-13

The concepts of the Runway Strip and the RESA are combined under FAA rules. The Runway Safety Area (RSA) surrounds the runway and extends up to 300m beyond the runway threshold. The defined area is graded, cleared of obstacles and prepared to reduce the risk of damage to aircraft that undershoot, overshoot or veer-off from the runway (FAA 1999a, 2004).

The FAA also specifies a Runway Protection Zone (RPZ), which has no equivalent in ICAO Annex 14. The President's Airport Commission recommended the establishment of clear zones beyond runway ends in 1952 (IATA, undated). The FAA subsequently adopted Clear Zones and eventually RPZs. The trapezoidal area beyond the runway end serve to protect people and property on the ground in case of aviation accidents in the area. The airport is required to have sufficient interest in the RPZ to prevent incompatible land use or obstructions from being erected within (FAA 1996).

3.1.2.3 Engineering solutions

More recently, airports have also been adopting engineering solutions to mitigate relevant risks. In 1984, the US National Transportation Safety Board (NTSB) asked the FAA to initiate research on using submerged low-impact resistance structures for airports with inadequate RSAs beyond runway ends (NTSB 2001). Today, Engineered Material Arresting Systems (EMAS) have been installed at more than twenty airports across the US and UK (Airports World 2005, 2006). Essentially made up of crushable concrete cylinders, an overrunning aircraft would crush the material as it traverses the EMAS, slowing down in the process The EMAS bed is nonetheless strong enough to support emergency vehicles. The FAA issued its policy on EMAS use in 1998 (Heald 2005). An EMAS should be capable of stopping the runway's design aircraft leaving the runway end at 70 knots (FAA 2004b).

In May 1999, American Eagle Flight 4925 overran runway 4R at New York's John F. Kennedy Airport. The aircraft stopped after 248ft on the EMAS. The NTSB estimated that without the installation, the aircraft would have descended into Thurston Basin, which is only 600ft from the runway end (NTSB 2001, Tompkins 2005).

Despite a number of examples of aircraft successfully arrested by EMAS, scepticism remains with its equivalency to a standard RSA or RESA. While recognising the additional safety that EMAS provides, the NTSB does not consider it a substitute or safety equivalent to a standard RSA (NTSB 2003). New Zealand's Civil Aviation Authority takes a similar stance (Watson 2005). There are also concerns about the material's effectiveness and durability in very cold locations, such as Alaska (FAA 2004b). Finally, the consequences of an aircraft undershooting onto an EMAS bed is relatively untested. FAA research suggests that there would be no adverse impact on the aircraft, which is expected to 'skip off' the material then land normally on the runway (Giaquinto 2006). However, the outcome may be different for high velocity and downward momentum undershoots.

3.1.3 Land-use planning

In addition to aerodrome design rules, land-use planning regulations and guidelines also govern the way land is used around runways. While ICAO Annex 14 provides an international framework for safety areas in the immediate vicinity of runways, there are relatively few national regulations on land-use near airports, let alone an international agreement on the topic (ETSC 1999a). Nonetheless, third party risk is gaining attention in land-use planning and it is increasingly used as a tool to mitigate third party risk related to aircraft accidents (Caves 1996). The rationale for controlling land-use near airports is that the local probability of being affected by an aircraft accident is not the same for all locations around an airport. Areas closer to the runway are associated with higher risks (Ale et al. undated, DfT 1997). To prevent people and property from being exposed to unacceptable levels of third party risk, it is usually much cheaper to avoid incompatible land use in the area than to remove existing development (Dietz & Brody 2003).

3.1.3.1 The Netherlands

The Netherlands is at the forefront of controlling land use around airports to mitigate third party risk, especially since the Amsterdam El Al crash in 1992. The regulations employ two measures of third party risk – individual risk (IR) and societal risk (SR). IR measures the risk of death per annum to a person at a particular location due to an aircraft mishap (DfT 1997, Hale 2002) and is usually expressed by contours around the runway or airport. SR is concerned with accidents on a scale that would provoke a socio-political response and measures the probability of death of more than N persons, usually expressed by a FN curve. SR recognises the importance the public places on dramatic disasters with larger losses of life compared to a series of minor accidents that may still lead to identical overall fatalities (Brady & Hillestad 1995). Unlike IR, SR is not location-specific and only exists when people are present (Hale 2002).

In the early 1990s, the Dutch authorities imposed a limit on third party risk related to flight operations at Amsterdam Schiphol Airport. No more housing was to be built within the 10^{-5} to 10^{-8} individual risk contours and SR was capped (Ale & Piers 2000a). An airport could influence the size and shape of its IR contours by changing traffic levels, aircraft types, runway use as well as flight path arrangements (Hale 2001).

3.1.3.2 United Kingdom

In the UK, an area similar in shape to the FAA's Runway Protection Zone was introduced in 1958 following the recommendations of the Le Maitre Committee on Safeguarding Policy (Smith 2000). The dimensions of the original Public Safety Zone (PSZ), extending up to 4500ft from the runway end, were based on the subjective choice that 65 percent of landing and take-off crashes should be contained within the zone (Ale et al. undated). Unlike the American RPZ, however, the British PSZ was never managed under the Civil Aviation Authority. The Department of Transport, and subsequently the Department for Transport, administered the zones under the Town and Country Planning (Aerodromes) Direction of 1972 (Caves 1996).

PSZ policy underwent some significant changes in 1999. One of the key revisions is the use of individual risk modelling to set the size and shape of PSZs (DfT 1997, Kent & Mason 2001). As a result, PSZs today no longer resemble the FAA's RPZs, but are elongated isosceles triangles that taper away from the runway end, similar to the Dutch IR risk contours. The PSZ roughly follows the 10^{-5} IR contour based on traffic forecasts of fifteen years from the time of study (DfT 2002). New development as well as redevelopment projects are usually prohibited within the zone. The Secretary of State also expects all housing and workplaces within the 10^{-4} IR contour to be purchased and moved away (Eurocontrol 2005). There were 42 PSZs at twenty airports across the UK in 1999 (Kent & Mason 2001).

3.1.3.3 United States

Whereas the Netherlands and the UK have national regulations on land-use planning around airports, this responsibility is undertaken at the State level in the US, where California, Oregon, Washington and Wisconsin have published airport land-use planning handbooks (Dietz & Brody 2003). California is considered to have the most sophisticated rules so the following description concentrates on the Californian case.
Since 1970, the State of California has required every county with a public airport to form an Airport Land Use Commission (ALUC) (SDCRAA 2004). The Commission is made up of county and city representatives, aviation experts as well as the general

public. It is charged to prepare and adopt airport land-use compatibility plans and to review land-use and airport actions for consistency with the plan. The compatibility plan provides for the orderly growth of the airport and the surrounding area, safeguarding the general welfare of inhabitants within as well as the public in general (SDCRAA undated). The safety of aircraft occupants and third parties in the event of an aircraft accident is a key concern of the ALUC as well as noise, overflight and airspace protection (State of California 2002).

Unlike the Dutch and British airport land-use planning rules, the Californian regulations are not explicitly related to individual risk or societal risk. The Californian Airport Land Use Planning Handbook suggests a number of standard zones to be applied to areas near runway ends to restrict development within. Their dimensions depend on the runway length, its intended traffic type as well as its approach visibility minimums (State of California 2002).

3.2 Compliance & Costs

From aerodrome design to land-use planning around airports, a complex web of international and local regulations make up the total risk mitigation regime for accidents occurring upon landing and take-off. Simply considering the rules, though, may be misleading. There is a significant gap between the regulations and their compliance. This section examines the state of regulatory compliance, related costs and consequences of non-compliance.

3.2.1 State of compliance

3.2.1.1 ICAO Annex 14

It is not only Canada and New Zealand that have not incorporated certain ICAO Annex 14 rules on airport safety areas into their national legislations. Austria, Finland, Greece, Japan, Norway, Portugal, Russia, Spain, as well as the UK and US have filed differences with the ICAO regarding RESA standards (ICAO 2002a). Japan, for example, only provides 40m RESAs even though the ICAO Annex 14 minimum is 90m and the recommended length is 240m (ICAO 2000).

3.2.1.2 FAA AC150/5300-13

The largest national aviation system, that of the US, has its own aerodrome design regulations but fares no better in terms of compliance. The situation with Runway Safety Areas (RSA), the quasi-equivalent of ICAO's RESA, is telling. The FAA standard on RSA was adopted some 20 years ago but did not require retrospective compliance (Airports World 2005, Tompkins 2005). Until recently, airports built before the standard came into force did not have to provide standard RSAs unless runway improvement projects, e.g. runway extensions, were carried out. Today, many of these older airports find themselves surrounded by urban development, bodies of water or terrain without adequate space for full RSA compliance (Tompkins 2005). Out of the 22 runway ends under the administration of the Port Authority of New York and New Jersey, only eight meet RSA standards (ACI-NA 2005). Chicago Midway Airport's two runways lack RSAs at both ends (Szczesniak 2006) and a similar situation applies to Oakland International Airport in California (ACI-NA 2005). Burbank Bob Hope Airport, California, cites financial, political and legal impediments to providing a full length RSA (NTSB 2003).

In 1990, only 35 percent of runways used by air carriers met full RSA standards. The figure is 55 percent a decade later (FAA 2001). The FAA initiated the RSA improvement programme in 2000 to bring RSAs at runways used by commercial service aircraft into compliance where practicable (ICAO 2005). The programme incorporated the use of EMAS in 2002 (Marchi 2006). By 2005, 38 percent of the nation's 500 largest airports remain non-compliant (McCartney 2005). In the light of accidents at RSA-deficient airports like Chicago Midway and Teterboro, politicians like Senator Frank Lautenberg of New Jersey have pushed for greater compliance with FAA standards. In November 2005, president G. W. Bush signed the 2006 Transportation Appropriation Act, including the 'Lautenberg measure', which requires major commercial airports to be RSA-compliant by 2015 (Lautenberg 2005).

The situation of non-compliance is not restricted to that of RSAs. Building permits have been issued to homes and businesses for land within the RPZ for more than a decade at Brookings Airport, South Dakota. The city authorities only recently "discovered" the 1989 FAA order and is now considering options such as shifting and shortening the relevant runway (Aberdeen News 2005, 2006, Studer 2005).

Not only is there a large gap between regulations and official compliance, figures on the latter must be taken with a degree of doubt as well. At Martin County Airport, Witham, Florida, the airport submitted a map to the FAA related to a runway extension project that "failed to show the five streets and cluster of homes... that fell in a RPZ" (Ash 2005, Harris 2005, Palm Beach Post 2005a, 2005b, Samples 2005, Swartz 2005). Even after the project was completed, the FAA was unaware of the housing in the RPZ. The county now has plans to purchase the homes within the RPZ.

3.2.1.3 Land-use planning

The previous chapter has already cited the failure of the Dutch policy in capping third party risk at Amsterdam Schiphol at 1990 levels partly due to increased risk exposure of employees in the area (Post et al. 2006). Although there are few national statistics on land-use compliance in the US, especially given the local nature of the issue, it is evident that at least a number of airports are surrounded by incompatible development, e.g. Chicago Midway in Illinois, Burbank, Van Nuys and Santa Monica in California and Teterboro in New Jersey.

3.2.2 Cost of compliance

As non-compliant airports face increasing pressures to bring their safety areas up to standard, they often discover that far more than simple construction is involved. As the following cases from the US illustrate, installing standard RSAs and RPZs could entail complex and costly issues.

3.2.2.1 Changes to airport layout & operations

When ASAs cannot be simply added to runway ends, alternative measures must be considered. This may involve modifying the airports existing layout and associated operations. Implementing a full RSA at Cherry Capital Airport, Michigan, has meant shifting its runway to the north and adjusting the threshold, at the expense of US$1.5 million (McGillivary 2005).

3.2.2.2 Displacement of existing developments

Since airports and communities have grown nearer to each other over time, the area where ASAs should be is now frequently occupied by other developments. A project is being undertaken at Moore County Airport in North Carolina to purchase property and relocate two roads in order to bring its RSA and RPZ into compliance. The project will cost more than US$6 million (Gilkeson 2005). Peachtree City Airport in Georgia has a similar project for its RSA (Munford 2005) and so does Indiana County Jimmy Stewart Airport, Indiana, for its RPZ (Como 2005).

3.2.2.3 Environmental costs

ASAs are installed at an environmental cost too. The authorities at Tampa-Hillsborough County, Florida, gave permission to Tampa International Airport to clear vegetation and fill in eight acres of wetlands in order to keep wildlife out of its RPZ and to allow access for emergency vehicles (Salinero 2005). While the airport plans to recreate wetlands 28 miles away, there are concerns about the impact of the move on flooding, pollution and wildlife habitat. Similarly, Juneau International Airport, Alaska, plans to acquire 18.5 acres of Mendenhall Wetland State Game Refuge to expand its RSA and related works (Juneau Empire 2005). When a runway extension and RSA project at Pittsfield Municipal Airport in Massachusetts threatened colonies of spikerush, an endangered plant, the FAA allowed the width of the graded RSA to be reduced (Carey 2004a, 2004b). Trade-offs between safety benefits and environmental protection are not uncommon.

3.2.2.4 Development opportunity

From a development perspective, ASAs could be regarded as lost opportunities for airport expansion and local development. In the hand of airport operators, vacant land at the end of runways could be used for runway extension projects to increase capacity. Local authorities may also sell land around airports to developers to generate handsome revenues. Instead, precious real estate sit idle around airports in the form of ASAs.

This is not only true of existing safety areas. Local authorities may also want to safeguard land for future airport expansion. A five-star hotel development was proposed in Dania Beach, Florida near Fort Lauderdale/Hollywood International Airport. Even though the project would not infringe on any existing ASAs, the county commissioners were reluctant to grant approval because it potentially falls into the RPZ of an extended runway. The developers were accused of speculation, hoping that the county would be forced to buy the land if the development ultimately falls into a RPZ (Sherman 2005, Miami Herald 2006).

3.2.3 Cost of non-compliance

Having considered the costs and issues related to bringing an airport's ASAs into compliance, the price of having substandard ASAs must also be examined. Of primary concern is the higher risk levels. This has seldom been quantified but since 1982, there have been 23 fatalities and 300 injuries at FAA certificated airports due to overrun accidents alone, with the most serious cases occurring at airports without standard RSAs (Croft 2004). Financially, non-compliant federally obligated airports in the US may also lose their federal funding, although this is apparently rare.

Failure to prevent incompatible developments in ASAs may also damage an airport's growth. Proposals to build condominiums in the RPZ of Tri-Cities Regional Airport in Tennessee is threatening future runway extension and the airport's master growth plan (McGee 2005, Wig 2005).

Finally, inadequate ASAs are also matters of litigation. Upon approving a theme park to be built in the RPZ of Republic Airport, New York, the local authorities have been sued by the aviation community as well as the State Department of Transportation (McShane 2005). Little Rock National Airport in Arkansas has also been found negligent for having an inadequate safety area. US$2.1 million was awarded to a widow whose husband died piloting American Airlines Flight 1420 to land on a RSA deficient runway at Little Rock during a thunderstorm in June 1999 (Hammer 2005, KATV 2005). A precedent has thus been set for victims of air crashes to sue airports with substandard ASAs for large compensations.

3.3 Deficiencies of Current Measures

Substandard ASAs are often brought into compliance at significant costs. However, the current risk mitigation measures have intrinsic flaws and compliance to the stated rules may give a false sense of security. These deficiencies ought to be considered rather than blindly pursuing regulatory compliance.

The current rules' greatest shortcoming is the mismatch between actual risks and the protection afforded by the regulations. The margin of safety provided is far from uniform across airports and operations. This is especially true of the aerodrome design rules and, to a lesser extent, the European third party risk mitigation measures. The major issues are detailed below.

3.3.1 Risk factor consideration

The ICAO Annex 14 and the FAA Aerodrome Design Advisory Circular are anchored around a set of aerodrome or airport reference codes (ARC). ASA requirements are defined according to a number of criteria, which make up the ARC. In ICAO's case, the ARC is made up of two elements. The first relates to the critical aircraft's reference field length, classified under four groups. The second refers to the aircraft's wingspan or outer main gear wheel span, under six categories. Regulations may also differ depending if precision approach is available (Eddowes et al. 2001, GASR 2003). Similarly, FAA's codes operate with two factors – the aircraft approach speed and wingspan. The runway's approach visibility minimums also influence ASA requirements. According to these handful of criteria, then, the applicability and size of ASAs are set for all airports.

The risk of landing and take-off accidents varies according to a large number of factors. Investigation into the causes of previous accidents shows that aircraft and engine type, airport and runway characteristics, availability of navigational aids, meteorological and environmental conditions as well as human factors all contribute to the overall risk of accident occurrence. Nevertheless, the current regulation only considers an extremely small number of factors through the ARC system. Every airfield has features that make it especially vulnerable to certain types of accidents compared to the 'average airport' (Cowell et al. 2000). The level of risk and nature of hazard also vary from runway end to runway end (CAA 1998). The small number of factors taken into account through the ARCs suggests that safety margin requirements do not reflect the genuine risk exposure of specific locations (Kirkland 2001a).

The lack of consideration for local airport conditions is perhaps most apparent in the absence of meteorological factors in the ICAO and FAA rules. Despite the well known fact that poor weather is associated with heightened accident propensity (Khatwa & Helmreich 1998), ASA regulations do not distinguish between airports that are regularly exposed to bad weather and those that are not. The NTSB recognises that flights in Alaska face unique challenges in their operating environment and travel requirements (NTSB 2006a) yet FAA's aerodrome design rules make no distinction between airports in Alaska and, for example, those in Arizona, which enjoy far more aviation-friendly weather.

The specific ASA rules fail to take into account a vast number of risk factors, leaving a significant gap between the provision of safety margins and individual airports' holistic risk profile. When the regulations do attempt to adjust ASA requirements to different risk needs, they are not always supported by defendable analyses. Overall, there is considerable mismatch between the provision of safety margins through ASAs and airports' actual risk exposure.

3.3.2 Rigid & prescriptive rules

The ARC codes provide an easy system of setting ASA standards and for their oversight. While this ease of administration is acknowledged, the system's simplicity conceals vast differences in risk exposure too, perhaps beyond today's levels of public acceptance.

Research has shown that there is sometimes little relation between the ARC elements or their groupings and what actually influences risk levels at airports. Eddowes et al. (2001) found insignificant difference between code 1 and 2 runways and runways of code 3 or 4 in undershoot risk that would warrant the distinction in RESA size as required by ICAO. No justification is found for less stringent ASA requirements for non-instrument runways either.

The case of London City Airport may also be used to illustrate the system's rigidity and how it could be manipulated. The airport's runway used to be one metre short of 1200m and thus the recommended strip width was only 75m rather than 150m if it was one metre longer. Safety margins are mandated in large, rigid steps through the ARC system, but risk does not behave likewise.

Eddowes et al. (2001) concluded that Annex 14 does not provide consistent margins of safety. It provides levels of safety that in certain cases exceed a hypothetical

Target Level of Safety and fall short of it in others. Whereas risk varies dynamically from location to location, ASA regulations offer average levels of protection with relatively little discrimination.

3.3.3 Compliance mentality

Due to the traditional emphasis on regulatory compliance, there is a culture of focusing on meeting regulatory demands and assuming that as long as the rules are met, adequate safety margins have been provided. The current regulations give the impression that airports' safety obligations end at providing the full set of standard ASAs.

A significant number of airports have runways and safety areas that abut steep slopes and embankments that are sources of significant risk in the event of an accident. In close vicinity of ASAs are also ditches, rivers, transport infrastructure and other obstructions (Ashford & Wright 1992). The steep drop-offs at both ends of Luton Airport in the UK, and the major road and railway at the bottom of one of these have already been pointed out as sources of risk (Airports World 2005). The UK CAA responded by only highlighting the airport's compliance with ASA rules and dismissed the issue (Airports World 2006). One of the showcase deployments of EMAS technology is Greater Binghamton Airport, New York. Surrounding the EMAS fitted runway end are steep slopes on all sides. Pilot behaviour in accidents repeatedly demonstrate that areas beyond the standard ASAs matter to safety. In 1988, a pilot in an overrunning aircraft in Wheeling, Illinois intentionally veered his aircraft off the runway because of a drop-off at the runway end (NTSB 1988).

While risk is geographically continuous and extends beyond the limits of ASAs, airports as well as regulators may find undue assurance in simply complying with the regulations.

3.3.4 Compartmentalised approach

The requirements for ASAs are compartmentalised in Annex 14 and AC150/5300-13. Unlike the Dutch or British third party risk land-use planning risk contours, ICAO and FAA specify multiple safety areas. Although together these areas aim to reduce the risk of landing and take-off accidents, their interrelationships and inter-functionalities are not made explicit. This has implications for making appropriate decisions on what safety measures to provide at physically constraint airports.

At Greenwood Lake Airport, New Jersey, a take-off overrun occurred soon after the declared runway length was shortened to reduce its RPZ requirement so a nursing home would not fall inside the zone (Carroll 2005). Local officials then questioned if the reduced runway length contributed to the cause of the accident. The emphasis has been placed on complying with RPZ rules, at the expense of possibly more significant safety margins in terms of take-off distance available.

When airports like Greenwood Lake have to make trade-offs between safety features, the regulations do not allow for a holistic assessment of risk levels related to providing varying degrees of safety measures. Rigid, fragmented and compartmentalised, the relevant regulations leave no room for compensations between measures to reflect risk as a dynamic entity. This further adds to the current rules' rigidity and compliance mentality to increase the gap between mandated safety margins and actual risk levels.

3.3.5 Fragmented oversight

It has already been recognised that the responsibility and accountability for safety in aviation is diffused across a multitude of organisations – the airport operator, the airlines, the regulator etc. (ETSC 1999a). This fragmented institutional framework is mirrored in the administration of ASAs. There is generally a clear separation in the government of 'on-airport' and 'off-airport' ASAs (CAA 1998). Even though accident risk is continuous, civil aviation authorities tend to have oversight on the ASAs in the immediate vicinity of runways while local land-use authorities oversee safety areas related to third party risk.

In the early 1980s, the UK's PSZ was administered by the CAA on behalf of the DOT (DfT 2002). Today, under the rationale that PSZ is purely designed to control third party risk and is not concerned with aircraft safety (DfT 1997), the aviation authority is no longer involved in this function. Likewise, the US FAA is restricted to aeronautical concerns and a review of its aerodrome design rules would suggest that accident risk is not an issue beyond the RPZ (State of California 2002, Dietz & Brody

2003). Regarding development encroachment and incompatible land use around airports, the FAA points out that zoning is not its business but the locality's (Esler 2006).

This disjointed approach has created gaps in regulations where conflicts in interests may arise. Developers are believed to exert undue influence over local authorities and zoning boards (Avweb 2005), who may give priority to development opportunities over aviation accident risk mitigation. The aforementioned nursing home near Greenwood Lake Airport, New Jersey, was approved by West Milford township despite objections from the DOT as well as the state Attorney General (Carroll 2005). The federal government has little authority over local land use issues either (State of California 2002). The organisational and regulatory division in responsibility is a barrier to the effective use of ASAs to mitigate against aviation accident risk, which disregards boundaries of jurisdiction.

3.3.6 Opacity & lack of review mechanism

The formulation and objectives of ASA policies are not always quantitatively explicit. The Dutch and British third party risk land-use regulations are supported by a substantial amount of research that are in the public domain. They also state clear quantitative goals that their policies are intended to achieve. The equivalent for ICAO and FAA aerodrome design rules are much more vague. It is relatively difficult to trace the detailed methodologies, analyses and rationale used to develop the rules. Considerable expert judgement is believed to be involved (Caves 1996) and the drawbacks of depending on judgemental decisions are clear (Brooker 2006). Without explicit objectives, it is impossible to appropriately evaluate the effectiveness of ASAs as risk mitigation measures. It is thus difficult to ensure that the rules are kept up-to-date with evolving risk levels. In fact, there appears to be no periodical review mechanism for the effectiveness of ICAO and FAA ASAs.

3.3.7 Piecemeal & reactive approach

A plethora of usually prescriptive and reactive policies make up the total risk mitigation regime (Kirkland 2001a, Spriggs 2002). The FAA's RSA dimensional requirements have been increased over time to cope with changing traffic characteristics (ICAO 2005). In 1999, ICAO amended Annex 14 and a RESA of

90m became the standard rather than a recommendation, which is now 240m (NZCAA 2000). These occasional leaps in requirements are not conducive to the provision of relatively homogenous safety margins across airports. Regulatory step changes do not provide a predictable and farsighted approach to managing risk in the long-term.

The function and role of certain ASAs are also altered at times in response to new needs. For instance, the RPZ originates from the approach protection zone, aimed at preventing the creation of airport hazards. It then became the clear zone, used to preclude obstructions and control construction near runway ends. RPZ only took up its current name and role in controlling third party risk in 1989 (FAA 1999b, State of California 2002). FAA's latest SAFO on landing distance assessment is a stated reaction to the Chicago Midway overrun of 2005. While it is beneficial that the system is revised as risks are identified, there are doubts that continuing to add more piecemeal, and at times judgemental, decisions to an already fragmented system that lacks explicit targets will ensure adequate safety margins.

3.3.8 Regulatory rationale

Annex 14 specifications are set from the perspective of sizing an airport according to traffic needs. Not considered is the fact that aerodrome design rules could limit what aircraft an existing airport could serve because altering airport layout and size is not always feasible. Most airports' physical infrastructure simply cannot expand in pace with traffic growth and developments such as the New Large Aircraft from a green-field basis. As a result, safety margins are being stretched and Annex 14's original intent of providing safety margins from a purely airport sizing standpoint is not being realised. The rationale of current ASA regulations fail to reflect today's relationship between airports' operational needs and their physical, environmental and financial constraints.

3.4 Summary of Findings

Current risk mitigation measures for aircraft landing and take-off accidents have been reviewed. These include aircraft certification and operational rules as well as international and local aerodrome design standards and land-use planning regulations. Their compliance situation was examined and the associated costs reported. The research revealed a number of deficiencies related to their formulation and effectiveness as risk mitigation measures. Rules regarding ASAs only consider a very limited number of risk factors. Intuitively important factors such as exposure to poor meteorological conditions are not taken into account. Moreover, the regulations often come in the form of rigid and prescriptive rules. Coupled with the simple compliance mentality of airport operators, they result in average levels of safety being provided across vastly different airports, leading to significant discrepancies in terms of the margin of safety available. The overall risk mitigation strategy suffers from a compartmentalised and fragmented approach. The regulatory regime was also found to be reactive and opaque. These key deficiencies are targeted throughout the remainder of the thesis.

CHAPTER 4 SAFETY MANAGEMENT & RISK ASSESSMENT

Some shortfalls of current ASA regulations are closely related to the traditional approach to safety oversight in the aviation industry. More recently, this conventional approach has been shifting towards the adoption of Safety Management Systems (SMS) industry-wide. This chapter explores this new approach to safety management and highlights the need for better airport risk assessment, which the thesis contributes to.

4.1 A Paradigm Shift in Safety Oversight

The traditional approach to safety management centred on regulatory compliance regardless of risk levels and reacting to accident investigations (Morier 2005, DOT 2006). It is now a consensus that further safety improvements are hard to achieve with traditional safety management, which is no longer adequate given the dynamics of the industry (Roelen et al. 2000, GAIN 2004). A comprehensive reform of safety oversight and management is hence taking place. Through the introduction of SMS in aviation organisations, management by oversight is being replaced by management by insight and prescriptive safety control by objective-based safety regulations (GASR 1998, Leveson 2004). The UK CAA has switched from setting and enforcing rigid rules to auditing licensees, who must demonstrate that safety risks have been identified, assessed and mitigated (Kirkland 2001b).

A number of policy and regulatory changes are also driving the adoption of SMS. Mandatory airport licensing is advocated by the European Transport Safety Council, which would require integrated safety management programmes to be established and maintained (ETSC 1999). The burden of proof, then, lies with the aerodrome licensee to prove to the national aviation safety authorities that it can successfully implement a SMS to keep risks within an acceptable level (GASR 1999).

As the privatisation and commercialisation of airports gather pace, governments find themselves increasingly removed from the direct management of airport safety. Legislative and regulatory measures are therefore put in place to require the implementation of adequate safety policies and procedures by operators (GAASR 1997, ICAO 2006).

An equally important driver in the implementation of SMS is the general desire to improve the operational and financial efficiency of policies regarding aviation safety. There is increasing demand for safety to be measured and monitored similar to other aspects of aircraft operations (Rose 2005). The industry's growth, the pressure to lower accident rates as well as budgetary constraints call for more effective ways of directing financial and human resources to safety measures that would yield tangible benefits (FAA 2005, Fiorino 2005, Button & Drexler 2006).

In the broader aviation industry, airlines are also being required to run safety management systems (GAIN 2004). The Hampton Review was published in 2005 to promote more efficient regulatory inspection and enforcement in the area of aircraft maintenance in the UK (Glaskin 2006). The US Air Transportation Oversight System has also been launched in 1998 as a risk-based approach to carrier safety oversight (GAO 2005b, DOT 2006).

4.2 Core Features of SMS

The ICAO defines an airport SMS as "a system for the management of safety at aerodromes including the organisational structure, responsibilities, processes and provisions for the implementation of aerodrome safety policies by an aerodrome operator, which provides for the control of safety at, and the safe use of, the aerodrome" (ICAO 2002b). Under a SMS, the airport operator takes up a much more active role in assessing risks and managing safety than under the traditional approach to safety oversight. Managing safety becomes an explicit element of corporate management responsibility and a key business function (CAA 2003, ICAO 2006).

SMS has a clear structure and a number of core features. These are detailed below.

4.2.1 Data-driven

One of the fundamental principles of SMS is the collection and analysis of relevant data for identifying risks and developing mitigation measures (GAIN 2004). The evidence-based system discourages the use of expert judgement which has little empirical support. Data collection and analysis fuel, validate and calibrate the entire safety management process.

4.2.2 Risk-based

SMS is data intensive because quantitative risk assessment is used to identify priority areas on which to focus risk mitigation efforts (DOT 2006, GAIN 2006). Instead of following rigid and prescriptive rules that often mismatch risk levels and safety margins, airport operators need to attune their risk mitigation strategies to local, demonstrated needs. This evidence-based approach represents a more targeted and effective way of using safety management resources.

4.2.3 Proactive

Another hallmark of SMS is the emphasis on proactive risk control (ICAO 2002b). Instead of reacting to new sources of risk as made evident by actual accidents and incidents, SMS seeks to identify new risks before adverse events occur. SMS makes use of hazard and incident reports as well as flight operational data to reveal latent unsafe conditions, spot system vulnerabilities and to develop mitigation measures accordingly (ICAO 2006).

4.2.4 Objective-based

Clear safety objectives are set against which a SMS is evaluated and improved upon (ICAO 2002b). There may be an overall safety target which the aerodrome operator should achieve (GASR 1998) or more specific goals for particular risk mitigation measures. SMS allows an airport's safety performance to be measured (ICAO 2006).

4.2.5 Transparent

The explicit nature of SMS is not restricted only to its objectives. A key characteristic of SMS is its transparency. From data collection and risk assessment to the development of risk mitigation measures and their evaluation, all safety-related activities are documented and visible (ICAO 2006). The UK CAA requires a Safety Case to be developed and maintained. It includes all necessary documentation and references to demonstrate that a system meets its safety requirements (CAA 2006).

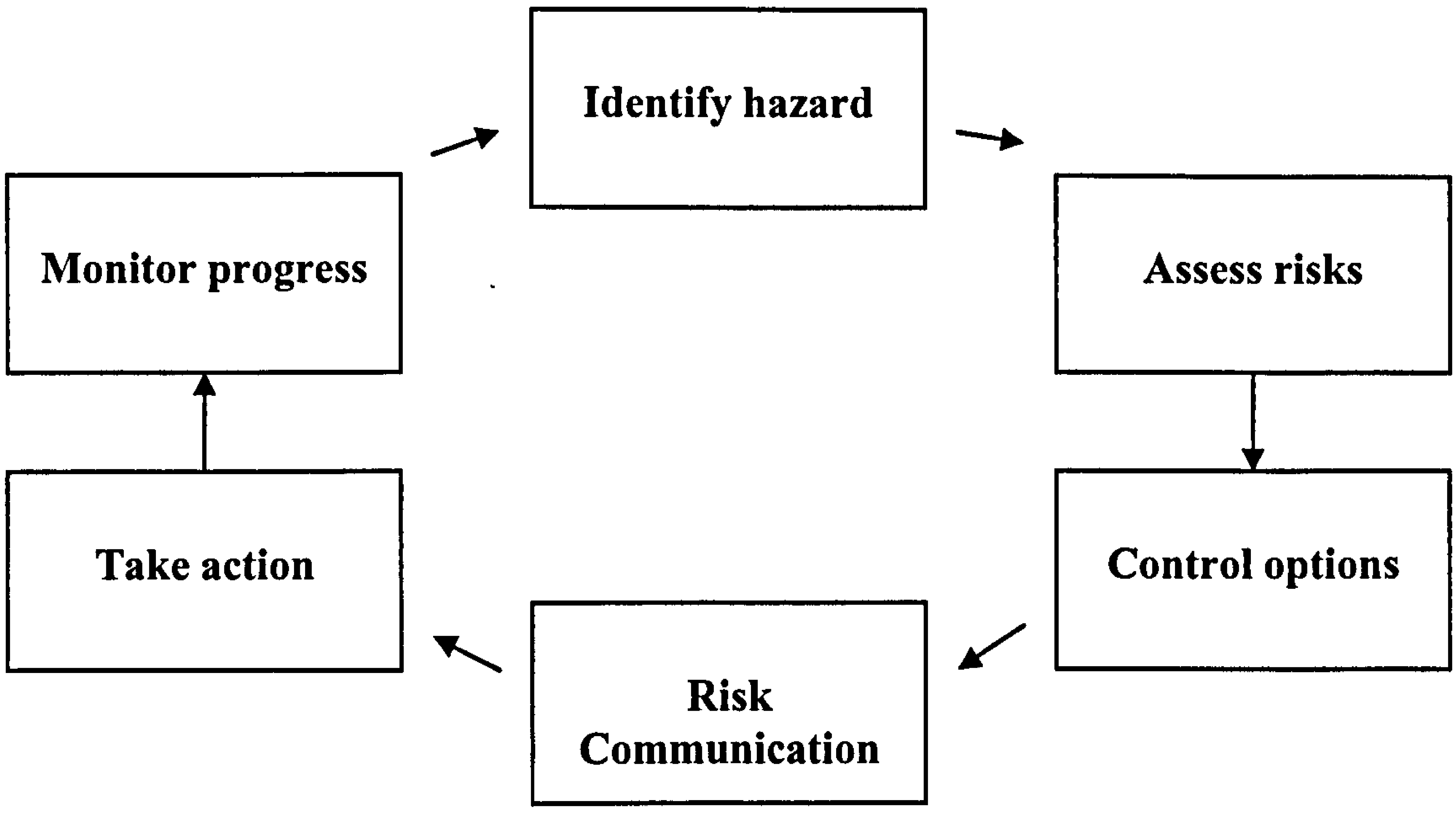
4.2.6 Systematic

Safety activities under SMS follow a stated path that is predetermined. The steps of safety management are followed consistently throughout an organisation (ICAO 2006). There is hence a high level of uniformity between the formulation and assessment of different risk mitigation measures.

4.2.7 Continuous

SMS is a continuous process with a feedback-loop (ICAO 2002b). As illustrated in Figure 4.1, safety management is a cycle of data collection for risk assessment, formulating and implementing mitigation measures and evaluating their effectiveness (Roelen et al. 2004). Safety policies are constantly monitored and updated to reflect changes in risk.

Figure 4.1 The SMS safety cycle



Source: ICAO 2006

4.3 Risk Assessment

Risk assessment is a crucial step and intrinsic element of the Safety Management System. Also systematic and structured, it is a process for identifying hazards and evaluating their risk in terms of probability and severity of consequences (CAA 2006). The output of risk assessment feeds into the rest of SMS to help prioritise decisions on risk control and to evaluate the effectiveness of safety measures (Smith 2000, Spriggs 2002). SMS' data-driven nature stresses the importance of quantitative risk assessment. This involves expressing the likelihood of hazard realisation and related consequences in relatively precise numeric terms, indicative of at least the order of magnitude.

The four essential steps of risk assessment consist of the identification of potential safety hazards, the estimation of their probability of occurrence, the estimation of their consequences and the comparison of the results to the acceptability criteria (Andrews & Moss 1993). This thesis is concerned with the specific risk of landing and take-off accidents on or near airports. The research undertaken contributes to the second step of the typical risk assessment process, i.e. estimating the probability of occurrence. In particular, it quantifies the likelihood of accident occurrence taking into consideration specific airports' exposure to risk. This adds precision and relevance to the risk assessment exercise, strengthening the entire SMS.

CHAPTER 5 FORMER AIRPORT RISK ASSESSMENT STUDIES

The preceding chapter has underlined the importance of risk assessment as a crucial step in safety management. The role of risk assessment will only grow with the increasing emphasis on SMS and quantitative analysis. This chapter reviews former airport risk assessment studies, their main concerns, analytical approaches and key shortfalls. This provides the context in which the current research is carried out.

From designing aircraft systems to stipulating operational standards and air traffic control rules, risk assessment is used in many aspects of aviation. However, the exercise of assessing the risk of accidents occurring near and at airports is relatively overlooked. Previous relevant studies can be broadly categorised into four families according to their prime objective and approach taken.

5.1 Categories of Former Airport Risk Assessment Studies

5.1.1 Airport design studies

The first family of studies aims to assess risk from an airport design standpoint. For example, the UK CAA's 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 aerodrome design rules (Eddowes et al. 2001). It reviewed design standards such as runway length and reference codes, the RESA, separation distances between runways and taxiways and obstacle limitation surfaces. It made concrete recommendations as to how to amend ICAO Annex 14 safety areas in order to achieve a specific target level of safety. In the US, studies have also been carried out to set forth criteria for the design of airport safety areas, especially in California. Garbell (1988) pioneered the accident-potential concept and led to the adoption of safety areas at a number of airports.

5.1.2 Third-party risk studies

Another family of airport risk assessment focuses exclusively on third party risk. 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 & Piers 2000b).

The Netherlands is a leader in using and enforcing quantitative risk targets (Hale 2002). Since 1990, a series of reports have been published on measuring and managing third party risk at Amsterdam's Schiphol Airport (Smith & Spouge 1990, Smith 1991a, 1991b, Technica, 1991, Piers et al. 1993, Piers 1996, Ale & Piers 1999, 2000a, Piers & Ale 2000, Pikaar et al. 2000, Roelen et al. 2000, Hale 2001, 2002). These studies have a strong land-use planning focus and contributed to models and risk calculations from which regulatory bodies have set planning rules.

The British third party risk studies are similar in nature to their Dutch counterparts. Models were developed by National Air Traffic Services Ltd. (NATS) to calculate individual risk around airports (Evans et al. 1997, Cowell et al. 1997, 2000, Kent & Mason 2001). This set of research provided the basis for modifying the traditional size and shape of UK PSZs.

These techniques have since been applied to a number of airports in Europe and elsewhere (University of Sydney 1990, Irvine 1992, Eddowes, 1994a, 1994b, Purdy 1994, Aho 1995, Gouweleeuw 1995, Loog, 1995, Kent 1998, Kent & Mason 1999a, 1999b, 1999c).

5.1.3 Facility risk studies

A third family of studies seek to assess the risk that aircraft operations pose to specific developments near airports. Concerned with the safety of nuclear power plants, the US Nuclear Regulatory Commission developed a standard methodology by which it could determine if a site was far enough from airports and airways (Eisenhut 1973, NRC 1981). The Department of Energy also has a methodology for assessing the risk of an aircraft crash into its nuclear weapons and material storage facilities, notably the Pantex nuclear weapon production facility near Amarillo International Airport, Texas (Kimura & Bennett 1993, Alexander et al. 1996, DOE 1996). 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). Other similar studies include Hornyik & Grund (1974), Solomon & Kenneth (1975), Smith (1983), Phillips (1987), Roberts (1987), Jowett & Cowell (1991) and Slater (1993).

5.1.4 Operational risk studies

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

5.2 Shortfalls of Previous Airport Risk Assessment Studies

All four families of previous airport risk assessment studies have certain fundamental shortfalls, some of which are reflected in the deficiencies of existing ASA policies as described in Chapter 3. These are discussed in turn.

5.2.1 Singular-view approach

The four types of airport risk assessment all approach the subject of airport risk from a single standpoint, i.e. the airport's, the third party's, the facility's and the operation's. This in fact reflects the fragmented oversight of risk mitigation measures. Studies on third party risk have little regard for aerodrome deign (Ale et al. undated, Couwenberg 1994, Davies et al. 1994, Smith 1995, DfT 1997, Piers 1994, 1996, 1998a, 1998b, Ale & Piers 1999, 2000a, 2000b, Pikaar et al. 2000, Spriggs 2002, Bienz 2004) while airport design studies fail to look beyond the airport boundary when analysing risk (CAA 1998, Eddowes et al. 2001, Davies & Quinn 2004a, 2004b). Similarly, operational studies narrowly focus on the safety of aircraft take-offs and landings (Enders et al. 1996, Khatwa et al. 1996, Khatwa & Helmreich 1998, CAST 1999) whereas facility-specific risk assessments only attend to the risk exposure of the identified structures or sites (Alexander et al. 1996, Kimura 1997, Prassinos & Kimura 1998, Ghosh & Sagar 2002, Kimura et al. 1995, 2004, Weidl &

Klein 2004). Such divisions in the investigation of the complex issue of airport risk does not offer the comprehensive understanding that would support an integrated approach to risk management and control, which is clearly desirable when both the problems of individual studies and their solutions are in fact intricately related.

5.2.2 Limited risk factor consideration

Other than failing to include related risks in a coherent study, former risk assessments also have a traditional neglect for assessing risk factors relevant to the occurrence of accidents. With the exception of operational risk studies, most of the analytical and modelling effort is devoted to assessing the location and consequences of accidents, rather than the causes or the circumstances related to the accidents' occurrence. The great majority of third-party risk assessments, facility risk studies as well as airport design studies calculate the frequency of accident occurrence using simple historical crash rates based on aircraft or engine types. For example, the study on the third party risk of Manchester Airport's second runway calculated crash frequency based on the historical crash rates of commercial jet landings and take-offs, and a combined crash rate for general aviation (Davies et al 1994). The NLR Schiphol studies' crash rates only distinguished between a handful of aircraft generations (Ale et al undated, Couwenberg 1994, Piers 1994, 1996, 1998a, 1998b, Ale & Piers 1999, 2000a, 2000b, Pikaar et al. 2000). In addition to aircraft type and generation, the studies on the UK Public Safety Zones also considered whether the aircraft was Western-built or Eastern-built, the engine type as well as the operation type (passenger vs. cargo) (DfT 1997, Spriggs 2002). Facility risk studies such as Kimura et al. (1995) and Alexander et al. (1996) distinguish risk rates purely on operation type (air carrier, air taxi, military, general aviation and aerial application). This crude approach to calculating crash frequencies fails to take into account a wide spectrum of factors that have been identified by accident investigation authorities as relevant to accident risk, e.g. exposure to poor meteorological conditions. It therefore contributes towards the lack of sensitivity of risk control measures as well as the mismatch between actual risks and the provision of safety margins.

One of the principal reasons for this oversimplification of accident frequency modelling is the lack of data on flight exposure to various risk factors in normal operations. Without this normal operations data, the crash rates related to the presence of risk factors cannot be established. Closing this gap in research is a major achievement of this thesis. The subject is further elaborated in the next chapter when the approach of the current study is described.

5.2.3 Data & applicability limitations

The data used by former risk studies often place constraints on the applicability of their results. Some studies are based on only a very small sample of accidents. For instance, the Joint Safety Analysis Team's analysis of approach and landing accidents only considered a total of twelve accidents (CAST 1999). Drawing general conclusions from such analyses and applying them must therefore be done with caution.

Apart from sample size, the sampling strategy of former risk assessments also limit their future use. From analysing the risk of flight manoeuvres to justifying land-use regulations, former risk studies were conducted for a variety of purposes. As such, they are usually based on accident data that has been specifically tailored to the needs of the particular study. For example, airport-specific studies may disregard some accident cases because it does not correspond to certain features of the airport concerned (DfT 1997). Third-party risk studies of both Amsterdam Schiphol airport and Manchester airport exclude accidents that involve mountainous terrain (Davies et al. 1994, Piers 1994, 1996). The results of these studies are hence specific to their target airports only and the models cannot be simply applied to other sites.

5.2.4 Limited modelling capability

The modelling capability of former risk assessments is often limited. Indeed, most operational studies only offer an analysis of a set of accidents and are not models as such. Other more advanced studies such as the NLR and NATS models were developed to justify zoning policies and not designed for deriving risk reduction initiatives (Hale et al. 1999, Hale 2002). So other than the data applicability issues mentioned above, these methodologies offer limited scope for considering the impact of changes in risk parameters to the overall risk and the need for ASAs. Scenarios of risk exposure and other "what ifs" cannot be assessed easily.

Previous efforts to build more generic models of ASA-related risks also have deficiencies in terms of modelling capacity. Eddowed et al. (2001) and Kirkland et al. (2003a) presented a series of generally applicable one-dimensional models. The latter pioneered the modelling of accident risk using weight and runway criticality while the former examined accident risk related to factors such as excess runway available and approach type. However, flights do not experience individual risk factors in isolation from other risk factors. It is well known under Reason's 'Swiss cheese' model that accidents occur often because of exposure to a series of risks (Reason 1990, 1997, Rose 2004). The inability of these models to consider the combined effects of multiple risk factors on accident occurrence is a major handicap in aircraft accident risk assessment.

5.3 Summary of Findings

This chapter reviewed former airport risk assessment studies relevant to ASAs and grouped them into four families according to their principal concerns. Four fundamental shortfalls of these studies were then exposed, including their scope, risk factor consideration in addition to data and modelling limitations. The current research aims to make advances in these areas, as described in the next chapter.

CHAPTER 6 PROPOSED RISK ASSESSMENT METHODOLOGY

The previous chapter has laid out the principal shortfalls of existing airport risk assessment studies and models. This chapter presents the proposed risk assessment methodology, justifies the chosen approach and highlights the advances made. The chapter ends by setting out the structure of the analysis and modelling, which corresponds to the subsequent chapters of the thesis.

6.1 The Three-part Model

The majority of previous risk models in the field break down the risk assessment exercise into three key components – accident frequency, location and consequence (Caves 1996, Piers 1998a, Eurocontrol 2005). The frequency model considers the probability of an accident occurrence, while the location model assesses the likely wreckage site in relation to the runway or a specific facility, and the consequence model deals with the resulting fatalities, injuries and sometimes the financial impact. This three-part approach is well established and supported by extensive peer review (Hale 2002). The Dutch NLR as well as British NATS studies follow this three-step analysis (Piers 1996, DfT 1997). The current research follows the same rationale of risk analysis and concentrates on advancing the state-of-the-art of accident frequency modelling.

6.2 Advances in Methodology

This thesis offers a new approach to accident frequency modelling addressing some key deficiencies of current risk mitigation measures and risk assessment methodologies as described in previous chapters. Explained below, these advances were made possible by expanding the traditional scope of airport risk assessment studies, building comprehensive and compatible accident and normal operations databases and developing multi-dimensional quantitative models that explicitly take into account previously neglected risk factors.

6.2.1 Integrated approach

This research takes an integrated approach to airport risk assessment rather than focusing on a single stakeholder or element of the aviation system. The study crosses existing regulatory boundaries and considers aircraft crash risk on both sides of the airport fence, reflecting the geographically continuous nature of accident risk. This facilitates complementary policies in aerodrome design, land-use planning and operational parameters to be developed in lieu of the current fragmented and compartmentalised risk control measures. It has never been done before and avoids the difficulties of drawing from studies with different objectives and assumptions. The need for such an approach is evidenced in the responses to the New Zealand Civil Aviation Authority's consultation on its RESA policy where respondents suggested that more aerodrome physical requirements be assessed along with the RESA in a single coherent study (Watson 2005).

6.2.2 Single comprehensive database

Another advance made by this study is the comprehensive accident database developed. Unlike previous studies that focused on a specific type of accident, such as approach-and-landing accidents (Enders et al. 1996, Khatwa & Helmreich 1998), third-party accidents (Piers 1996, DfT 1997) or overruns (CAA 1998), all accident types that are implicated by ASAs are included in this study – take-off and landing overruns, undershoots, veer-offs as well as crashes after take-off. This facilitates the assessment of all accident types in a coherent manner, rather than based on multiple databases with different inclusion criteria. All accident types are sampled from the same period and for the same parameters using a set of standardised rules. More definitive conclusions on ASA policies could therefore be drawn. For example, Kirkland's work (Kirkland et al. 2003a) considered overruns but not undershoots or crashes after take-off. Having included the latter two types of accidents for modelling, the current study provides the complete analysis of RESA and PSZ needs.

The building of such a comprehensive accident database per se is a breakthrough and provides a strong basis for future studies. The California Department of Transportation (2002) has in the past signalled the importance of such a database.

6.2.3 Normal operation risk exposure

Another major methodological advance of this study is the use of normal operations (i.e. non-accident flight) data for risk modelling. Various studies have already identified the lack of normal operations data (NOD) as a major obstacle to the development of quantitative risk models (DOT 1979, Piers et al. 1993, Khatwa et al. 1996, Khatwa & Helmreich 1998, Eddowes et al. 2001, Li et al. 2001). For example, a NLR study on the impact of crosswind on aircraft operations noted that "the significance of [risk] factors can only be established when the number of non-accident flights, under identical circumstances is known" (Van Es et al. 2001). Enders et al. (1996) stated that the unavailability of NOD hampered the calculation of accident occurrence rates and the ICAO concurs that the absence of NOD "compromises the utility of safety analysis" (ICAO 2006). Indeed, 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 may have also experienced the factor without incident. With NOD, the number of operations that experience the factor singly and in combination with other factors could be calculated, so risk ratios could be generated and the importance of risk factors quantified. This would allow the allocation of resources for safety improvement to be prioritised (Enders et al. 1996).

This thesis represents an important step forward in the field of airport risk assessment in collecting a large and representative sample of disaggregate NOD covering a range of risk factors, allowing their criticality to be quantified. Incorporating this risk exposure information into the accident frequency model enhances its predictive power and provides the basis for formulating more risk-sensitive and responsive ASA 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 ASA regulations are accounted for using the models developed in this study. Moreover, this normal operations database is not only valuable for the current project but can also be used for future studies. The detailed source and sampling strategy of this database is described in Chapter 9.

6.2.4 Factors considered

Only in human factor and crew resource management analysis is the use of NOD relatively established. Khatwa and Helmreich (1998) used Line Operations Safety Audits (LOSA) to analyse crew errors during non-accident flights. Work at the University of Texas at Austin (Helmreich et al. 1999, Klinect et al. 1999) also used LOSAs to build conceptual models that represent the operating environment.

Beyond human error analysis, the use of NOD in risk assessment is limited, especially for airport-related risks. Enders et al. (1996) and Roelen et al. (2000) used aggregate NOD to establish risk ratios for various risk factors such as the availability of Terminal Area Radar and other airport navigational aids. Many attempts to incorporate NOD in risk assessment failed because the available risk exposure data does not allow subdivision in movements based on the risk factors of interest (Piers 1994, 1998a). Kirkland et al (2003a) broke new ground in the use of disaggregate NOD for assessing aircraft overrun risk. Using a limited sample of NOD, three overrun risk models were built. Two of them assessed overrun risk based on aircraft weight as a percentage of the maximum take-off and landing weight respectively and the third model considered landing overrun risk based on the distance of excess runway available. Although some insightful conclusions were drawn, the number of risk factors that could be modelled remained small.

One notable gap in research is the quantification and modelling of the criticality of meteorological risk factors to accident occurrence. The lack of data on flights' exposure to meteorological conditions meant traditional risk assessment had to rely on qualitative judgements (Eddowes et al. 2001) or simply ignore meteorological conditions as risk factors, as do most ASA policies. Although Enders et al. (1996) acknowledged that adverse weather conditions is one of the most regularly cited factors in accident reports, they were unable to include the terms in their analysis. Kirkland also cited the lack of meteorological NOD as a major shortcoming of his work (Kirkland 2001a). The current study was able to collect exposure data on a range of meteorological parameters and include them in accident frequency modelling – ceiling height, visibility, crosswind, temperature, fog, precipitation, electric storm, snow, frozen precipitation and icing conditions. Other factors not commonly modelled were also taken into account, e.g. airport hub size, terrain surrounding the airport, dawn and dusk conditions as well as foreign or domestic operation. This is in addition to the more traditional parameters of aircraft, engine and operation type. The current research is thus able to provide a far more comprehensive analysis of risk factors relevant to airport risk assessment and develop state-of-the-art frequency models of accident occurrence covering an unprecedented spectrum of risk factors.

6.2.5 Enhanced modelling capability

Using disaggregate, multidimensional NOD, the accident frequency modelling capability of the current study is much better vis-à-vis former works in the field. The depth and breadth of the risk exposure data collected meant that multiple risk factors could be modelled in a single analysis, as opposed to a series of one-dimensional analyses, as in Kirkland et al. (2003a) and Enders et al. (1996). The multidimensional model developed adjusts for the joint influences between risk factors and provides a single risk formulae for the combined effects of multiple risk factors. It is able to offer risk estimates for individual flights as well as assess the risk profile of an airport with specific traffic and environmental characteristics. The increased modelling capability and flexibility add much value to the models as risk assessment tools. The use of multidimensional NOD and multivariate modelling is hence another important breakthrough in airport risk assessment methodology.

6.3 Causal Association

6.3.1 Caveats of causal modelling

In principle, aircraft accident frequency could be calculated by considering all possible cause-effect relationships that lead to aircraft mishaps (Piers et al. 1993, DfT 1997). Regulators such as the Dutch government have long desired to develop such a fully causal model. The advantages of such a causal model are clear. It would capture the precise cause of accident occurrences and allow a definite assessment of the effectiveness of risk mitigation measures (Hale et al. 1999, Hale 2002). A series of studies have therefore been carried out to develop a causal model of air transport safety (Roelen et al. 2000, 2002 2004, Ale et al. 2005). Whereas a modelling framework involving Bayesian belief nets has been presented, the effort has not to date produced a full working model.

A number of fundamental issues hinder the development of a fully causal accident frequency model. Causal modelling emphasises the identification, quantification and prediction of accident causal factors. However, causes of accidents are theoretically infinite in number. Accidents rarely have a single cause but are usually multi-layered events involving simultaneous failure of multiple systems and the compounding and interaction of technical, human and cultural causal factors (DOT 1979, Piers et al.

1993, Khatwa et al. 1996, Khatwa & Roelen 1997, Maurino 1997, Roelen et al. 2002, Rose 2004, Hale et al. 2006). The large number of accident causation and occurrence scenarios would lead to a combinatorial explosion in quantitative techniques such as fault-tree analysis and Bayesian belief nets, resulting in an extremely complex and inefficient model (Roelen et al. 2002, Brooker 2006). Simplifications and the use of numerous assumptions are thus necessary.

The lack of relevant data is another key difficulty in developing causal models. Even if all accident causes could be exhaustively identified, some of them would certainly be hard to quantify, e.g. cultural and organisational factors, let alone accounting for their complex interrelationships (DfT 1997). It is inherently difficult to predict the occurrence of infrequent events and the use of too many assumptions may lead to unrealistic risk estimates (Brooker 2006). The general lack of data led an earlier NLR study as well as other researchers to conclude that even relatively rudimentary quantitative causal models are not feasible (Piers et al. 1993, Piers 1998a). Beyond a certain level of detail, the modelling of causal risk factors must rely on human estimates (Hale et al. 1999), which contradicts the purpose of developing statistical models to lessen the role of expert judgements on decision-making.

The complexity and huge data burden of causal models not only contribute to their difficulty in development but also mean they are strenuous to use and apply. If a model is only accessible to a small number of specialists removed from the decision-making process, it would vastly reduce its value as a risk assessment tool.

6.3.2 The empirical approach

The accident frequency model developed in this study is essentially an empirical one. Rather than depending on the exhaustive identification and modelling of accident scenarios, it relies on historical records of actual accidents as a basis of risk assessment. Studying the experience of previous accident occurrences has been identified as a crucial element of and the most appropriate approach to risk assessment (Smith 1995, Goossens & Hale 1997). The use of historical data is often preferred to theoretical estimates because the former represents real world observations (Roelen et al. 2004). While two accidents are never identical, much can be learnt from the similarities and differences of previous incidents as accidents are not just random combinations of events (Roelen et al. 2002, Muir & Thomas 2004). In a multi-causal system as that of aircraft accident occurrence, it would be reasonable to assume that the frequency of accidents at a particular location is comparable to that of another site with a similar risk exposure profile, without specific consideration of causal inferences (Piers et al. 1993). As in former works in the area, such as Enders et al. (1996) and Li et al. (2001), the current study identifies and quantifies risk factors that demonstrate a positive association with accident occurrence without implying causality. Past empirical models have been found to be broadly compatible with each other (DfT 1997). With the comprehensive accident database developed as part of this research, the analysis could be conducted with even greater confidence and statistical validity. Unlike the causal models that set out to explicitly identify and model causal relationships, the approach adopted is less complex, have more realistic data requirements and is easier to implement for aviation stakeholders. The approach used is also similar in structure and rationale to existing methodologies used by the international aviation regulatory community and would therefore be more readily accepted and implemented.

6.3.3 Limitations of the selected methodology

There are two key criticisms of the selected approach to risk assessment based on demonstrated associations between risk factors and accident occurrence using historical accident data. The first concerns the inability to imply causality, which is seen as a failure to explicitly explain the root causes of accidents and formulate strategies accordingly (Piers et al. 1993). However, the core concern of the present thesis is in developing a predictive model of accident occurrence, rather than drawing conclusions on accident causation. While the value of being able to make inferences on causality is acknowledged, the predictive ability of the risk models is of prime interest to ASA policy makers (Hale et al. 1999). As a matter of fact, the Dutch and British studies on land-use planning and PSZs only computed accident frequency based on aircraft and operation type without any consideration for causality. By taking into account a range of additional risk factors, the current study has already implicitly expanded the model's causal dimension compared to existing methodologies, while avoiding the practical difficulties of full causal modelling as described in section 6.3.1.

The second criticism centres on the use of historical accident data. With the general long-term decline in accident rates and the continued safety improvements advanced by organisations such as the FAA, NTSB and European Aviation Safety Agency, accident rates based on historical data would overestimate current risks (DfT 1997). At least in principle, accident investigations lead to changes in the system such that similar accidents would not occur again (Brady & Hillestad 1995, FAA 1997). Historical models, then, cannot account for future accident scenarios (Hale 2002). The problem is especially acute for causal models because the analysis is based on explicitly identifying and modelling specific chains of events that lead to accident occurrence. Not only is the current research approach free from explicit causal inferences, the inclusion of a multitude of risk factors also lessens the impact of the improvement of any individual aspect of the safety system which is multi-layered. As to the overall trend of safety improvement, previous improvements in equipment and procedures have only resulted in relatively stable developments in safety levels (Piers et al. 1993). While acknowledging that the use of historical data may overestimate current accident rates, Eddowes et al. (2001) concluded that it is still within the general bounds of uncertainty of risk assessment.

6.4 Structure of Analysis

The current risk analysis and modelling were carried out in three major parts – univariate, bivariate and multivariate analyses. Previous studies of aviation risk, such as Li et al. (2001), have a similar structure. The univariate analysis considers the nature and characteristics of accidents alone. Bivariate analysis then draws on the NOD and uses normal flights' exposure to risk as the basis for characterising and quantifying the criticality of a series of individual risk factors. The multivariate analysis then builds accident frequency models that are capable of taking into account the combined effects of multiple risk factors. These and the development of the accident database are the contents of the subsequent chapters of the thesis. The detailed methodology of each part of the analysis is presented in the relevant sections.

CHAPTER 7 THE ACCIDENT DATABASE

As with other safety issues, conclusions on the need of ASAs cannot be based on isolated events or anecdotal information (ICAO 2006). However, the low accident rate of aviation means that no particular airport has sufficient accident occurrences in the recent past to support a model with reasonable statistical confidence (Piers et al. 1993, Piers 1994, Hale 2001). Therefore, a robust risk assessment must draw from a large database of relevant accident cases. The development of such a comprehensive database that brings together all accident types that matter to ASA dimensions is a major contribution of the current research to the field of airport risk assessment. This chapter describes its development. This phase of the project took over two years and was undertaken with other members of the EPSRC research team.

7.1 Accident Types Included

ASAs are safety measures aimed at aircraft take-off and landing accidents. Accident types commonly associated with the safety areas include overruns, veer-offs, undershoots, crashes after take-off and third party accidents. However, these accident classifications are based more on consequence than cause. For example, third party accidents may simply be undershoots or crashes after take-off if no third parties were present. Similarly, an aircraft overrunning the runway end and another veering off the side of the runway are often just different manifestations of the same root problem, differing only in crash kinematics and airfield conditions. The current database classes all take-off and landing related accidents under four categories – landing overruns (LDOR), landing undershoots (LDUS), take-off overruns (TOOR) and crashes after take-off (TOC). This classification essentially separates landing and take-off accidents then ground-based and airborne accidents. This facilitates their analysis by cause rather than consequence, which is especially appropriate for developing the accident frequency model. Incorporating third party accidents within these four accident types instead of considering them in isolation reflects the geographically continuous nature of accident risk. Keeping the number of accident categories to a small number also helps to increase the statistical significance of subsequent analyses and models.

Appendix A presents the detailed classification scheme of all accident types. Only cases in which at least one ASA was directly challenged were included in the database. This means that the aircraft has exited from the 'normal' areas of operation on the airfield, e.g. veering off the runway or hitting obstacles on landing or take-off.

Some accidents are very complex and may not fit intuitively into one of the four types of accidents to be studied. The United Airlines Flight 232 accident in Sioux City of July 1989 is a good case in point. The flight has already encountered severe controllability problems during approach but with exceptional piloting skills it touched down on the runway then veered-off onto a field (NTSB 1990). Accidents involving complex accident sequences are classed according to the first instance where an ASA was challenged, which in this case was a landing overrun. Although it is acknowledged that the accident could have easily resulted in an undershoot instead, it is impossible to accurately predict alternative crash sequences, let alone assign probabilities to each scenario. The adopted approach is in line with the essence of empirical research, which relies on historical data to provide realistic and credible data, avoiding the inherent modelling uncertainties of the deterministic approach.

7.2 Data Source & Fields

The database was intended to include all relevant accidents in the major English-speaking countries of the developed world. Priority was given to collecting data from the US for a number of reasons. The US represents the largest national aviation system in the world in terms of air traffic, aircraft and airfields. The US NTSB is also the largest aviation accident investigator with an established database of accidents that have been investigated in a relatively systematic and consistent manner. The preference for studying US aviation safety data has been echoed by other studies such as Button & Drexler (2006).

A list of relevant accident parameters was drawn up based on previous risk assessment studies and discussion within the research group. These data fields covered a multitude of parameters including aircraft, flight and airport characteristics, weather conditions, wreckage location and injury levels. Appendix B provides the full list of data fields of the accident database. The NTSB online accident database alone is not sufficient for the purpose of the current research. Therefore, as with

Kirkland (Kirkland 2001a), it was necessary to obtain individual accident reports and docket files from the NTSB. Accident reports are only published for relatively serious accidents but a docket file is available for all incidents investigated by the NTSB, even though the amount of information contained in each docket varies greatly. From these sources all available relevant information was extracted. Certain variables required additional calculation based on available data. For instance, crosswind strength was computed from data on wind direction, wind velocity and true runway orientation. The definitions of individual data fields and rules regarding how the database was completed are detailed in Appendix C. The database took two full-time researchers approximately two years to complete. This involved collecting the relevant documents from the NTSB and its subcontractor General Microfilm Inc., reading them in the form of electronic files, hard copies or microfiche, extracting the relevant data, checking for consistency and applying judgement where necessary then inputting the information into a database systematically.

7.3 Accident Inclusion Criteria

Other than directly challenging at least one ASA or impacting ground or obstacles within 10km of the landing or take-off runway threshold, a number of other criteria were used to filter the NTSB accident database to identify the accidents of interest. These filters and their justification are given in Appendix D. In essence, they eliminate cases that involve airports outside the US, irrelevant aircraft types and operations as well as accidents with minimal consequences. These filters were developed considering data availability and quality, compatibility with the normal operations data, the need for statistical significance, relevance to large and small airports as well as the criteria used by previous airport risk assessment studies. The 10km cut-off was considered appropriate and slightly conservative since airfield effects on crash risk is judged to be relevant up to 8km from the airport boundary (Phillips 1987).

The final database contains all relevant accidents between 1982 and 2002 inclusive, totalling 440 cases, of which 199 are landing overruns, 122 are landing undershoots, 52 are take-off overruns and 67 are crashes after take-off. The breakdown of these cases by accident type and aircraft FAR part is shown in Table 7.1.

Table7.1 Breakdown of accident database by accident type & aircraft FAR part

FAR part	LDOR	% LDOR	LDUS	%LDUS	TOOR	%TOOR	TOC	%TOC
091	90	45.2%	42	34.4%	19	36.5%	29	43.3%
121	42	21.1%	15	12.3%	12	23.1%	16	23.9%
129	1	0.5%	2	1.6%	2	3.8%	1	1.5%
135	63	31.7%	60	49.2%	19	36.5%	21	31.3%
Public Use	3	1.5%	3	2.5%	0	0.0%	0	0.0%

7.4 Data limitations

Quantitative as well as qualitative limitations of accident data 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 analysis is restricted by the availability and quality of the data extracted from NTSB docket files. The major data limitations are outlined below.

7.4.1 Missing data

The NTSB accident investigation records principally consist of a number of standard forms and reports. Even within these standard areas of interest, it is extremely rare that every field is filled in. The docket files of minor accidents frequently contain less than a dozen pages of forms accompanied by a brief synopsis of the occurrence. The accident wreckage site is often only given by a very crude description without supporting maps or diagrams. Just a small proportion of data fields are systematically recorded for every accident. The amount of missing fields in the database is therefore high, restricting the number of parameters that could be analysed.

The docket files contain mostly information which the accident investigators deemed relevant to an accident's occurrence. Outside of this judgement, few potential risk factors are included. This is a major handicap in building a database that consistently and systematically records a set of risk exposure parameters. The data available for analysis and model-building ultimately depended on the NTSB's accident investigation mentality and policies. Besides, there is no alternative source of data. The problem is especially acute concerning unconventional or latent risk factors beyond the well established sources of risk such as airframe and engine failure. Parameters such as weight and runway criticality that require additional calculation are often impossible to compute because of missing data.

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

7.4.2 Poor data quality

Former studies using data from accident reports and docket files have already reported on the poor data quality (Hagy & Marthinsen 1987). Erroneous or conflicting information within the same docket is not uncommon. One example is that the wreckage location diagram provided 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 judgement to obtain a final figure according to the best information available.

7.4.3 Inherent 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 rely mostly on pilots' subjective reporting. However, runway surface conditions may change rapidly according to precipitation, temperature, usage and runway treatment so actual conditions may differ significantly from that which was reported (FAA 2006b). Icing conditions too are known to be difficult to determine despite their important impact on aircraft performance (Winn 2006).

The reporting of meteorological conditions in general is not as straightforward as it seems. The weather measured from ground stations may vary significantly from that experienced by the accident flight (Jerris et al. 1963), especially if the weather station is located far from the accident location, although the latter is only common among very remote airports. Another difficulty lies with the dynamic nature of meteorological conditions. Wind strength and direction may constantly change during the course of an approach. It may not always be clear as to which reading is most relevant. Judgement must therefore be applied to enter the most appropriate reading into the database.

7.4.4 Unregistered accidents

When considering aircraft overruns, the issue of unregistered, or "dark-side", occurrences must be considered. These are flights that used more than the nominal runway distance required (take-off or landing) to complete the operation but without directly challenging ASAs due to excess runway available. As shown in Appendix A, these cases are normally considered as "normal operations" and would not feature in accident records. The same applies to operations that take up more runway width than normally required. Of equal concern are otherwise registered, or "semi-dark-side" cases, which exceeded the nominal runway distance requirement but are only reported as accidents for reasons other than challenging ASAs.

Although these dark-side cases may provide additional data to the database, it is not feasible to systematically identify them within the timeframe of the project. They are expected to be so rare that the amount of normal flight data needed to yield a meaningful number of dark-side cases is so great that it is beyond the means of the current study. Moreover, normal operations data on actual runway distance used proved difficult to obtain despite extensive efforts. Finally, the presence of excess runway may alter pilot behaviour such that more runway distance is used than otherwise.

7.4.5 Limited geographical scope

Due to subsequent time constraint, the project was unable to collect data from sources other than the NTSB. While more data would allow additional statistical confidence in the model building, the gathered NTSB data provided nonetheless a solid basis from which statistical models could be developed. Besides, focusing on a specific aviation system gives a more homogenous set of data for analysis, eliminating the issue of comparability between national safety records and practises (DfT 1997).

7.5 Incidents

Given the limited time and resources available, the thesis concentrated on occurrences with the greatest potential for safety improvement, i.e. accidents with at least minor damage or injury. It is acknowledged that by excluding incident data the project is not taking into account potentially serious occurrences. However, with the accident data, the models developed focus on factors that have, in reality, turned what could have otherwise been innocuous incidents into serious accidents. As such, risk assessment based on these models would also identify the more important risk factors. Including innocuous incidents in the database would affect the goodness of fit of the intended models. Furthermore, 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.

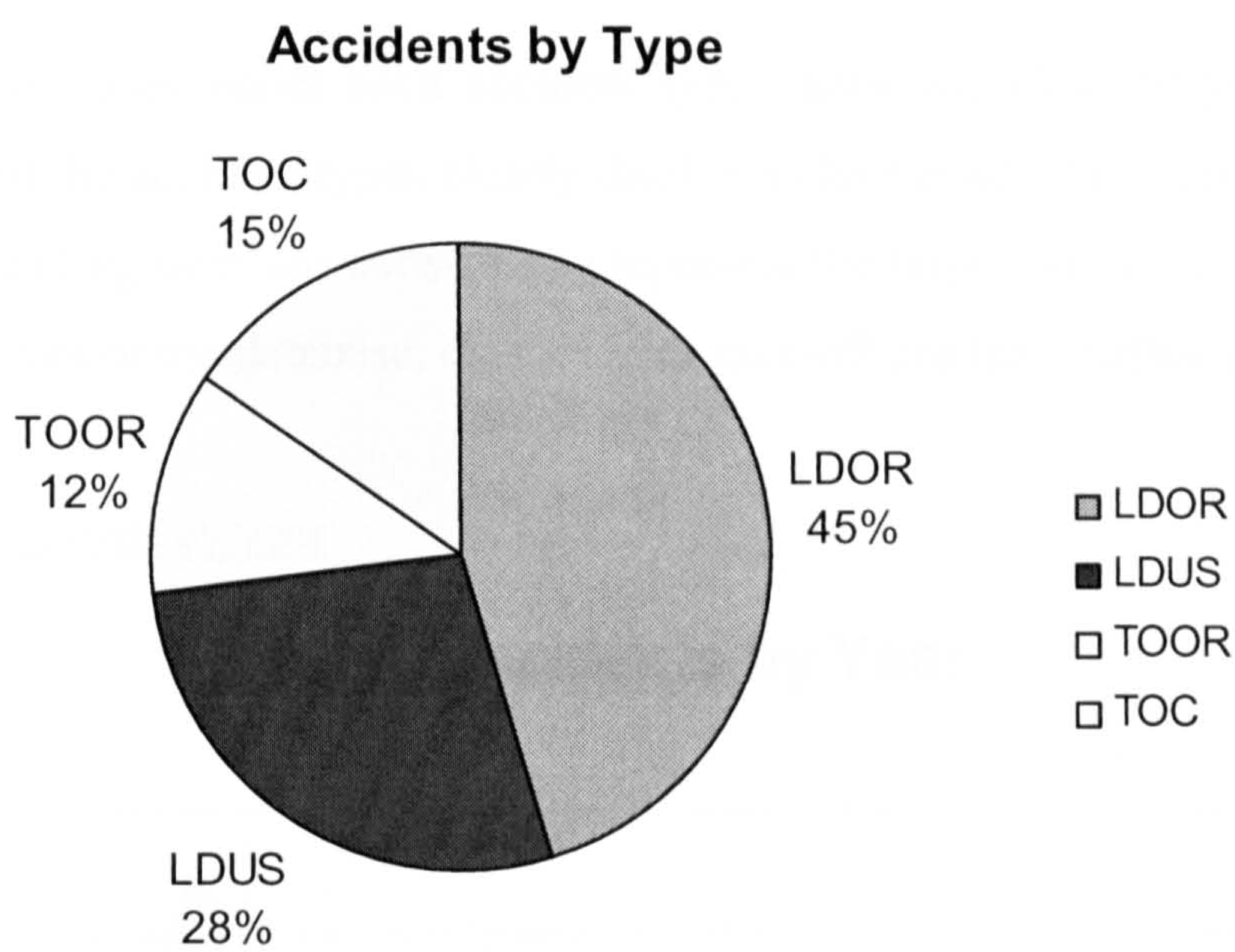
CHAPTER 8 UNIVARIATE ANALYSIS – ACCIDENT DATABASE ANALYSIS

This chapter presents the univariate analysis of the accident database before NOD was incorporated in later analyses. The analysis aims to give a basic description of the accidents in the database, provide a better understanding of their nature and background conditions and to allow comparisons to be made between the four accident types. As such, it builds a foundation for the subsequent bivariate analysis and multivariate modelling. Many previous studies have identified the causes and contributory factors of take-off and landing accidents. Examples include CAA (1998), CAST (1999), FSF (2000) and Thurber (2006). This thesis does not repeat that exercise but examines the prevalence of a number of key risk factors that are relevant to the core objectives of the research, i.e. quantifying the criticality of risk factors and building predictive accident frequency models. Numerous references report that poor weather conditions such as adverse wind conditions and low visibility are associated with take-off and landing accidents (FSF 1999, NTSB 2005, 2006b, Veilette 2006). Special emphasis was therefore placed on providing a comprehensive study of the pervasiveness of poor weather conditions in ASA-related aircraft mishaps.

8.1 Database Overview

The breakdown of the database by accident type is given in Figure 8.1. The database is clearly dominated by landing accidents. The ratio of landing accidents to take-off ones is 1:2.7. Landing overruns and undershoots together account for over 70 percent of occurrences over the period. Kirkland's overrun database had a similar split of landing and take-off cases (Kirkland 2001a).

Figure 8.1 Accident database breakdown by accident type

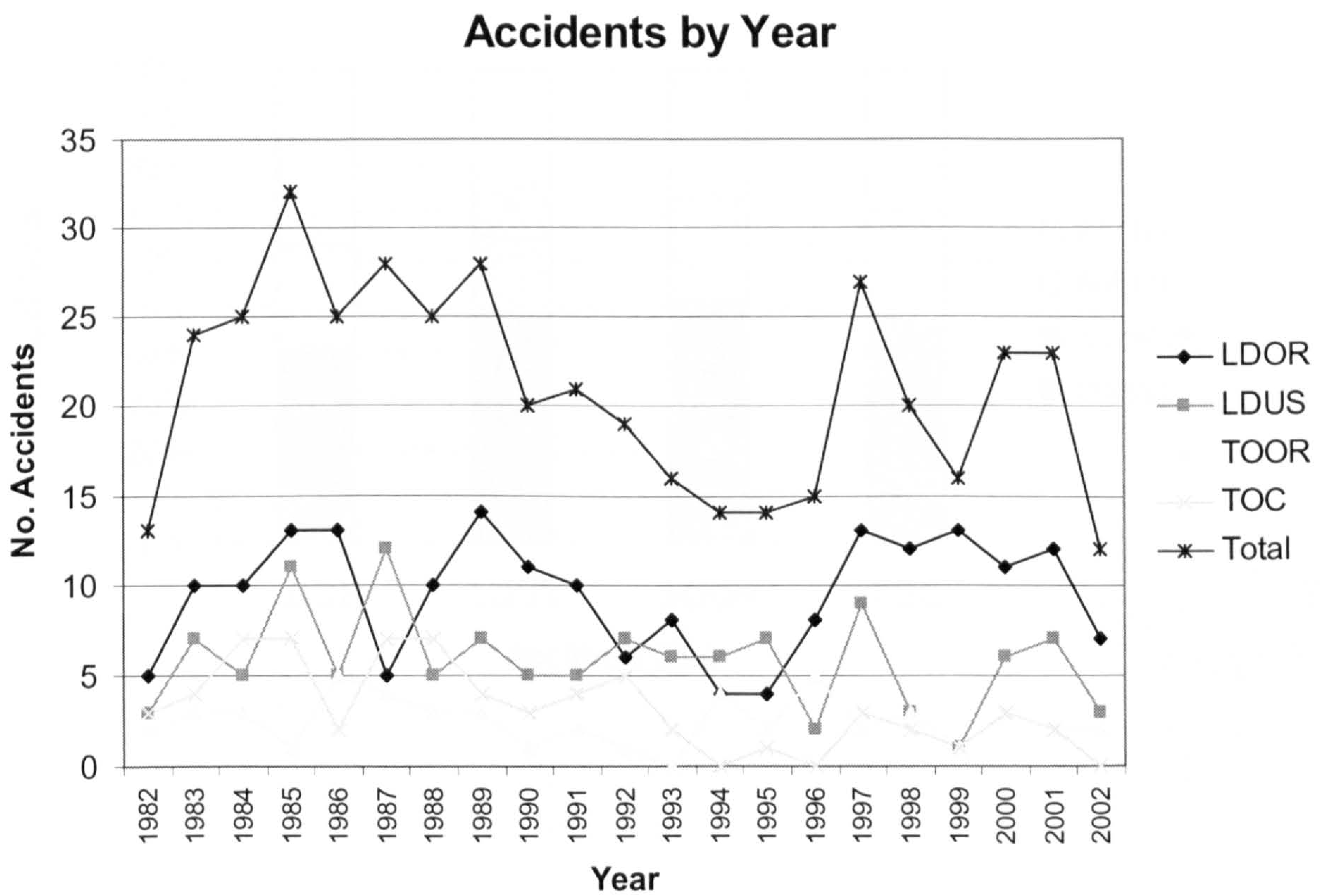


8.2 Accidents by Year

Figure 8.2 shows the evolution of the number of cases under each accident type as well as the total number of ASA-related accidents since 1982. Considerable fluctuation in the number of total cases per year can be observed. While there appeared to be a period of decline in the total number of accidents between 1991 and 1996, the situation has since peaked in 1997 with 27 occurrences and fallen to only 12 in 2002. The large fluctuations suggest that fitting a trend line to the data would not be meaningful.

The number of cases under each accident type varies significantly year-to-year as well. None of the accident types clearly display a clear trend of increase or decrease. Since 1996, landing overruns consistently represent the largest group of accidents. In the last five years of the database, crashes after take-off are the smallest group.

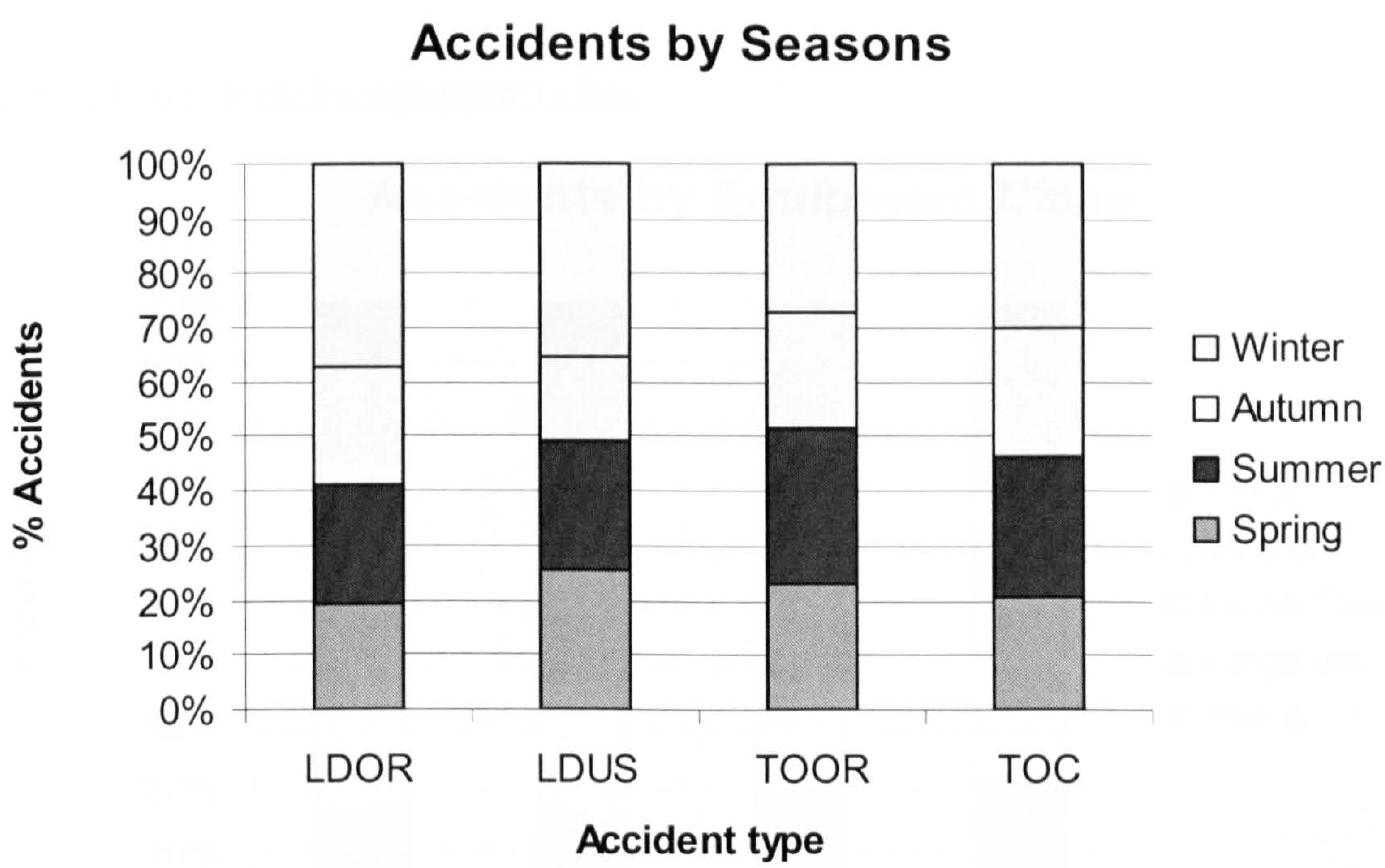
Figure 8.2 Accidents by year



8.3 Accidents by Month

The accidents were also grouped by month of occurrence. It was observed that a significant portion of accidents occurred during the winter months. Considering December, January and February as the winter season, the latter accounts for 34 percent of all cases of the database. With the exception of take-off overruns, more accidents occur in winter than any other season. Figure 8.3 shows the breakdown of accidents by season of occurrence. Winter-related incidents feature especially prominently for the two landing accident types. 37 percent of landing overruns and 35 percent of landing undershoots occurred in winter. Similar findings were reported by Kirkland (2001a) who found a higher proportion of overruns between November and February than in the rest of the year. This suggests that winter conditions is a potentially significant risk factor that warrant further analysis.

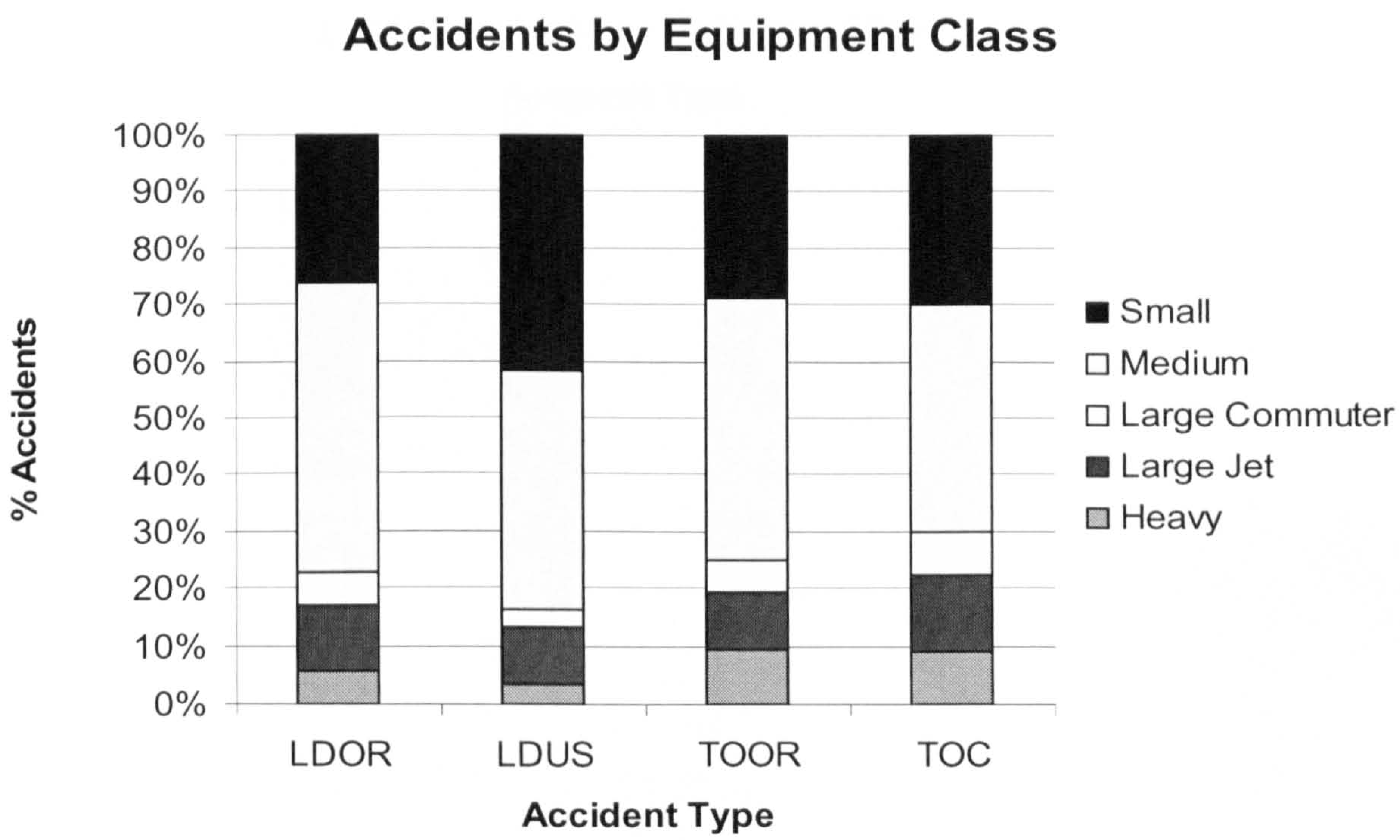
Figure 8.3 Accidents by season



8.4 Equipment Class

Small and medium aircraft dominate each accident type in terms of equipment class (Figure 8.4). These are aircraft with a maximum take-off weight (MTOW) of 41,000lbs or under. Medium size aircraft typically include business jets such as the Learjet 35 while small aircraft are under 12,500lbs, e.g. the Beech 90. Large jets include those above 41,000lbs up to 255,000lbs, such as the B737 and A320. Large commuters are in the same weight bracket but are generally smaller than large jets, e.g. regional jets. Heavy equipment refers to aircraft of MTOW more than 255,000lbs. Together, medium and small aircraft make up more than 70 percent of all accidents. The figure is even higher for landing undershoots at 84 percent. Although the public's attention usually focuses on large aircraft mishaps, the accident database consists of many more cases involving smaller aircraft, which may differ significantly in nature from the high-profile accidents. It could also be observed that a larger share of take-off accidents involve heavy equipment than landing accidents.

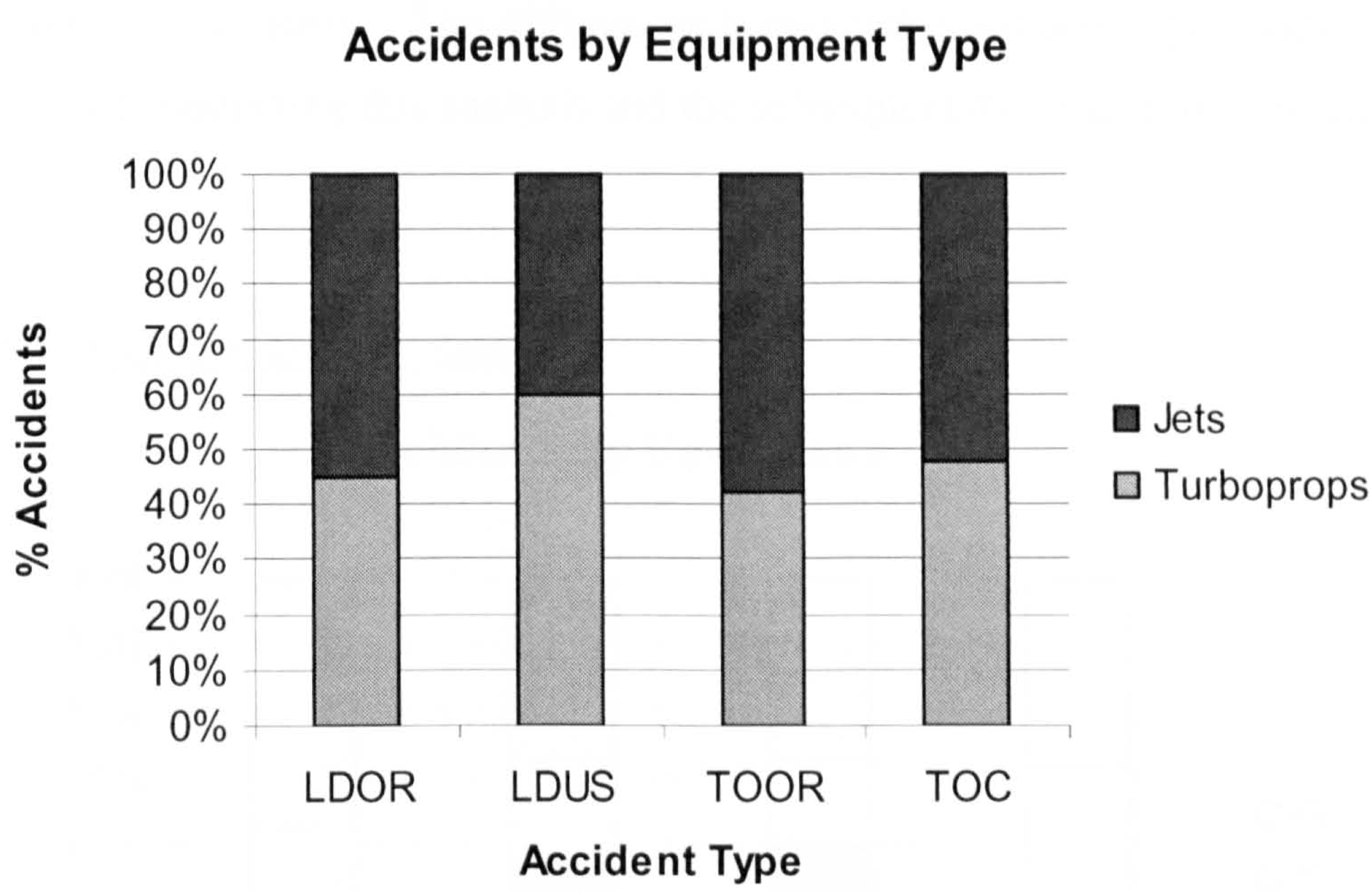
Figure 8.4 Accidents by equipment class



8.5 Equipment Type

The split between turboprops and jet aircraft is fairly similar across all accident types, varying from 42 percent turboprops for take-off overruns to 60 percent for landing undershoots (Figure 8.5). Overall, overrun accidents involve a higher share of jets (average 56 percent) than airborne accidents (average 46 percent).

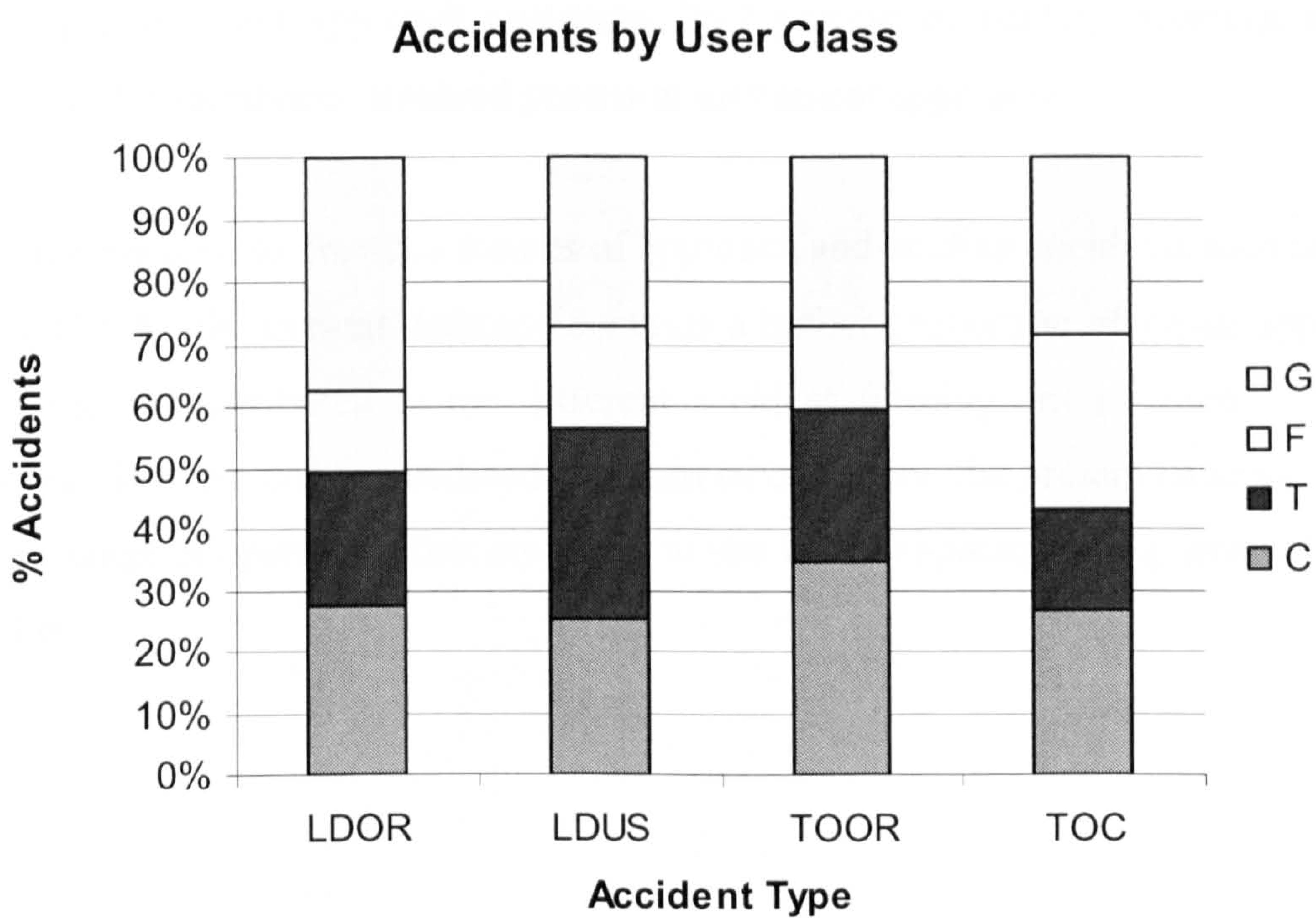
Figure 8.5 Accidents by equipment type



8.6 User Class

The accident database was also broken down by user class, i.e. operation type (Figure 8.6). Commercial operations account for no more than roughly a third of the cases under each accident category. Air taxis are especially prominent for landing undershoots, representing 31 percent of the accident type whereas the average is only 24 percent. Crashes after take-off have a higher share of freight operations than all other accident types. By contrast, landing overruns have the highest proportion of general aviation incidents. The differences between the accident types highlight the importance of conducting this analysis and the subsequent modelling in a disaggregate manner.

Figure 8.6 Accidents by user class



8.7 Foreign Origin or Destination

Only a very small proportion of accidents involve flights with a foreign origin or destination. These flights account for an average of 4.9 percent of all accidents but this varies from 1.0 percent for landing overruns to 11.5 percent for take-off overruns.

8.8 Hub Type

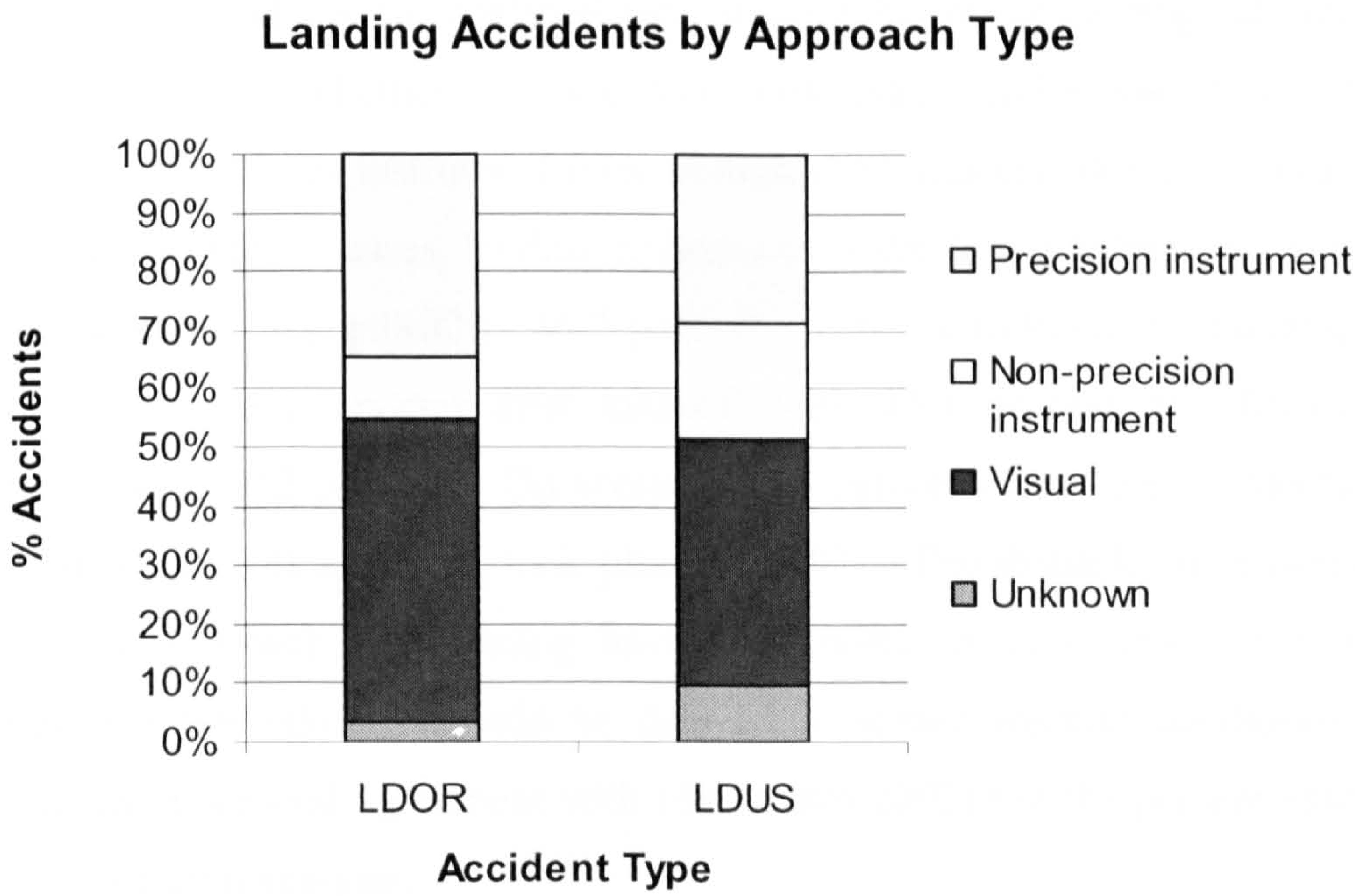
The accidents were grouped by the size of the airports at which they took place. The 2001 FAA airport statistics were used to class airfields as hubs or non-hubs. The former include small, medium as well as large hubs according to conventional FAA definitions while non-hubs include all other airports, including non-hubs, non-primary and non-commercial service airfields. Without exception, more than half of the cases involve non-hub airports. They make up roughly 70 percent of all accident types except crashes after take-off, the figure for which is 52.2 percent.

8.9 Approach Type

The database was also analysed for the approach type that was used in landing accidents. As shown in Figure 8.7, just over 50 percent of landing overruns involved visual approaches. The figure is slightly lower for undershoots but the approach type used was unknown for approximately 10 percent of undershoots. Nevertheless, visual approach is the most common approach type for both classes of accidents. Among instrument approach accidents, 76.7 percent of landing overruns and 59.3 percent of undershoots involved precision instrument approaches.

When compared to previous studies of approach and landing accidents such as Enders et al. (1996), the current database contains a higher proportion of visual approaches. This may be attributed to the different accident filtering criteria used. Whereas Enders' database only considered commercial operators, the present database covers a wider range of operations that are likely to use visual approaches, e.g. general aviation flights.

Figure 8.7 Accidents by approach type



8.10 Go-around

Due to the poor quality of the accident data, it was not possible to gauge the prevalence of go-around operations among landing accidents with confidence. For 38 percent of both landing overruns and undershoots, it was impossible to ascertain whether the accidents involved a go-around manoeuvre. For the remaining cases, 28.0 percent of landing undershoots followed a go-around and 16.9 percent of overruns did. This is intuitively correct as uncertain landing conditions are understood to be related to undershoots more than overruns.

8.11 Aborted Take-offs

For take-off accidents, the proportion of cases that involved aborted take-offs was considered. As expected, the share of accidents that entailed an aborted take-off is much higher for overruns than crashes after take-off. Aborted take-off was implicated in 67.3 percent of overruns but only 10.4 percent of crashes after take-off. The majority of the latter type of occurrence would involve a late aborted take-off that failed to prevent the aircraft from becoming airborne.

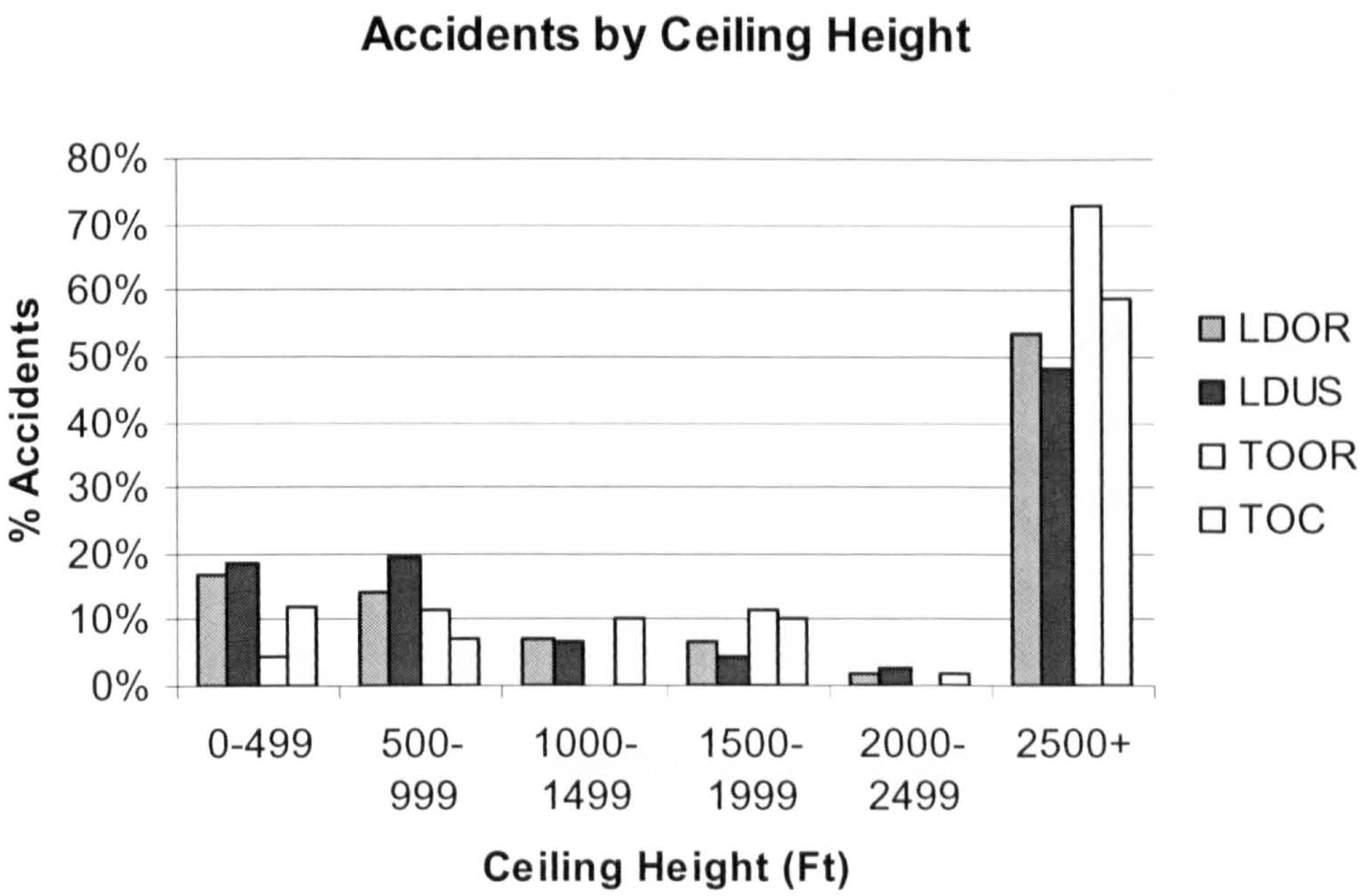
8.12 Visual and Instrument Meteorological Conditions

The accident database was analysed against a number of meteorological factors. The first of these is whether the accident took place under visual meteorological conditions (VMC) or instrument meteorological conditions (IMC). Considering the individual accident classes, landing undershoots were found to have the highest share of incidents involving IMC at 46.7 percent. This is followed by landing overruns with 36.7 percent, crashes after take-off with 25.4 percent and finally take-off overruns with 19.2 percent. On average, 40.5 percent of landing accidents and 22.7 percent of take-off accidents took place in IMC. The disparity is reasonable since flights on approach and landing have less choice as to whether to continue the operation while take-offs could be delayed in severe weather conditions. These results are in general agreement with (Benedetto 2002) but the present study did not involve a causal analysis.

8.13 Ceiling Height

The ceiling height in which the accidents took place was then examined. It was observed that, similar to VMC and IMC, the mean ceiling height for landing accidents was clearly lower than their take-off counterparts. Whereas the average ceiling heights were 1,963ft and 1,821ft for landing overruns and undershoots respectively, take-off overruns averaged 2,416ft and crashes after take-off 2,142ft. Figure 8.8 displays the percentage of cases of each accident type that occurred under different ceiling heights. It is evident that a greater share of landing accidents took place in the lower ceiling height categories (e.g. under 1000ft) than take-off incidents.

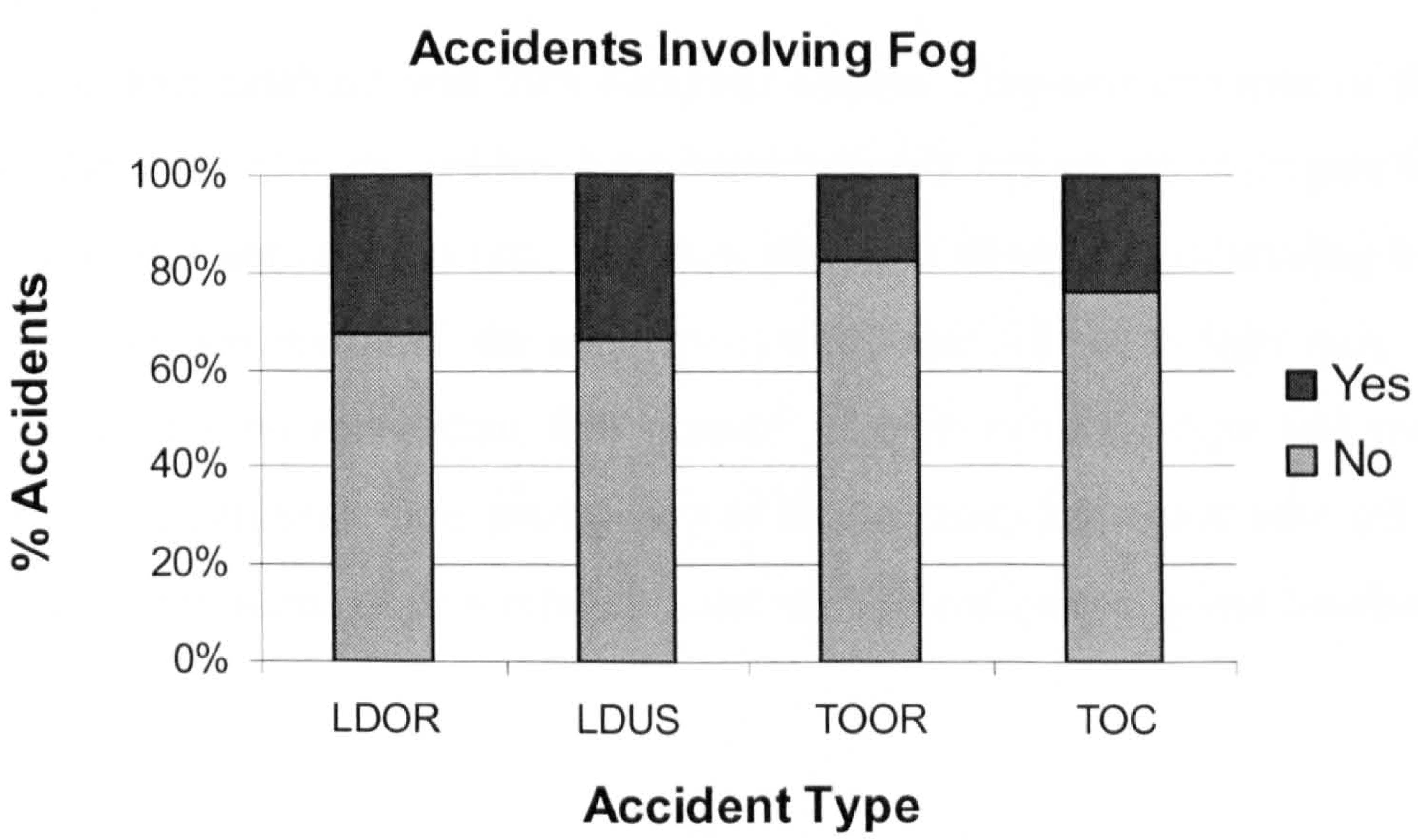
Figure 8.8 Accidents by ceiling height



8.14 Fog

The proportion of cases involving fog also shows an imbalance between landing and take-off accidents, as Figure 8.9 displays. More than a third of landing undershoots took place in fog but only 17.3 percent of take-off overruns did. This finding is consistent with the concept that flights on approach have reduced ability to avoid poor weather conditions compared to take-off operations.

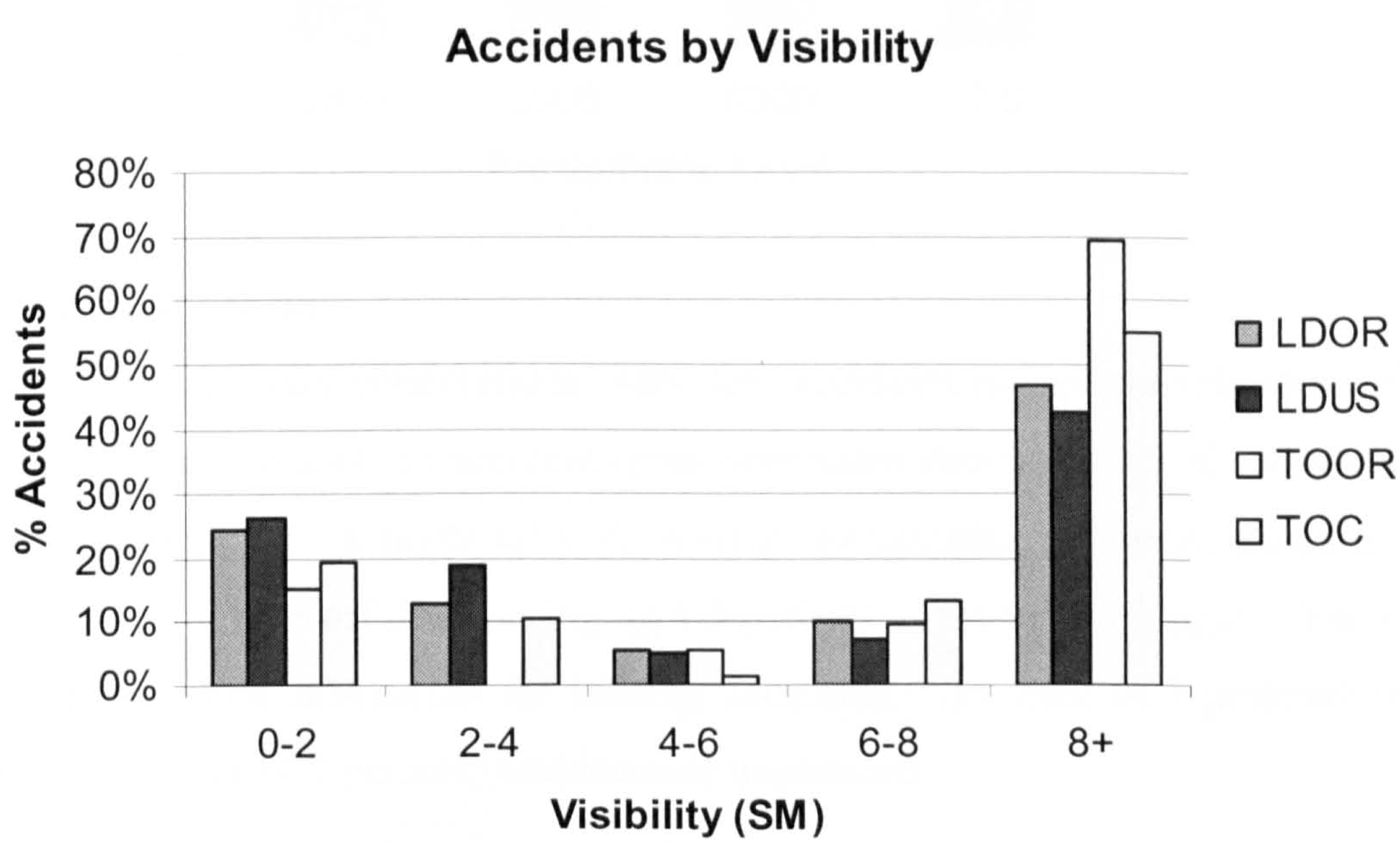
Figure 8.9 Accidents involving fog



8.15 Visibility

When the proportion of cases of each accident type that took place in different visibility conditions was assessed, a similar situation to that of ceiling height was obtained (Figure 8.10). There is again a greater share of landing incidents that occurred in low visibility compared to take-off accidents. 37.7 percent of landing overruns and 45.1 percent of undershoots occurred in visibility under four statute miles whereas the figures are considerably lower for take-off incidents, at 15.4 percent and 29.9 percent for take-off overruns and crashes after take-off respectively.

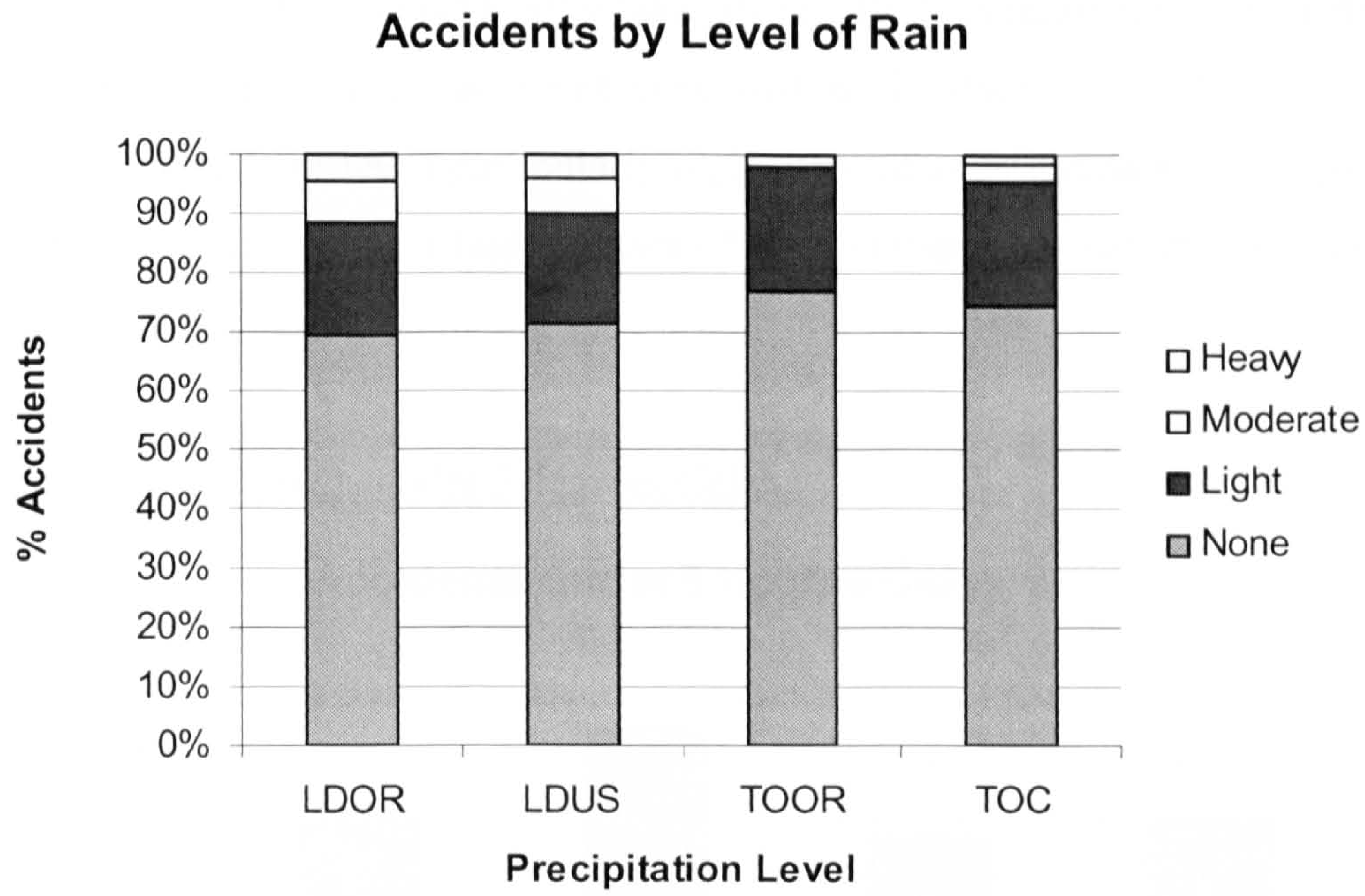
Figure 8.10 Accidents by visibility



8.16 Rain

The accident database was then analysed against a number of types of precipitation. First, the share of each accident type involving rain was assessed (Figure 8.11). Most accidents did not occur in rain, although just over 30 percent of landing overruns did. Where rain was involved, the majority of cases was related to light rain. Heavy rain accounted for no more than five percent of each accident type and moderate rain under eight percent. The prevalence of landing accidents over take-off accidents is not so clear in terms of rain-related incidents but could nonetheless be observed.

Figure 8.11 Accidents by level of rain



8.17 Electric Storm

Despite the common connotations, very few accidents actually involved an electric storm. In fact, none of the accident types have more than 5 percent of cases related to electric storms. Not a single take-off overrun encountered an electric storm and only one crash after take-off did, making up 1.5 percent of the accident type. The figures are slightly more substantial for landing accidents, with nine (4.5 percent) landing overruns and six (4.9 percent) undershoots implicated.

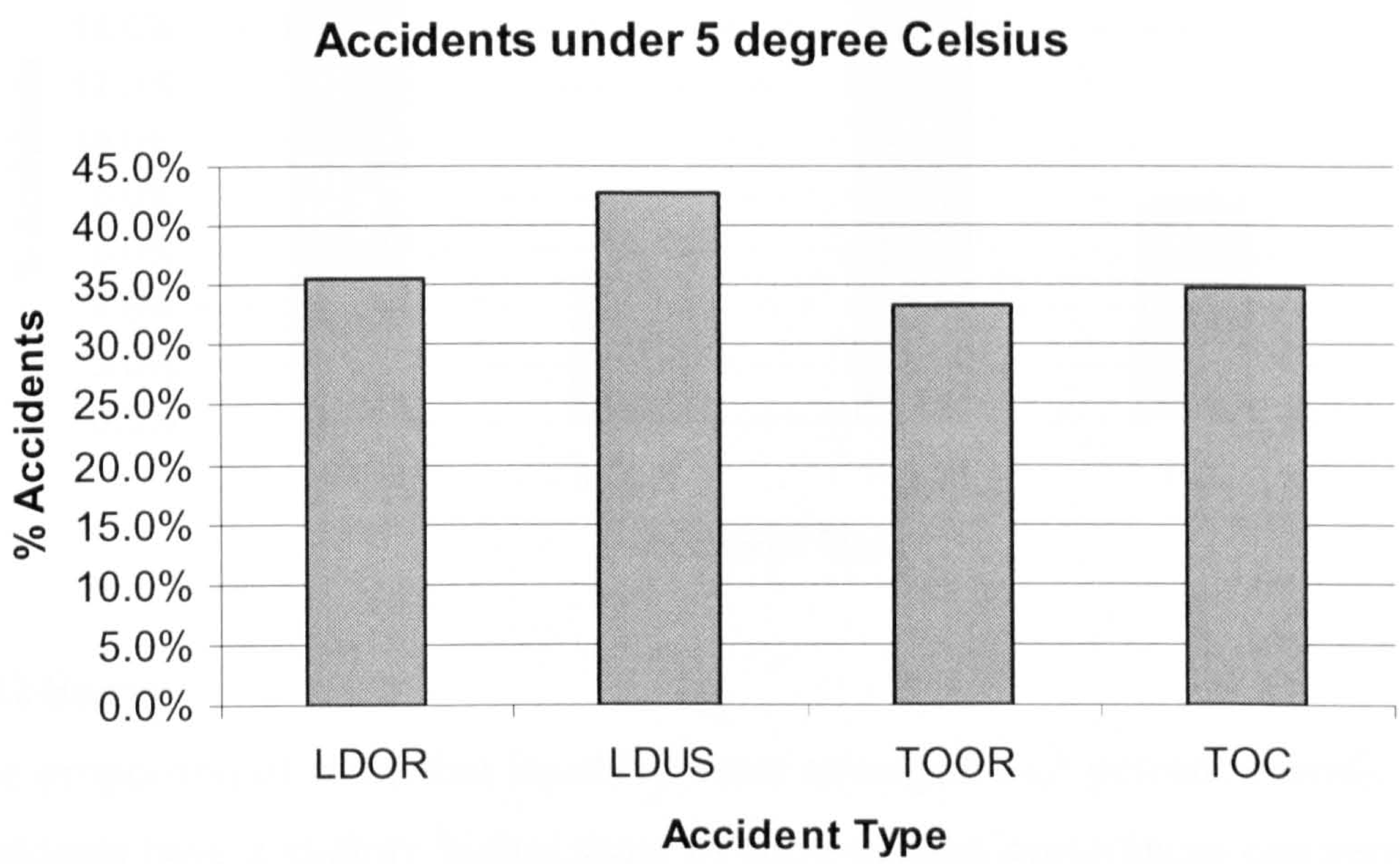
8.18 Frozen Precipitation

Similar to electric storm, the number of accidents that involved frozen precipitation, e.g. freezing rain and hail, is very small. Overall, only 3.4 percent of cases of the accident database encountered frozen precipitation. Considering the individual classes of accidents, crashes after take-off have a markedly higher share of frozen precipitation-related cases. 7.5 percent (five cases) of crashes after take-off involved frozen precipitation while only 3.1 percent, 2.5 percent and 1.9 percent of incidents were involved for undershoots, landing and take-off overruns respectively.

8.19 Temperature

On average, landing accidents took place in lower temperatures than take-off accidents. The average temperature in which landing overruns and undershoots took place is 10.8°C and 9.9°C respectively. Both are lower than the averages for take-off overruns (12.0°C) and crashes after take-off (11.4°C). Figure 8.12 shows the share of cases belonging to each accident type that took place in conditions under 5°C. Landing undershoot has a particularly high share of such incidents (42.7 percent) and landing overrun too has a higher share of low temperature occurrences than take-off accidents.

Figure 8.12 Accidents under 5 degrees Celsius



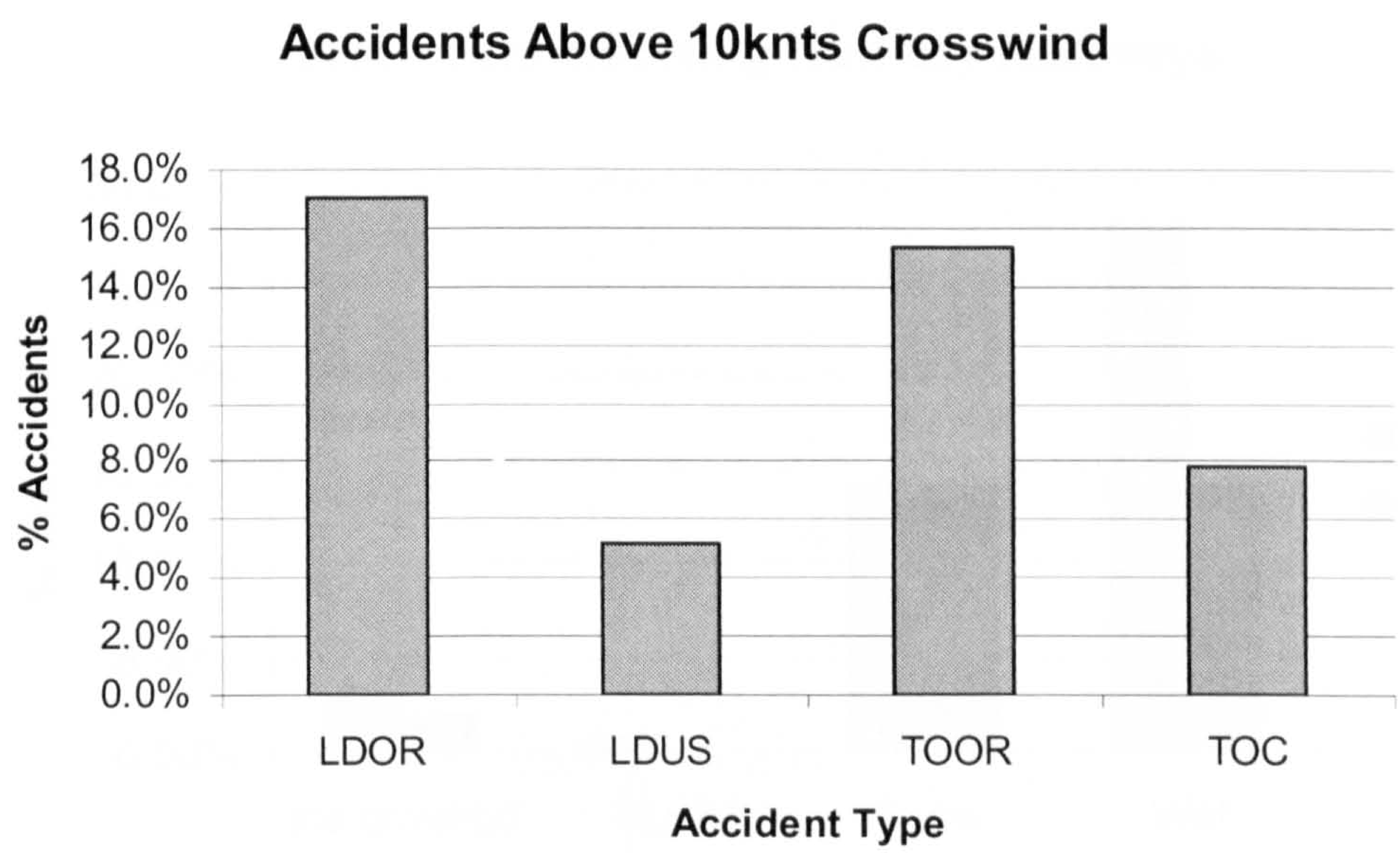
8.20 Icing Conditions

As expected, the results for icing conditions mirrored that of low temperature conditions, but to a smaller degree. Landing undershoot has the highest proportion of cases that took place in icing conditions (10.7 percent). It is also interesting to note that a substantially higher share of airborne accidents involved icing conditions than overruns. The former averaged 10.1 percent while the latter averaged only 5.6 percent.

8.21 Crosswind

From the information available, the crosswind experienced by the accidents was calculated and compared. 87.8 percent of all accidents occurred with crosswind of under 10knts. Considering the high crosswind cases of above 10knts, Figure 8.13 reveals the difference between overruns and airborne occurrences. High crosswind was experienced by a distinctly high proportion of landing and take-off overruns compared to undershoots and crashes after take-off. Even taking into account all cases in each accident group, the mean crosswind of both overrun types are higher than the respective means of either airborne accident types.

Figure 8.13 Accidents above 10knts crosswind



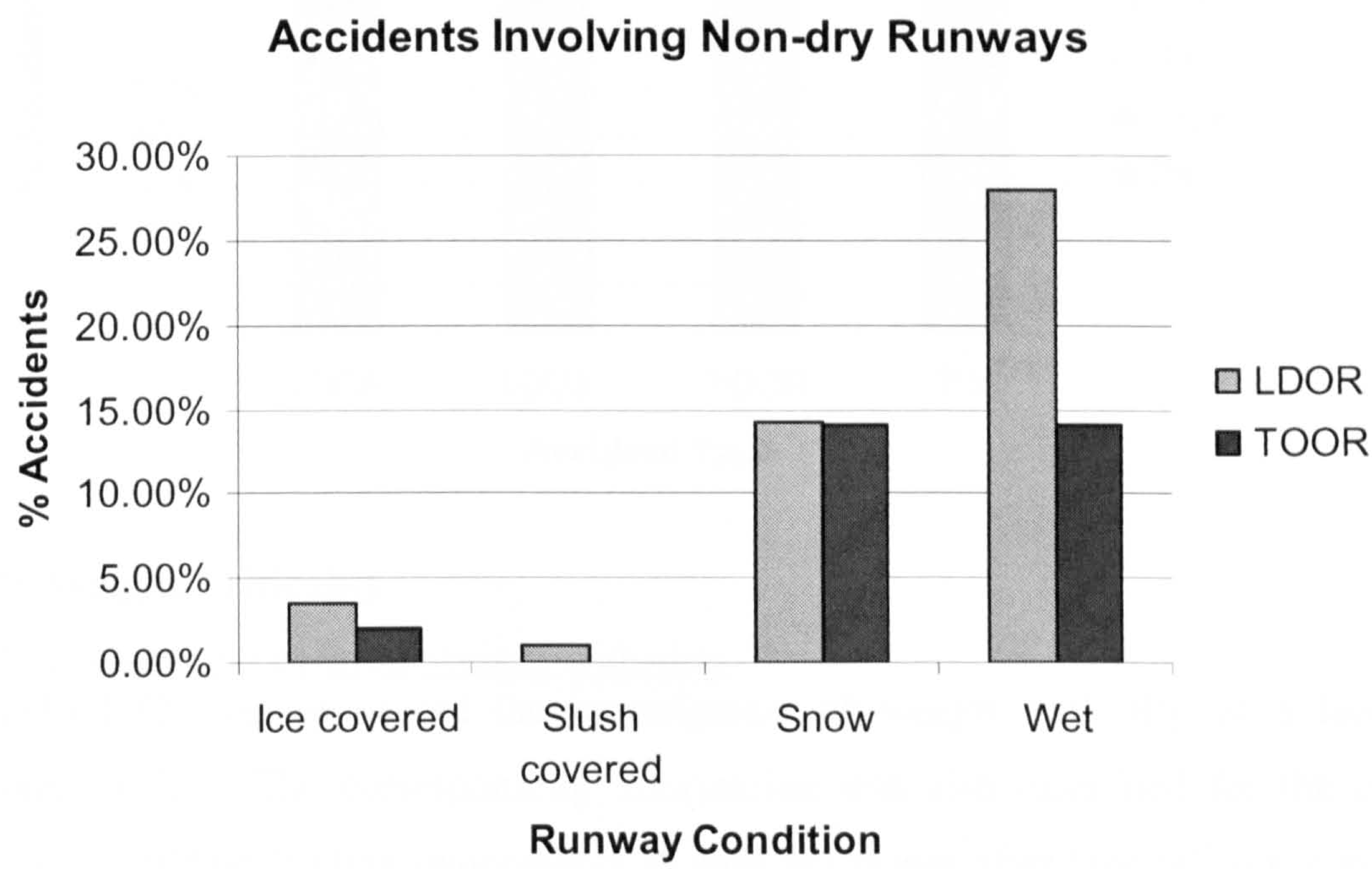
8.22 Snow

The proportion of cases that involved snow averaged 14.3 percent overall. Landing accidents have a slightly higher share of snow-related occurrences compared to take-off accidents. The contrast is greatest between landing undershoots (17.2 percent) and crashes after take-off (11.9 percent). The statistic is similar between both landing and take-off overruns, at approximately 13.5 percent.

8.23 Runway Condition

Transport Canada reported that the majority of landing accidents involve wet or icy runways (FSF 2003). The current database found 47.0 percent of landing overruns and 30.0 percent of take-off overruns took place on non-dry runways. Figure 8.14 shows the breakdown of these cases. Overall, 62 out of the 107 overruns that occurred on non-dry runways involved wet runways. However, a remarkably higher share of landing overruns took place on wet runways compared to take-off overruns. Snow is the second most frequent non-dry runway condition, followed by ice. Only two landing overruns involved slush-covered runways and none of the take-off overruns. For every category of non-dry runway state, the share of landing overruns involved is higher than the take-off equivalent. This follows the pattern where a greater proportion of landing occurrences are related to adverse weather conditions than take-off accidents.

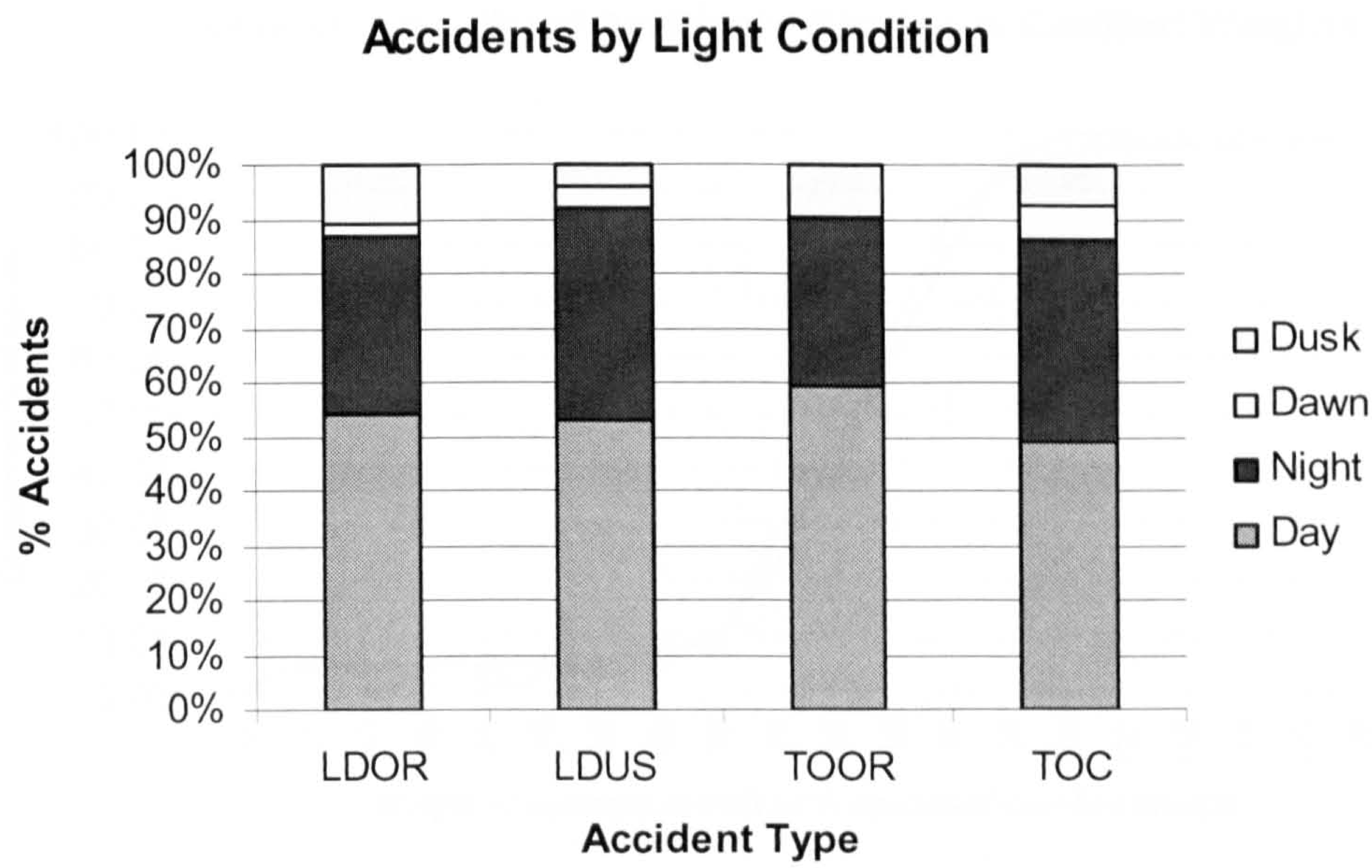
Figure 8.14 Accidents involving non-dry runways



8.24 Light Condition

Figure 8.15 shows that roughly half of all accidents occurred in daylight conditions. The proportion of cases that took place at night ranged from 30.8 percent of take-off overruns to 38.5 percent of landing undershoots. The breakdown of cases by light condition is broadly similar for all accident types. Crash after take-off, however, has the highest share of cases that occurred in non-daylight conditions (50.8 percent) as well as the highest share of cases that took place in dawn or dusk (13.4 percent).

Figure 8.15 Accidents by light condition



8.25 Weight Criticality

8.25.1 Maximum certified weight criticality

Kirkland (2001a) pioneered the investigation of weight criticality as a factor of overrun risk. The corresponding information was also examined for the current database, adding landing undershoots as well as crashes after take-off to the analysis on top of overruns. The analysis depended on cases for which the actual weight of the aircraft at the time of accident occurrence was reported. This ranged from 53.7 percent of crashes after take-off to only 29.6 percent of landing overruns. As such, the following analysis must be interpreted with care, especially as the NTSB tends not to report information that its investigators consider as irrelevant[1].

Figure 8.16 shows the aircraft weight at accident occurrence as a percentage of the relevant aircrafts' maximum certified weight in a cumulative format. Take-off accidents were found to be generally more weight critical than landing ones.

[1] Kirkland (2001a) may have provided a more complete study of weight criticality by using sources other than the accident docket files to determine the weight of the aircraft at accident occurrence. This was not carried out in the current study because of the lack of NOD on weight criticality, which implies that the factor could not be included in the subsequent accident frequency models.

Figure 8.16 Accident weight criticality (% maximum certified weight)

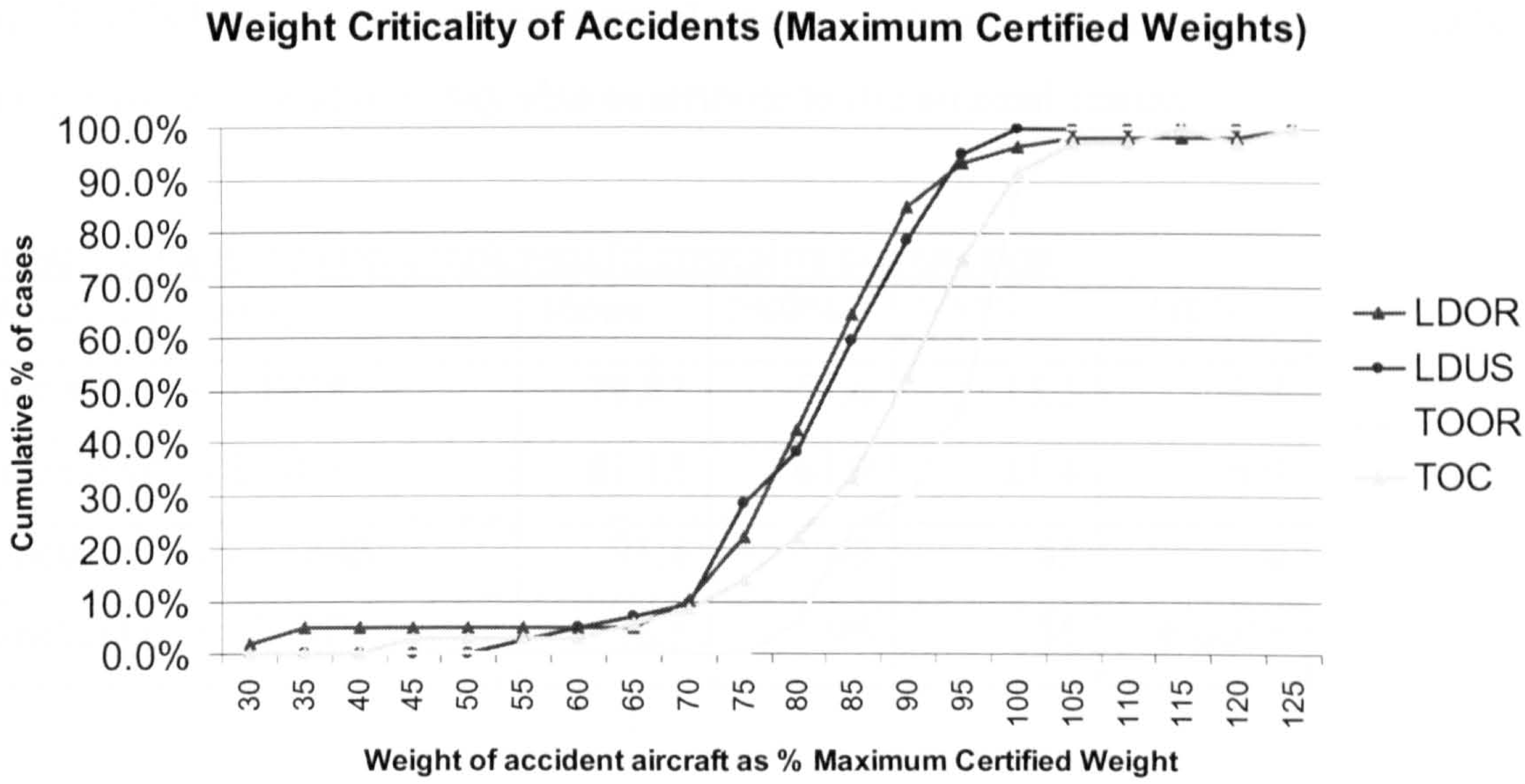


Table 8.1 compares the findings with Kirkland's results. The weight criticality of the current study's take-off overruns are similar to those found by Kirkland. The mean weight criticality of take-off overruns of the two studies are almost identical. As expected, both take-off overruns as well as crashes after take-off were found to be generally more weight critical than the sample of NOD Kirkland obtained from a large European airline. This is noticeable at the mean, 80 percent and 90 percent levels, and is particularly evident in the proportion of accident flights that were heavier than the maximum certified weight.

Table 8.1 Take-off operations weight criticality comparison

Weight Criticality	Mean	>80%	>90%	>100%
Current study TOOR	92.5	94.1	70.6	11.8
Current study TOC	87.3	77.8	47.2	8.3
Kirkland study TOOR	92.0	85	65	11
Kirkland study NOD	81.0	60	30	0.06

However, the current study's weight criticality findings diverge significantly from Kirkland's in terms of landing overruns. Table 8.2 highlights some results for landing operations. Kirkland's landing NOD seems to be even more weight critical than landing accidents of the current database, except for cases which exceed the maximum certified weight. This may be related to the small number of cases in the present database that report the aircraft weight at the time of accident occurrence, i.e.

29.6 percent of landing of overruns and 34.4 percent of undershoots. The fact that the NOD belongs to a large commercial operator whereas the current database include many smaller operations may also contribute to the unusual results.

Table 8.2 Landing operations weight criticality comparison

Weight Criticality	Mean	>80%	>90%	>100%
Current study LDOR	79.87	57.6	15.3	3.4
Current study LDUS	81.15	61.9	21.4	0.0
Kirkland study LDOR	91.4	95	65	6
Kirkland study NOD	87.5	95	35	0.0015

8.25.2 Maximum allowable weight criticality

Kirkland also conducted an analysis of weight criticality as measured by the aircraft weight at accident occurrence as a percentage of the relevant operation's maximum allowable weight, although a comparison with NOD was not feasible. Figure 8.17 shows the results of the same analysis for the latest database. Overrun cases were found to be generally more weight critical than airborne accidents but these results are even more severely limited by the small number of cases available for analysis. Only 7.0 percent of landing overruns report this information, rising to 28.4 percent of crashes after take-off.

Figure 8.17 Accident weight criticality (% maximum allowable weight)

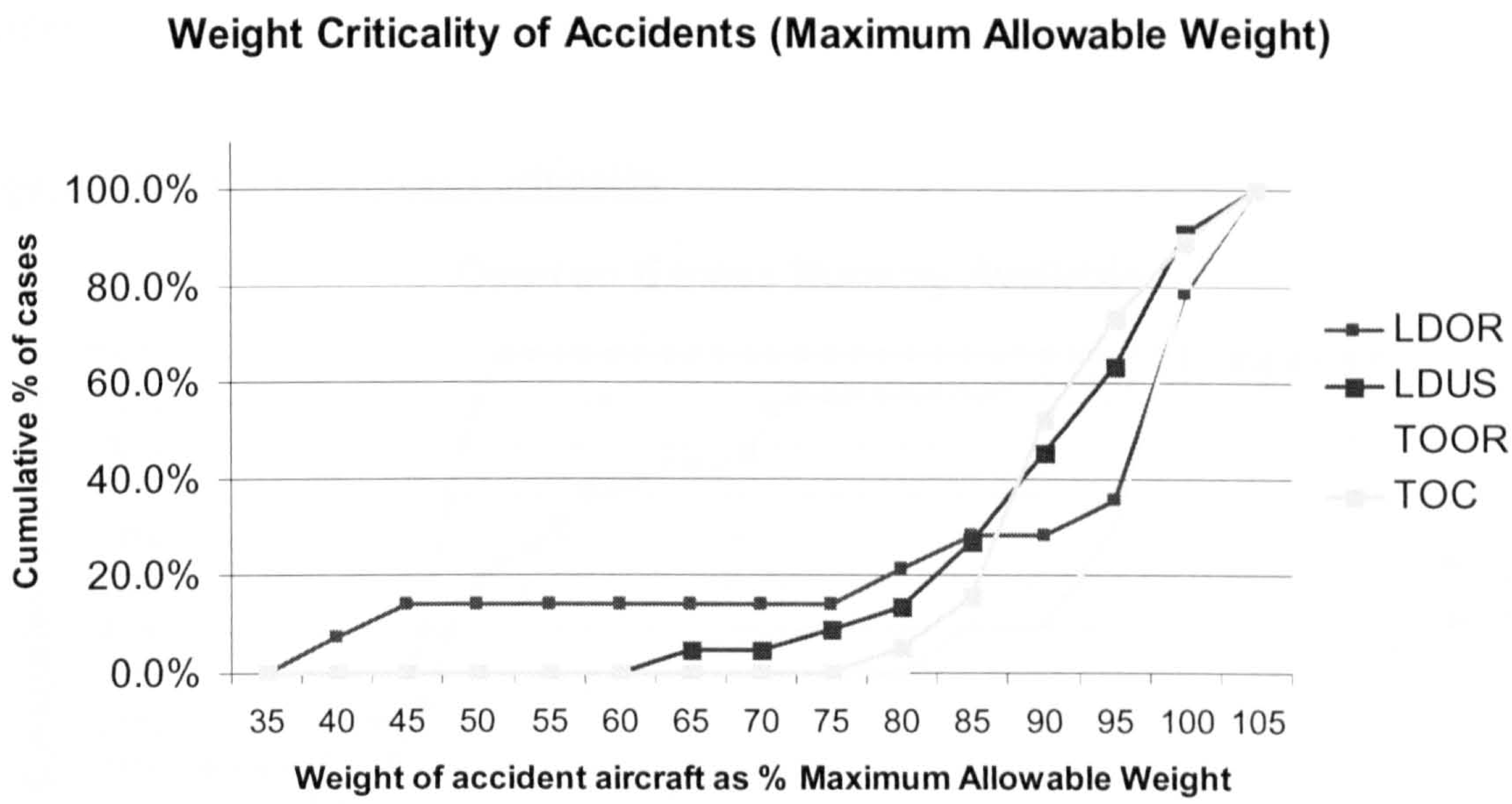


Table 8.3 shows the weight criticality of the four classes of accidents as measured by percentage of maximum allowable weight. In line with expectations, the accidents are even more weight critical when measured against maximum allowable weight compared to maximum certified weight. For all accident types, this is true concerning the mean weight criticality as well as the proportion of incidents at 80 percent, 90 percent and 100 percent criticality. The results confirm Kirkland's finding that many accident flights were weight restricted, most likely because of weather conditions or runway length (Kirkland 2001a).

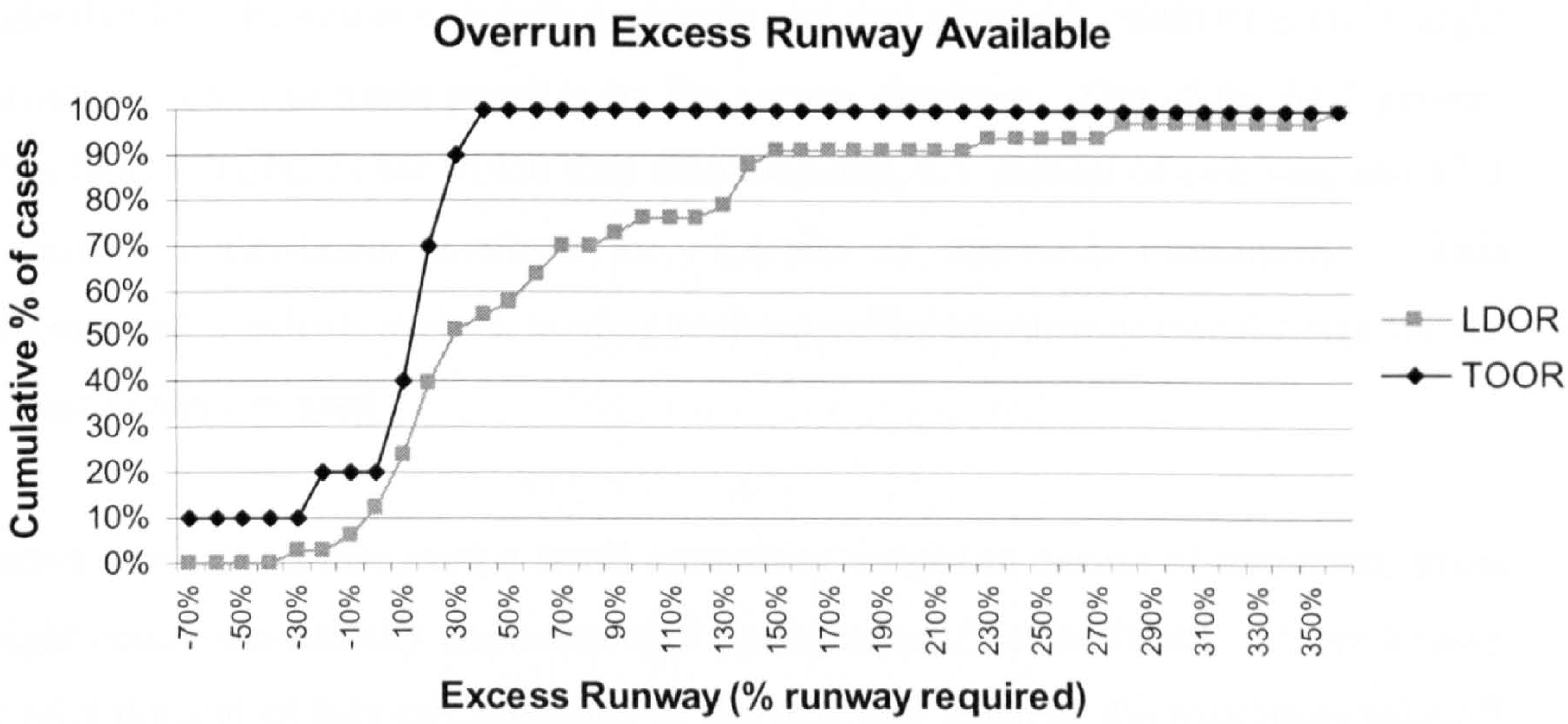
Table 8.3 Accident weight criticality measured as % maximum allowable weight

Weight Criticality	Mean	>80%	>90%	>100%
Current study LDOR	87.3	78.6	71.4	21.4
Current study LDUS	90.0	86.4	54.5	9.1
Current study TOOR	95.2	100.0	90.0	20.0
Current study TOC	91.0	94.7	47.4	10.5

8.26 Runway Criticality

Another breakthrough of the preceding study by Kirkland (2001a) is the assessment of runway criticality as an overrun risk factor. A similar analysis was conducted using the current database. Figure 8.18 shows the runway criticality of take-off and landing overruns as measured by the amount of excess runway available. The latter is measured by the difference between the available and required runway distances as a percentage of the latter.

Figure 8.18 Overrun runway criticality



The results suggest that take-off overruns tend to be more runway critical, i.e. have less excess runway available, than their landing counterparts. This is in agreement with Kirkland's findings. However, the analysis must again be interpreted with care due to the small number of cases that report information on runway distance required[2]. Only 16.6 percent of landing overruns (33 cases) and 19.2 percent (10 cases) of take-off overruns could be used for this analysis. Even fewer cases of landing undershoot and crash after take-off contain the relevant data so these classes of accidents were not analysed. Nonetheless, some intuitively correct results were obtained. A similar proportion of landing overruns in Kirkland's database and the present one involved negative excess runway distance, i.e. insufficient runway length. The former reported 10 percent and the latter registered 12.1 percent. As expected, these figures are significantly higher than the NOD Kirkland obtained from a major European airline. Regarding take-off overruns, cases with less runway distance available than required represent 20 percent of the current database but only 4 percent of Kirkland's. The discrepancy may be due to the reporting bias of NTSB investigations. Since NTSB tends to only report what is considered as relevant, it is

[2] Similar to weight criticality, Kirkland relied on sources other than the accident docket files to compute runway distance required. This was not done in the current study because of the lack of representative NOD for model building. More fundamental concerns about using runway criticality as a predictive factor of accident occurrence are discussed in the next chapter.

not surprising that using the available data alone would yield more extreme results compared to an analysis of all cases.

8.27 Violation of Minimums & Restrictions

Understanding the extent to which accidents violated approach minimums and weight restrictions was also made possible by the current database. Out of the 61.7 percent of landing occurrences for which data was available, 5.5 percent of overruns and 17.2 percent of undershoots involved the violation of approach minimums. This encompassed incidents such as landing without sufficient runway visual range for the approach category used.

Studies have found that even a small amount of weight in excess of maximum gross weight could dramatically impact aircraft performance (Turner 2006). It was known for 66.4 percent of take-off accidents in the database whether the maximum take-off weight was violated. Of these known cases, 1.9 percent of take-off overruns and 6.0 percent of crashes after take-off exceeded the maximum take-off weight. This is intuitively correct as one would expect more crashes after take-off to be weight related compared to overruns.

8.28 Summary of Findings

This chapter has presented the first stage in analysing the accident database, which involved identifying overall trends and assessing the prevalence of certain risk factors among the different accident types. More than 25 variables were examined although the database covered even more accident parameters. Since the ultimate objective of the research is to develop predictive risk models, this part of the study concentrated on factors that are relevant to the subsequent modelling work. Certain results confirmed the findings of previous studies such as (Kirkland 2001a).

Numerous variables that were not tested previously were examined. Rather than simply grouping rain, snow and hail under precipitation as in Kirkland et al. (2003a), these factors were independently identified and analysed. In all, over ten meteorological factors were examined. Some significant trends were revealed. For instance, it was found that the majority of adverse meteorological conditions featured more prevalently among landing accidents than take-off occurrences.

The inclusion of landing undershoots and crashes after take-off in the dataset complemented the overrun incidents to provide a complete analysis of the types of accidents that occur during the take-off and landing phases of flight. The univariate analysis characterised each of the accident types on a series of variables and the nature of each accident type was compared. Crashes after take-off, for example, were found to differ from the other accident types for a number of variables. These ranged from a particularly high proportion of freight operations to a higher share of cases involving frozen precipitation and non-daylight conditions.

The findings of this stage of the analysis have potential implications on the development of predictive models and were further investigated in the bivariate and multivariate analyses.

CHAPTER 9 THE NORMAL OPERATIONS DATABASE

The collection and incorporation of NOD in the risk modelling are major contributions of this thesis to the field of airport risk assessment. It is therefore crucial that appropriate NOD is collected. This chapter describes the development of the normal operation database, including the data sources, sampling strategy as well as the extensive efforts spent on ensuring that it is compatible with the accident database.

9.1 Sources of NOD

The challenges of obtaining appropriate NOD for risk assessment are well documented (Piers 1994, DfT 1997, Roelen et al. 2002). Unavailability, incompleteness and difficult access are only some of the hurdles that must be overcome. A number of sources of NOD were considered for use in the current study.

9.1.1 Flight data recorder data

The prime source of NOD would come from the aircraft operators. Flight data recorders measure a range of potentially pertinent operating parameters for understanding normal flights' exposure to risks. In the US, such data is collected under the Flight Operational Quality Assurance (FOQA) programme. Numerous US and UK airlines were contacted directly and through umbrella organisation such as the Global Aviation Information Network (GAIN) requesting access to a sample of FOQA data. However, all cited safety sensitivities and pilot union concerns as preventing the provision of relevant data, even in aggregated or de-identified format. One carrier did provide a sample of FOQA data on aircraft weight but the data only covered one type of regional jet and its variant, which is insufficient to build a representative sample for analysis.

Requests were also made to third party organisations that possess various forms of FOQA data, including the FAA, aircraft manufacturers, aviation safety software companies and NASA's Aviation Performance Measuring System. Unfortunately, none of these were able to provide an adequate sample of NOD and suggested contacting the airlines. The International Air Transport Association (IATA) has a

Safety Trend Evaluation Analysis & Data Exchange System (STEADES), which is a database of de-identified incident reports. However, the system is not capable of delivering the desired parameters of this thesis either.

Kirkland sourced a sample of NOD from a major European airline, with which individual models were built assessing the criticality of individual risk factors (Kirkland 2001a). This data source was not used for the current thesis because of its mismatch with the accident database. Whereas the latter concerns US events, an extremely high proportion of the NOD from this airline would involve operations to or from the carrier's hub airport in Europe. Moreover, the accident database covers a very broad spectrum of aircraft types and operators while Kirkland's NOD source only includes several large aircraft models operating on commercial flights. In fact, using NOD from a particular airline inevitably leads to the issue of incompatibility with the accident database in terms of aircraft, operation and airport characteristics. Given the difficulty in gaining access to the airlines' data, it would be hard to collate a representative NOD sample from multiple airlines.

The possibility of using airline load sheets to calculate normal flights' weight criticality was also considered. Unfortunately, access to such operational data was equally difficult and the problem of unrepresentative sampling would not be remedied unless the data is collected from a multitude of different aircraft operators.

9.1.2 Airport sources

An alternative source of NOD was therefore sought through airport operators, especially in terms of aircraft landing weights. At least two airports were supportive of providing the relevant information. However, even though these airports do charge landing fees according to maximum landing weight, the actual weight of the aircraft at landing is seldom recorded. As such, airport data on landing weights is not precise enough for risk assessment purposes.

9.1.3 FAA sources

A satisfactory solution was found in the data provided by the FAA's Aviation Policy and Plans Office (APO). The APO hosts a number of online databases that record flight activity and associated information. Two of these stand out as especially useful sources of NOD. The first is the Aviation System Performance Metrics (ASPM) which provides take-off and landing counts at specific airports in fifteen-minute or hourly segments, including information on aircraft and operation type, runway orientation as well as certain meteorological parameters such as ceiling height and visibility. However, the database only covers fifty-five large and medium hub airports. This would misrepresent actual traffic characteristics of normal flights and fail to match the accident database.

The related Enhance Traffic Management System Counts (ETMSC) was therefore used instead. ETMSC provides hourly traffic counts for over 450 airports as well as the relevant traffic characteristics for individual flights, including aircraft, engine and operation type. One of the key advantages of the ETMSC database is that, unlike specific airport or airline FOQA data, it encompasses a wide variety of airport sizes and includes commercial, air taxi, freight as well as general aviation flights. It is therefore not necessary to collate multiple sources with potential compatibility issues to ensure that the flight population concerned is correctly represented[3]. However, ETMSC does not provide the associated weather and runway orientation information as does ASPM. Supplementary sources must therefore be used to cover these data gaps, as described later in this chapter.

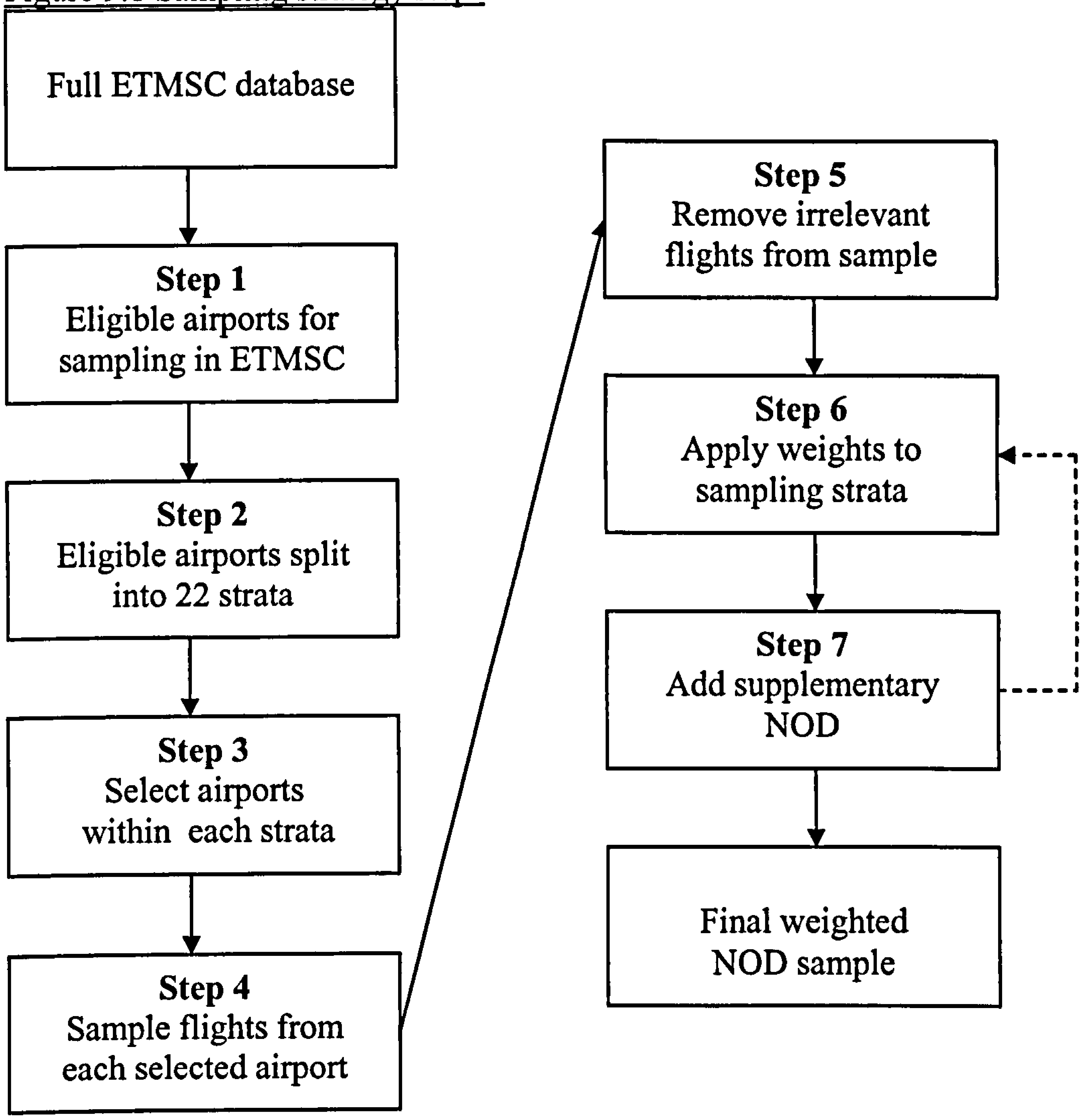
9.2 Sampling Strategy

While the accident database contains all relevant occurrences within the period of study, a sampling strategy must be developed for collecting the appropriate sample of NOD. The prime concern is to gather a sample that is representative of the risk exposure of the overall normal flight population of interest.

The process of extracting a representative sample of NOD from the ETMSC database and adding supplementary risk exposure information from other sources could be broken down into seven key steps. These are set out in Figure 9.1 and explained in detail below.

[3] It should be noted that ETMSC only records flights that filed a flight plan. Given that the filtering criteria of the accident database has already eliminated smaller aircraft types such as single and piston engine aircraft, this caveat is unlikely to significantly affect ETMSC's capacity to represent risk exposure of the flight population of interest.

Figure 9.1 Sampling strategy steps



9.2.1 Safeguarding for crosswind calculation (Step 1)

Before the sampling was carried out on the ETMSC database, a preliminary airport selection exercise was conducted. Crosswind is one of the risk factors that the current study aims to quantity and include in the risk modelling. Because ETMSC does not provide meteorological information, supplementary sources of NOD must be used, as with visibility, ceiling height etc. However, unlike the latter factors, crosswind strength is dependent on the orientation of the flight path and must be calculated using runway orientation information. ETMSC does not indicate the runway configuration in use at specific flight times. A solution was found by using airports with single or parallel runways and those with multiple non-parallel runways that only operate them in parallel or single configurations. The latter was confirmed by checking against the ASPM database, which provides the operational frequency of airport runway configurations. Multiple non-parallel runway airports not covered by

ASPM were automatically eliminated. This reduced the number of eligible airports for sampling to 125.

9.2.2 Stratified sampling

Random sampling of the ETMSC database would not be appropriate as it may bias against airports of certain risk profiles and misrepresent the genuine risk exposure of normal flights. A stratified sampling strategy was hence developed to select airports from which normal flights were then sampled.

9.2.2.1 Stratification factors (Step 2)

The eligible ETMSC airports were stratified by three factors. The first is airport size (hub and non-hub). Hub airports include all large, medium and small hub airports as classified by the FAA in 2001, as listed in Appendix E. Non-hub airports cover all remaining airfields. This accounts for the difference in risk exposure of flights related to large and small airports including aircraft size, operation type, navigational aid availability, airport infrastructure etc (Piers 1994).

The second stratification factor is FAA region. The nine FAA administrative regions as shown in Figure 9.2 represent a reasonable division of the key geographical regions of the US[4]. As such, it is a useful stratification factor to account for differences in regional weather patterns and hence normal flights' exposure to various meteorological conditions. Although weather patterns obviously vary within individual regions as well, using FAA regions is nonetheless an effective way to account for the broad differences in weather exposure. Due to the limited number of airports available for sampling as well as the effect of other stratification factors, it would be impractical to stratify the sample into even smaller meteorological regions.

[4] Hawaii is part of the Western Pacific Region

Figure 9.2 FAA regions

Source: FAA

The third stratification factor is the presence of significant terrain near the airport as the latter is expected to influence accident risk, especially for landing undershoots. The NOD sample ought to reflect the proportion of flights that are exposed to more challenging topographic environments. An airport is considered to be situated near significant terrain if the terrain within the Instrument Approach Procedure planview 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. Detailed terrain is depicted in the Instrument Approach Procedures of these airports according to this definition in the FAA US Terminal Procedures Publication (FAA 2007). 257 airports met this criteria as of April 2006, as listed in Appendix F (FAA 2006c). The ETMSC airports were thus further stratified according to whether it is situated near significant terrain.

9.2.2.2 Extraneous & empty strata

The two airport classes, nine FAA regions and two terrain categories theoretically lead to 36 strata from which the NOD sample should be drawn. However, seven of these never featured among the airports of any FAA Terminal Area Forecasts (TAF) from 2000 to 2005, which comprehensively includes FAA towered airports, federally contracted towered airports, non-federal towered airports as well as non-towered airports. It is therefore reasonable to assume that no airport exists under these strata. An example would be a large hub in the central region in significant terrain. Eliminating these non-existent hypothetical strata resulted in 29 strata with actual airport traffic.

The 125 ETMSC airports suitable for NOD sampling were therefore split according to the 29 strata. However, no airport fell under seven of them. The limiting factor for five of them is significant terrain. For instance, none of the eligible ETMSC airports is an Alaskan non-hub airfield in significant terrain. Earlier elimination due to runway number or layout was responsible for the remaining two strata without sampling candidates. For example, all hubs in New England in normal terrain have multiple runways in non-parallel layouts. Appendix G identifies all twenty-nine strata and indicates the empty ones.

The impact of the empty strata was considered before the described sampling strategy was accepted. From TAFs, it was calculated that all airports nationwide belonging to the seven empty strata which cannot be sampled collectively account for 4.2 percent of the total relevant traffic from 2000 to 2005[5]. This figure is considered sufficiently small as to not affect the overall representation of risk exposure of the great majority of relevant normal operations.

9.2.2.3 Intra-stratum sampling (Step 3 & 4)

There remained, then, 22 strata with airports to sample from. If there were five or fewer airports in a particular stratum, all of them were sampled. For strata with more than five candidate airports, five were sampled from each. The five were selected such that airports of different traffic levels are represented. For example, if there were ten airports in the stratum, every other airport would be sampled in the order of descending traffic level. This ensures that the sampled airports correctly reflect the traffic characteristics of the overall normal flight population. This resulted in a total of 78 selected airports, as detailed in Appendix H. These sampled airports account for 48,924,040 operations from 2000 to 2005 inclusive, i.e. 25.5 percent of all relevant traffic during that period.

[5] See Appendix I for the calculation of relevant TAF traffic

Clearly, it is impractical and unnecessary to use all operations from these sampled airports for analysis. Therefore only flights on the first day of February, May, August and November of 2002, 2003 and 2004 were sampled to constitute the final NOD sample for risk assessment. The selection of the four months allows seasonal variations in weather exposure to be captured.

9.2.2.4 Removing irrelevant NOD (Step 5)

The next stage involved ensuring that the sampled NOD traffic does not contain traffic types outside the scope of the accident database. This exercise followed the accident database filtering criteria as detailed in Appendix D. Where certain ETMSC data was missing, alternative sources were used to the extent possible to identify the relevant information, e.g. equipment class. Flights under equipment type 'Helicopter', 'Piston' and 'Other'; equipment class 'Other'; user class 'Military' and 'Other'; and general aviation flights of aircraft under 12,500lbs were removed. A small number of flights with incomplete data to verify its relevance was also removed. Having eliminated the irrelevant traffic, the final NOD sample consisted of 242,420 flights.

9.2.2.5 Accounting for sampling fractions (Step 6)

Before the sampled NOD could be considered as representative of the overall population of normal operations of interest, the differences in sampling fraction between the 22 strata must be resolved. Sampling every stratum as described above led to certain strata being over-sampled and others under-sampled when compared to the actual composition of the overall normal flight population, since the proportion of available airports for sampling varies stratum to stratum.

Proportionate allocation was therefore applied via the use of weights. A specific stratum's weight was derived by dividing the stratum's fraction of traffic in the overall population by the stratum's fraction of traffic in the sampled population. This is similar to inversing the sampling fraction of each stratum but avoids inflating the total number of sampled flights. Appendix G shows the traffic fractions and weights for each stratum. It could be seen that before the application of weights, non-hubs in the southern region in non-significant terrain were hugely under-sampled and non-hubs in significant terrain of the same region were over-sampled. These imbalances were addressed by applying the weights, which calibrated the final NOD sample to reflect the overall normal flight population.

9.3 Supplementary NOD (Step 7)

The ETMSC database provides landing and take-off counts of hourly segments at specific airports broken down by aircraft, engine and operation type. For other risk exposure parameters, additional sources of NOD were found to supplement ETMSC's traffic data.

9.3.1 NOAA TD3505 database

The National Oceanic and Atmospheric Administration's Integrated Surface Hourly (TD3505) database was selected to measure the sampled ETMSC flights' exposure to a range of metrological factors. TD3505 was selected for its wide coverage of airports and weather parameters. Its quality control, completeness and depth are also superior to other hourly weather databases such as the Local Climatological Data Publication (NOAA 2004).

TD3505 data for the sampled airports and times was therefore acquired and collated with the ETMSC traffic data. This involved converting GMT times (used by TD3505) into local times (used by ETMSC), paying attention to time zones and daylight saving hours of different US regions, which proved to be time-consuming and labour-intensive. The was accentuated by the fact that TD3505 often provides more than one reading per hour so a systematic reading selection method had to be devised to extract the most relevant weather readings.

Weather observations were missing from the TD3505 database for a small proportion of time periods. The great majority of these concerned hours of closure for eight small airports when no flights took-off or landed overnight and were therefore inconsequential. Only a small number of hourly segments with ETMSC flight operations lacked the corresponding TD3505 data. These were removed from the normal operations database. There was no reason to suggest that these missing weather observations biased against any particular meteorological condition. Upon removing these time periods and associated flights from the NOD sample, the weights applied to each sampling strata were recalculated to ensure that the NOD sample remained representative of the overall flight population. This is especially important as a disproportionate number of these removed time periods belonged to non-hub airports. The weights presented in Appendix G are the updated and final weights applied.

9.3.2 Weather parameters

9.3.2.1 TD3505 parameters

Having collated the appropriate TD3505 data to the relevant ETMSC time segments, it was possible to quantify the normal flights' exposure to a large number of weather parameters. These include visibility, ceiling height, temperature, precipitation, snow, fog, icing condition, electric storm and a host of other weather measures.

9.3.2.2 Crosswind

Whereas most meteorological conditions were readily identified in TD3505, others required further calculation. TD3505 data on wind direction and velocity was coupled with the true runway orientation of flight operations to compute the crosswind factor. This was relatively straightforward for airports with single or parallel runways. For airports with multiple runway operational orientations, the ASPM database was used to ascertain the runway configuration in use for all sampled flights. This was another lengthy exercise.

9.3.2.3 Light condition

Another parameter that required further computation was light condition. The accident database recorded whether each incident occurred in daylight, night, dawn or dusk. For normal operations, dawn was defined as the hour before official sunset time and dusk the hour after official sunset. 2002 civil twilight times were used to determine sunrise and sunset hours at locations across the US. If sunrise occurred after 30 minutes past the hour, that hour was considered dawn. Otherwise, the previous hour was marked as dawn. If sunset occurred before 30mins past the hour, that hour was considered dusk. Otherwise, the next hour was marked as dusk. It was found that, for all states other than Alaska, dawn and dusk fell on the hours indicated in Table 9.1.

Table 9.1 Dawn & dusk hours (all states except Alaska)

	Hour of Dawn	Hour of Dusk
February	06	17
May	05	20
August	05	20
November	06	17

The calculations took into account daylight saving hours as well as the latitude of airport locations. It was checked that the above hours applied to Nantucket Memorial Airport, Massachusetts, one of the most northerly sampled airports, as well as Los Angeles International Airport, California, one of the most southerly. The figures for Alaska were calculated based on a centrally located Alaskan airport in the sample, Fairbanks International Airport, and are shown in Table 9.2.

Table 9.2 Dawn & dusk hours (Alaska)

	Hour of Dawn	Hour of Dusk
February	09	17
May	04	22
August	04	23
November	08	16

According to these designated hours, then, sampled flights that took-off or landed in dawn and dusk were identified. Hours after dusk were identified as night-time and the rest daylight.

It is acknowledged that the definitions and methodology used to identify light conditions are somewhat crude and may have overstated the duration of dawn and dusk hours. However, given the hourly time segments of ETMSC, more precise definitions were not possible.

9.4 Compatibility with Accident Database

Once the NOD sample was collected and collated with the relevant supplementary data, it must be made compatible with the accident database. Unless the two were in a compatible state, bivariate and multivariate analyses could not be carried out. For most variables, the process involved collapsing discrete variables into fewer categories. For example, TD3505 distinguishes between many forms of fog and snow. These were consolidated into generic groups so as to match the accident database. Commercial and air taxi operations were also merged into one category because ETMSC air taxi operations involve heavier aircraft than those in the accident database and it proved difficult to split the ETMSC air taxi operations into more groups without using aircraft size as a criterion, which would lead to multicollinearity later in the analysis. For periods when TD3505 only reported measures of precipitation in millimetres, they were converted into light, moderate or heavy rain as in the accident database[6]. Units of continuous variables were also standardised.

9.5 Advances Achieved

The achievements reported in this chapter are considerable. From finding the best source of NOD to devising an appropriate sampling strategy, significant time and effort were required. The care and precision needed to collate the supplementary NOD to the matching time segments and to ensure accuracy were also substantial. To the author's knowledge, such a comprehensive database on normal operations' risk exposure has never been developed. The breadth of the database – covering a large range of big and small airports, from locations across the US – as well as its depth – taking into account such a wide spectrum of operational and meteorological risk factors – are groundbreaking. Kirkland, who pioneered the use of NOD for airport risk assessment, used a very limited sample of NOD from a single European airline, covering only several risk factors (Kirkland 2001a). The current database is far more representative of the overall population of flights of interest and covers more than a dozen risk factors. Furthermore, the current database is multidimensional. Indeed, exposure to all risk factors studied were measured for the entire sample of normal flights, producing a single, integrated database. This is significant as Kirkland has previously highlighted the lack of multidimensional NOD as a major handicap to risk analysis. With the current multidimensional normal operations database, multivariate risk models could be developed instead of a series of disjoined bivariate models.

---

[6] Trace amounts to 2mm of precipitation was considered light; 2-6mm moderate and above 6mm heavy. These were calculated from hours when TD3505 recorded continuous as well as discrete measures of precipitation.

CHAPTER 10 BIVARIATE ANALYSIS – QUANTIFICATION OF RISK FACTOR CRITICALITY

With the comprehensive accident and normal operations databases, the difference in accident and normal flights' exposure to risk could be compared. Essentially, the analysis is of a case-control setup. Rather than simply focusing on the common characteristics of accident flights, case-control analyses reveal the factors that set accidents apart from normal operations and contribute to their occurrence (NTSB 2005). After explaining which factors were analysed, this chapter presents the case-control analysis that identified and quantified the criticality of a series of risk factors.

10.1 Factors Analysed

10.1.1 Prerequisites

Data on normal flights' exposure to the particular risk factor must be available if its criticality were to be quantified. Where NOD is available, extensive efforts were made to ensure that it is also compatible with the accident database. Both accident data and NOD may constrain the breadth and depth of the analysis. In the current study, for example, the TD3505 database provides much more in-depth data on weather factors than accident reports. On the other hand, ETMSC only provides limited information on traffic characteristics compared to accident reports. Despite these constraints, the great majority of risk factors studied in the univariate analysis were included in the bivariate and multivariate analyses.

10.1.2 Factors not analysed

This section explains the reasons behind not conducting the bivariate and multivariate analyses on certain potentially pertinent risk factors.

10.1.2.1 Runway & weight criticality

Any operation that used more runway distance than that required is in theory an overrun. The frequency and extent by which normal flights exceed their required runway distances should therefore be compared with that of accident flights, as suggested in Chapter 8. However, runway criticality was not carried forward in the current analysis due to practical difficulties in measuring the true amount of runway used by normal operations. In day to day operations, there is no onus on pilots to conduct the operation within the minimum runway distance required when excess runway is available. The location of runway exits and the braking force applied also influence runway distance used. Since pilot behaviour could vary from operation to operation, NOD on runway distance used is not an accurate measure of true runway criticality. In fact, runway criticality is not always easy to obtain for accidents either. Only a small proportion of accident reports include data on runway distance requirement and numerous assumptions on aircraft settings would be necessary to calculate the distance required from aircraft manuals.

The possibility of using weight criticality as a proxy of runway criticality was considered. However, difficulties in obtaining data on normal take-offs and landings' actual weights from sources such as FOQA and airline load sheets impeded such an analysis. Besides, the same data for accidents is not always available in accident docket files either.

10.1.2.2 Runway state

Runway condition is understood to be one of the most pertinent overrun risk factors. Unfortunately, fundamental issues related to the description and assessment of runway state have precluded it from the current study. The aviation industry lacks a standardised and accurate method in measuring and reporting runway conditions. Current techniques have been deemed either subjective (e.g. PIREPs) or inaccurate (e.g. runway friction values) (DeGroh 2006). These nomenclatural and technological deficiencies mean that accurate data on runway state is difficult to obtain for accidents as well as normal flights. Although the factor could not be directly analysed, some of its effects were captured through other meteorological factors such as icing conditions and snow.

10.1.2.3 Human factors

Numerous sources point to the importance of human error and other crew-related factors in contributing to take-off and landing accidents (Ashford 1998, FSF 1999, 2003, Li et al. 2001, NTSB 2006b). However, simply identifying human error as the cause of an accident (not uncommon in NTSB accident investigations) is not always constructive to safety management. Many underlying factors may be concealed under the term "human error" (Statler et al. 2003, ICAO 2006).

Indeed, the likelihood of human error has been found to be a function of endogenous and exogenous factors (Li et al. 2001). Rather than a purely intrinsic phenomenon of human behaviour, extrinsic attributes contribute to human error too. For instance, air crew error has been found to correlate strongly with weather and visibility conditions (Jerris et al. 1963). Adverse weather is consistently associated with higher risk of human error. Among factors associated with pilot, aircraft and crash circumstances, a number of studies identified IMC as most predictive of crew error. This could be explained by the stress model. Factors such as poor visibility are environmental stressors that add to pilot workload and performance demand, heightening the likelihood of pilot error and accident risk (Li et al. 2001).

While human error may be the proximate cause of aviation mishaps, it is crucial in terms of safety management to identify and understand its exogenous factors. The British CAA, for example, encourages airport operators to consider aerodrome-related factors that may increase the risk of human error when examining overrun risk (CAA 1998). Similarly, the current research indirectly considered the effect of human error through explicitly analysing and modelling some of its key established precursors – a range of weather parameters. Apart from these modelled factors, it was assumed that human error follows similar random distributions within accident and normal flights. This is not to dismiss the importance of understanding 'active [human] errors' as highlighted by Young et al. (2004). However, the lack of relevant data (accident & NOD) and concerns of collinearity prohibited a more explicit and direct examination of human error in the present study.

10.2 Data Preparation

Before the analysis was carried out, certain continuous variables required further preparation. When there is no cloud ceiling, the ceiling height entry in TD3505 is blank. Since blank fields would be omitted from the analysis, the blank ceiling fields were replaced with 3000ft as this is considered to be a generally safe ceiling height that would not contribute to accident occurrence. As very high ceiling heights are reported with less accuracy, any ceiling height reported as over 3000ft in TD3505 were also entered as 3000ft. For consistency, accidents with no cloud ceiling or one above 3000ft were entered as 3000ft too.

Likewise, large visibility values are also more likely to be less accurate. Therefore, all visibility values greater than ten statute miles in the accident as well as NOD databases were entered as ten statute miles.

Temperature is recorded in degree Celsius in the NTSB database. However, certain entries are so large that they are suspected to be in degree Fahrenheit. Those that are above 50 were assumed to be such cases and were converted into degree Celsius.

The small number of cases with missing data were removed from the analysis of the respective factors concerned.

10.3 Structure of Analysis

The analysis involved several statistical procedures. Each was used to explore a different aspect of risk factor criticality. Firstly, Pearson's chi-square test of independence and the independent t-test were applied to compare the mean values of risk exposure between accident and normal flights. Secondly, RAIRs were utilised to measure flight accident propensity under different conditions and various levels of risk exposure. Finally, bivariate logistic regression was employed to assess the risk factors' statistical significance in predicting accident occurrence and to quantify the magnitude and direction of the relationship between risk exposure and accident likelihood.

10.4 Comparison of Mean Exposure

As an initial investigation of the difference in risk exposure between normal and accident flights, chi-square analysis and independent t-test were performed on the two sets of data to detect significant differences in mean exposure and the related effect sizes. Pearson's chi-square test of independence was used to determine whether the two datasets differ significantly in the proportional distributions of exposure to categorical risk variables (Hutcheson & Sofroniou 1999). It is therefore also a test on whether accident occurrence is associated with the various risk factors. The NTSB used this statistical procedure as well to assess the extent to which general aviation accidents are associated with meteorological risk factors (NTSB 2005). The same was achieved for continuous risk variables using the independent t-test.

The analysis was conducted on each accident type independently. Take-off accidents were compared to normal take-off operations and landing accidents to normal landing operations.

10.4.1 Chi-square analysis results

The chi-square analysis results are shown in Table 10.1.

Table 10.1 Chi-square analysis results

	LDOR	LDUS	TOC	TOOR
Equipment Class				
Chi-square (Sig.)	**510.4 (<.0001)**	**747.0 (<.0001)***	**134.1 (<.0001)***	**174.8 (<.0001)***
Cramer's V	**0.067**	**0.081**	**0.033**	**0.038**
Equipment Type				
Chi-square (Sig.)	**100.3 (<.0001)**	**145.1 (<.0001)**	**15.2 (<.0001)**	**30.6 (<.0001)**
Cramer's V	**0.030**	**0.036**	**0.011**	**0.016**
User Class				
Chi-square (Sig.)	**123.8 (<.0001)**	**65.9 (<.0001)***	**18.6 (<.0001)***	**124.6 (<.0001)***
Cramer's V	**0.033**	**0.024**	**0.012**	**0.032**
Foreign Ori./Dest.				
Chi-square (Sig.)	**6.4 (0.011)**	1.5 (0.216)	**4.6 (0.033)***	0.0 (0.831)*
Cramer's V	**0.007**	0.004	**0.006**	-0.001
Hub				
Chi-square (Sig.)	**123.8 (<.0001)**	**67.5 (<.0001)**	**21.2 (<.0001)**	**7.1 (0.008)**
Cramer's V	**0.033**	**0.024**	**0.013**	**0.008**
Terrain				
Chi-square (Sig.)	0.1 (0.754)	**4.9 (0.027)**	0.1 (0.792)	2.8 (0.096)
Cramer's V	0.001	**0.007**	0.001	0.005
Dawn/Dusk				
Chi-square (Sig.)	**9.9 (0.002)**	0.2 (0.695)	0.9 (0.34)*	**5.6 (0.018)***
Cramer's V	**0.009**	0.001	0.003	**0.007**
Fog				
Chi-square (Sig.)	**444.0 (<.0001)**	**291.8 (<.0001)***	**21.5 (<.0001)***	**62.6 (<.0001)***
Cramer's V	**0.062**	**0.050**	**0.013**	**0.023**

Icing Conditions				
Chi-square (Sig.)	**494.5 (<.0001)***	**821.6 (<.0001)***	**12.3 (<.0001)***	**373.7 (<.0001)***
Cramer's V	**0.066**	**0.085**	**0.010**	**0.055**
Electric Storm				
Chi-square (Sig.)	**36.3 (<.0001)***	**27.3 (<.0001)***	0.4 (0.504)*	0.3 (0.569)*
Cramer's V	**0.018**	**0.015**	0.002	0.002
Frozen Precipitation				
Chi-square (Sig.)	**138.0 (<.0001)***	**56.5 (<.0001)***	**21.3 (<.0001)***	**428.5 (<.0001)***
Cramer's V	**0.035**	**0.022**	**0.013**	**0.059**
Snow				
Chi-square (Sig.)	**430.5 (<.0001)***	**438.2 (<.0001)***	**126.5 (<.0001)***	**126.3 (<.0001)***
Cramer's V	**0.061**	**0.062**	**.008**	**0.032**
Rain				
Chi-square (Sig.)	**83.4 (<.0001)**	**41.7 (<.0001)**	**7.2 (0.007)**	**13.2 (<.0001)**
Cramer's V	**0.027**	**0.019**	**0.032**	**0.010**

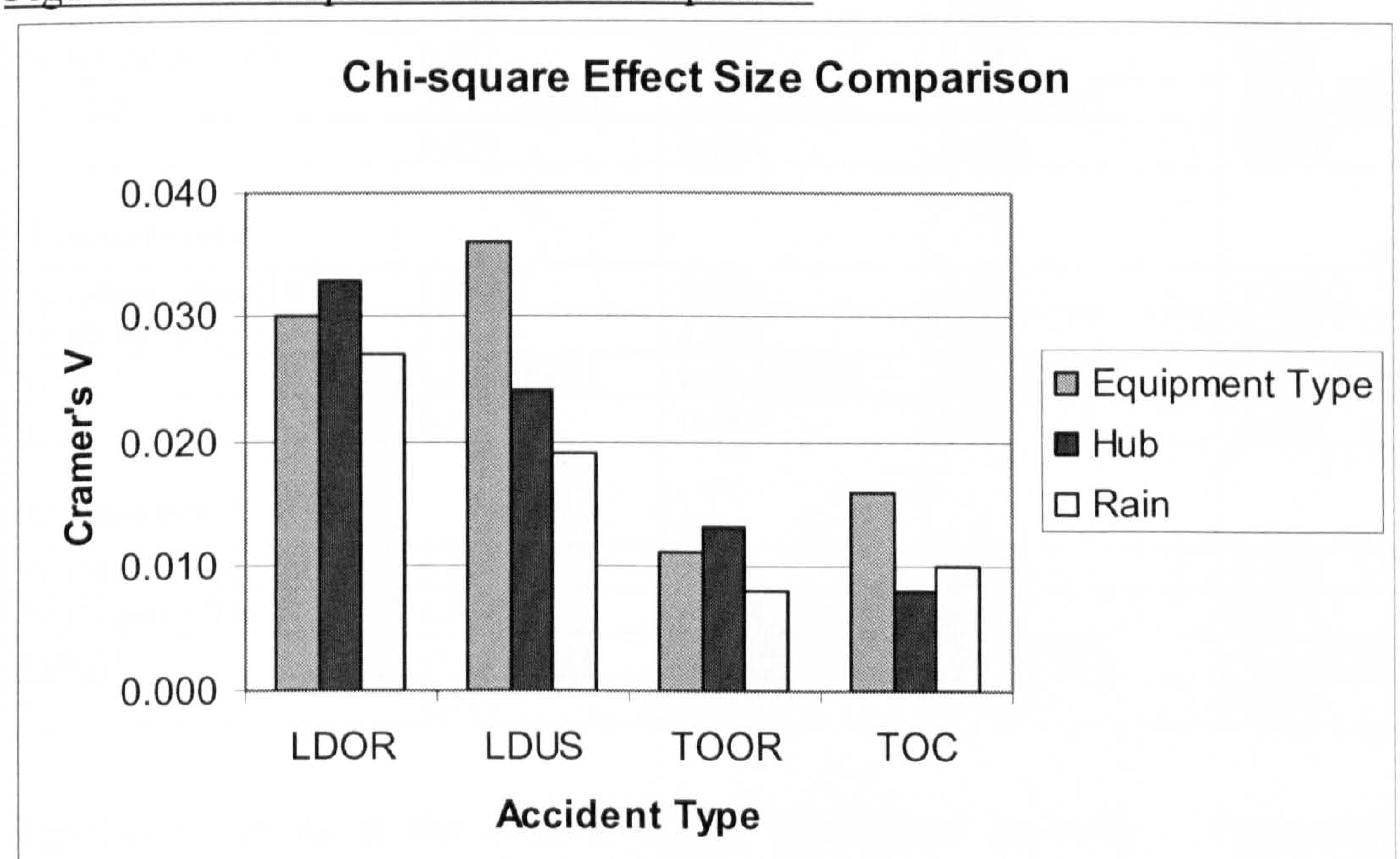
Risk factors associated with accident occurrence significant at the 0.05 level are highlighted in bold. The categories distinguished within all variables studied are identical to those discussed in the univariate analysis of Chapter 8. The only exception is user class, which due to data compatibility issues, commercial and air taxi operations were merged into one class.

Nine factors were found to be significantly associated with the occurrence of all accident types. These are equipment class, equipment type, user class, hub size, fog, icing conditions, frozen precipitation, snow and rain. Other factors were found to be significantly associated with certain accident types only. Foreign origin/destination was associated with landing and take-off overruns and dawn/dusk with landing overruns and crashes after take-off. A significant relationship was also observed between the occurrence of landing undershoots and significant terrain, which is intuitively correct. Finally, electric storm was associated with both types of landing accidents, which echoes the trend observed in the univariate analysis where adverse meteorological conditions featured more prevalently among landing than take-off occurrences.

When interpreting the results of chi-square analysis, however, the number of expected frequencies for each category must be considered. The usual assumption is that in 2 x 2 tables, the expected number of cases ought to be at least five for each category. Risk factors that did not meet this criterion were marked with an asterisk in Table 10.1 after the significance value. Equipment type, hub, terrain and rain meet this condition for all accident types. Icing, electric storm, frozen precipitation and snow failed across all accident classes due to the rarity of expected accident occurrences despite the large accident database. Results that involve expected frequencies under five should be interpreted with caution.

The Cramer's V statistic was calculated to measure the strength of association. Cramer's V varies from zero to one, the latter designating maximum effect size (Hutcheson & Sofroniou 1999). Figure 10.1 compares the Cramer's V measures of risk factors that meet the minimum frequency criterion across all accident types and for which significant associations were found.

Figure 10.1 Chi-square effect size comparison



It should first of all be noted that the effect size of all three risk factors are small for all accident types. Within this context, variations exist between factors and types of accident. All three factors generally show stronger strengths of association with landing accidents. It is perhaps surprising that even operational factors such as equipment type (i.e. jet or turboprop) and hub size (hub or non-hub) follow this pattern too. This will be further investigated in the bivariate logistic regression analysis.

10.4.2 T-test results

Independent t-test was conducted on risk factors measured as continuous variables (Hutcheson & Sofroniou 1999). Dependent t-test was not used because the accident data and the NOD were drawn from independent samples. Levene's test was carried out on each risk factor to determine if the assumption of equal variances held true. The t-test results were then obtained accordingly, as shown in Table 10.2.

Table 10.2 T-test results

	LDOR	**LDUS**	**TOC**	**TOOR**
Ceiling Height				
Accident mean (100ft)	**19.626**	**18.208**	**24.159**	**21.422**
NOD mean (100ft)	**27.499**	**27.499**	**27.296**	**27.296**
t (Sig.)	**9.1 (<.0001)**	**8.1 (<.0001)**	**2.2 (0.036)**	**4.1 (<.0001)**
r	**0.558**	**0.616**	**0.313**	**0.479**
Visibility				
Accident mean (SM)	**6.044**	**5.541**	**7.879**	**6.897**
NOD mean (SM)	**8.971**	**8.971**	**8.881**	**8.881**
t (Sig.)	**10.2 (<.0001)**	**9.3 (<.0001)**	**2.1 (0.044)**	**4.2 (<.0001)**
r	**0.589**	**0.644**	**0.278**	**0.456**
Temperature				
Accident mean (10°C)	**1.082**	**0.988**	**1.195**	**1.141**
NOD mean (10°C)	**1.652**	**1.652**	**1.657**	**1.657**
t (Sig.)	**6.3 (<.0001)**	**6.0 (<.0001)**	**2.6 (0.013)**	**3.3 (0.002)**
r	**0.423**	**0.487**	**0.342**	**0.380**
Crosswind				
Accident mean (knts)	**5.164**	4.134	5.232	4.616
NOD mean (knts)	**4.044**	4.044	3.975	3.975
t (Sig.)	**-3.1 (0.002)**	-0.3 (0.778)	-1.6 (0.111)	-1.1 (0.284)
r	**0.219**	0.001	0.222	0.135

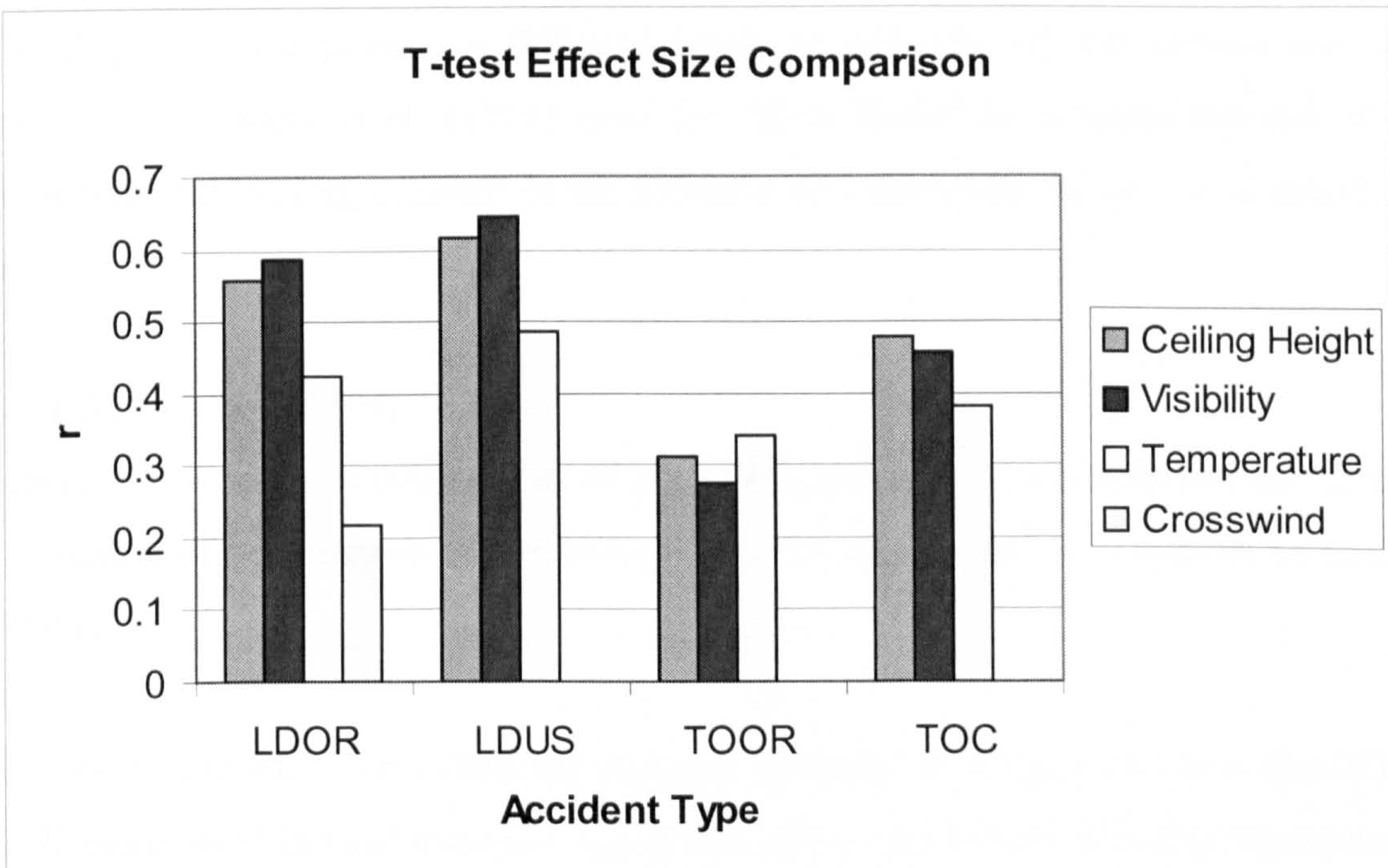
Significant results at the 0.05 level are highlighted in bold. The results show significant differences in the mean exposure of accidents and normal flights to ceiling height, visibility and temperature across all accident types, suggesting that the two groups of flights were exposed to generally different meteorological conditions. For example, on average, landing overruns took place in lower ceiling height (1963ft) and in poorer visibility (6.04SM) than normal landings (2,750ft and 8.97SM respectively).

Accidents also tended to occur in lower temperatures. The difference is starkest for landing undershoots, which on average took place in 9.9°C whereas the average for normal landings is 16.5°C. Since these findings were statistically significant, it is unlikely that the difference in exposure to risk factors came about simply by chance.

The results for crosswind are only significant for landing overruns, which on average, experienced crosswind of 5.16 knots compared to only 4.04 knots for normal landings. Similar findings were obtained for the other accident types but they were not statistically significant.

The effect sizes of these risk factors were evaluated by calculating their r values. Figure 10.2 shows the r values for the statistically significant findings.

Figure 10.2 T-test effect size comparison



Correlation values of 0.3 to 0.5 generally indicate a medium effect and values above 0.5 signal a strong effect. Most of the r values in Figure 10.2 show medium to strong effects. However, the effect sizes are not uniform across parameters and accident types. It is interesting to note that the results differ considerably between landing and take-off accidents. For landing accidents, visibility has the strongest effect on accident occurrence, followed by ceiling height then temperature. However, effect sizes are smaller across the board for take-off accidents. The order of impact of the three risk factors are also different, especially for take-off overruns. For the latter, ceiling height, visibility as well as temperature have medium effect sizes of similar strengths. For crashes after take-off, ceiling height shows the largest effect, followed by visibility and temperature. The dissimilarities in effect magnitude between risk factors and accident types indicate the four classes of accidents are affected to different degrees by the various risk factors and highlight the importance of disaggregating the analysis as performed. In order to further examine the relationship between these factors and accident occurrence, their respective Relative Accident Involvement Ratios (RAIR) were analysed.

10.5 Relative Accident Involvement Ratio (RAIR)

Chi-square analyses and t-tests compared accident and normal flights in terms of their mean values of risk exposure. To add further insight on the criticality of risk factors, the disparity in exposure to different levels or strengths of risk factors was also assessed. Enders et al. (1996) used the "Risk Ratio" to estimate the risk of an approach and landing accident in the presence of a particular factor. It is calculated as:

Risk Ratio = (a/A)/(f/N)

where; a is number of occurrences of a factor in accidents, A is number of accidents, f is number of occurrences of the factor in normal flights, and N is number of normal flights.

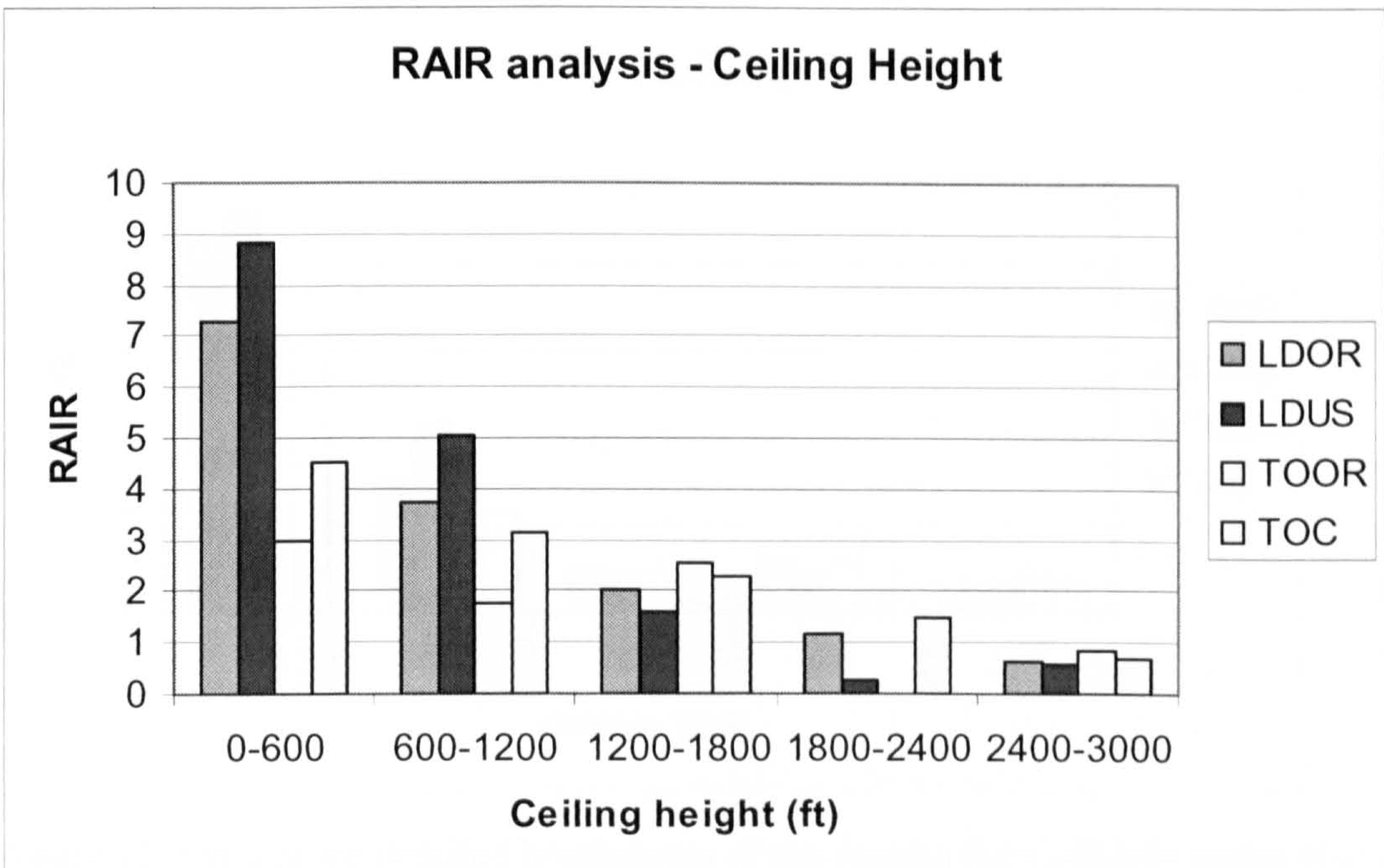
The same measure, but called the Relative Accident Involvement Ratio (RAIR), is well established in road transport safety research as a measure of accident propensity among driver groups. Ratios over unity indicate that the subgroup of drivers concerned is more likely to cause a crash under the circumstances considered (Stamatiadis and Deacon 1995, 1997, Hing et al. 2003, Yan et al. 2005). Here the measure was used to evaluate accident propensity of flights under different levels or strengths of specific risk factors.

For each parameter, its range of values was split into quintiles and the RAIR for each quintile calculated. This provided a simple description of the flight accident propensity associated with the different strengths of the parameter concerned. In cases where accident propensity is highly concentrated in a particular range, the latter was split into finer groups and the RAIRs recalculated. RAIR analysis was conducted on all continuous variables and discrete ones with multiple categories.

10.5.1 Ceiling height

Figure 10.3 shows the results for ceiling height. It reveals a clear trend in the parameter's relationship with accident propensity. Low ceiling conditions are associated with high accident propensity, which decreases with higher ceiling heights. This confirms and quantifies the idea of heightened accident risk in low ceiling conditions. This relationship is apparent for all accident types except take-off overruns, which saw higher accident propensity in 1200-1800ft ceiling height compared to 600-1200ft. Under ceiling height of 1200ft, it is clear that landings have higher accident propensity than take-offs and that landing undershoots have the highest RAIR figures. This suggests that ceiling height is somewhat more pertinent to landings as an accident risk factor than for take-offs at the low-end of ceiling height conditions. Within the same ceiling range, the RAIR of crashes after take-off is also larger than take-off overruns. This seems reasonable since take-off overruns stay closer to the ground than crashes after take-off. The RAIRs for all accident types drop below unity when ceiling height increases to beyond 2400ft, implying that accidents are relatively unlikely when ceiling height is above this level.

Figure 10.3 Ceiling height RAIRs



10.5.2 Visibility

As with ceiling height, a clear trend was observed between visibility and accident propensity. As visibility decreases, the likelihood of accident occurrence increases. Figure 10.4 shows that RAIRs tend to be above unity when visibility is under four statute miles. In this high risk visibility range, landing undershoots have the highest RAIRs, followed by landing overruns, crashes after take-off and finally take-off overruns. These results echo those of ceiling height and again suggest greater sensitivity of landing and airborne operations towards adverse weather conditions.

Figure 10.4 Visibility RAIRs

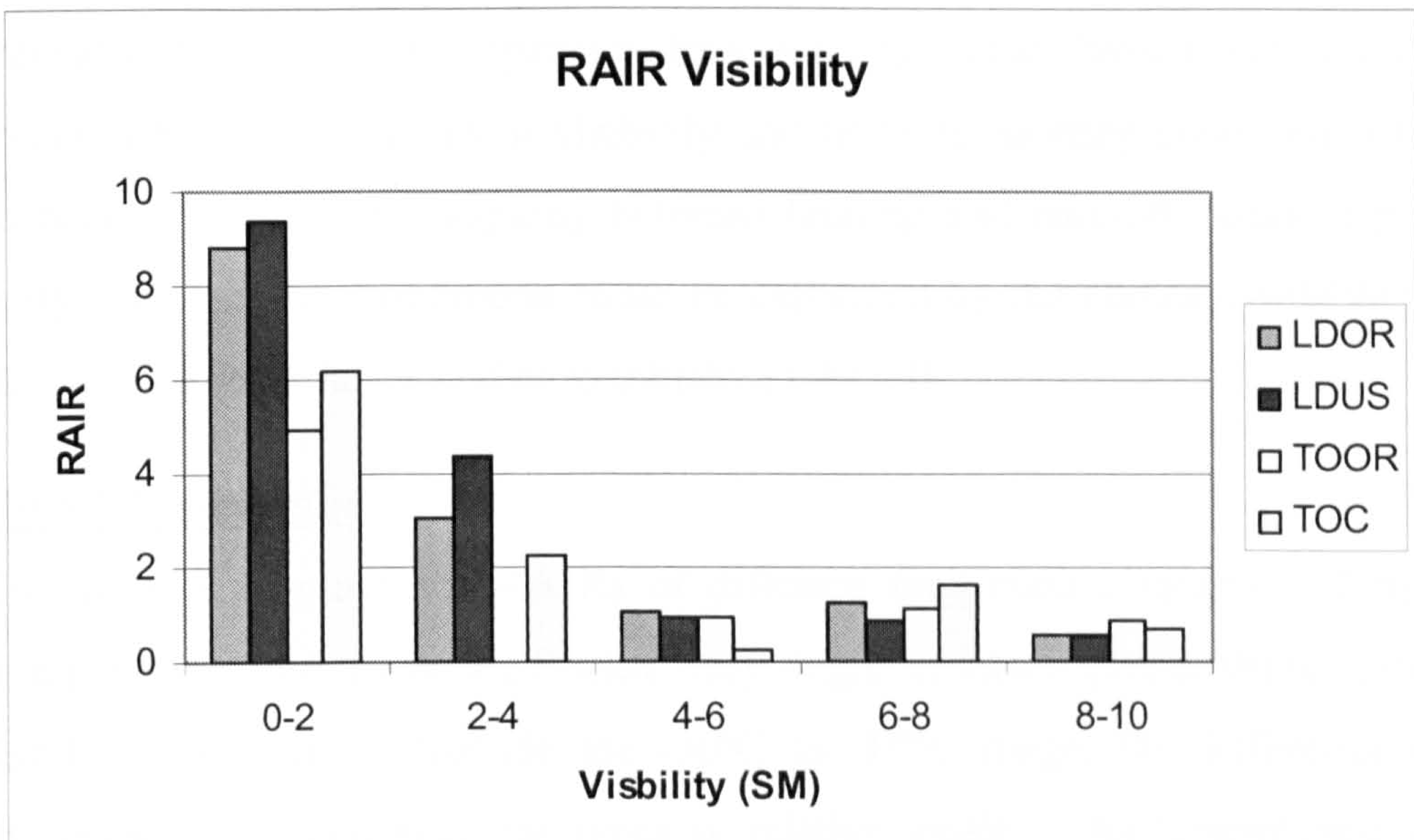
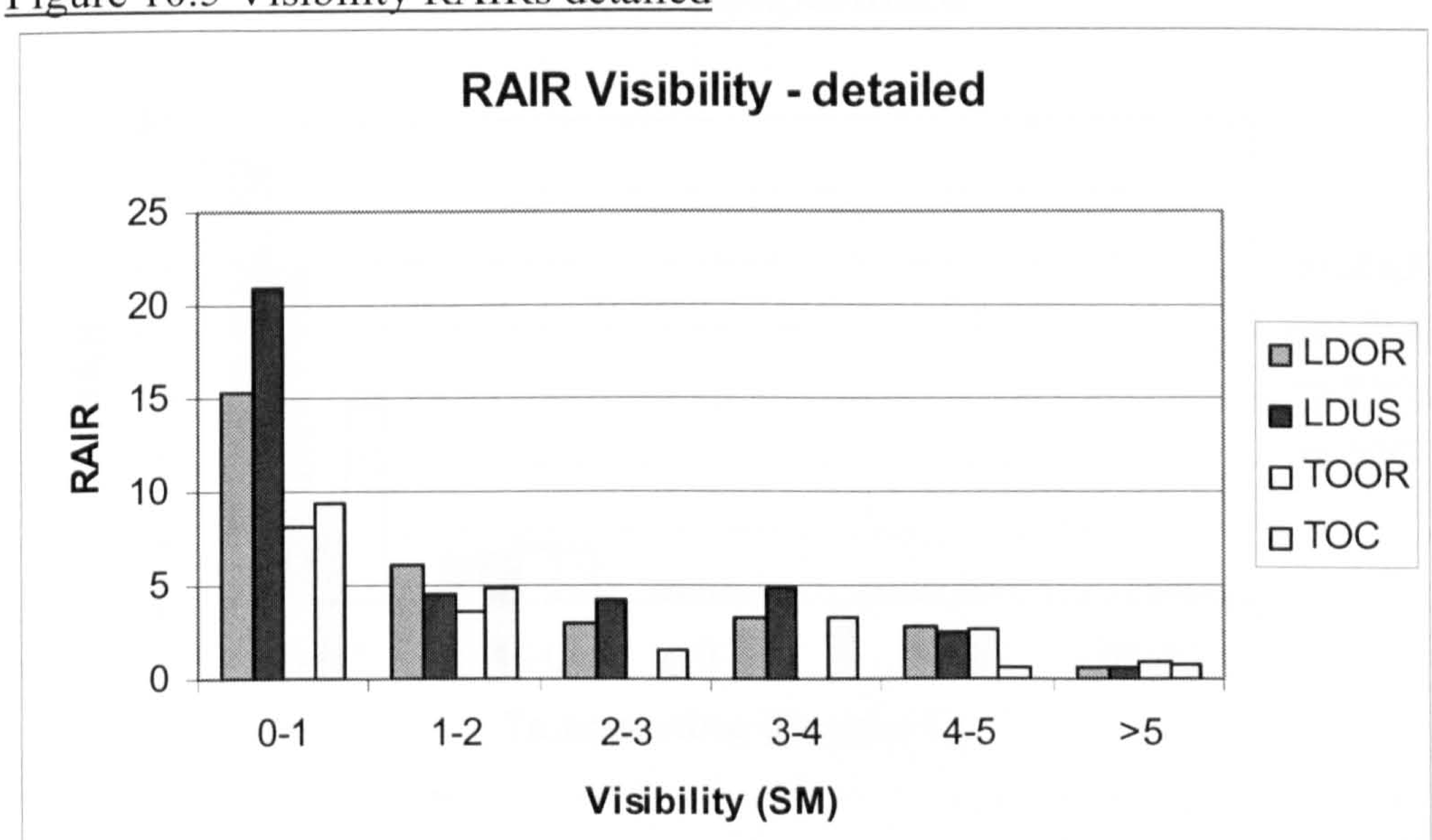


Figure 10.5 is a more detailed breakdown of the results for visibility under five statute miles.

Figure 10.5 Visibility RAIRs detailed



The general tendency of rising accident propensity with lower visibility remains but the detailed results also show the exponential increase in accident propensity when visibility decreases to under one statute mile. For example, RAIRs for landing undershoots are fairly stable at around 4.5 between visibilities of one to four statute miles. Once under one statute mile, however, its RAIR reaches over 20. This implies that landing undershoots are especially likely to occur in very low visibility conditions. This risk decreases dramatically when visibility improves to over one statute mile and RAIR falls below unity beyond five statute miles. The analysis revealed that accident propensity does not necessarily have a continuous or linear relationship with changes in visibility and helps to identify conditions of significant concern. Lastly, the disparity between landing and take-off accident propensity at very low visibility conditions could be explained by the choice available to pilots on the ground regarding whether to initiate a take-off.

10.5.3 Temperature

Figure 10.6 displays the RAIRs of different temperature ranges. Extremely low temperatures are associated with very high accident propensities, especially for landing accidents. Outside the -30°C to -15°C range, the difference in accident propensity between accident types is relative small. As temperature rises above freezing point, RAIRs cross the unity threshold.

Figure 10.6 Temperature RAIRs

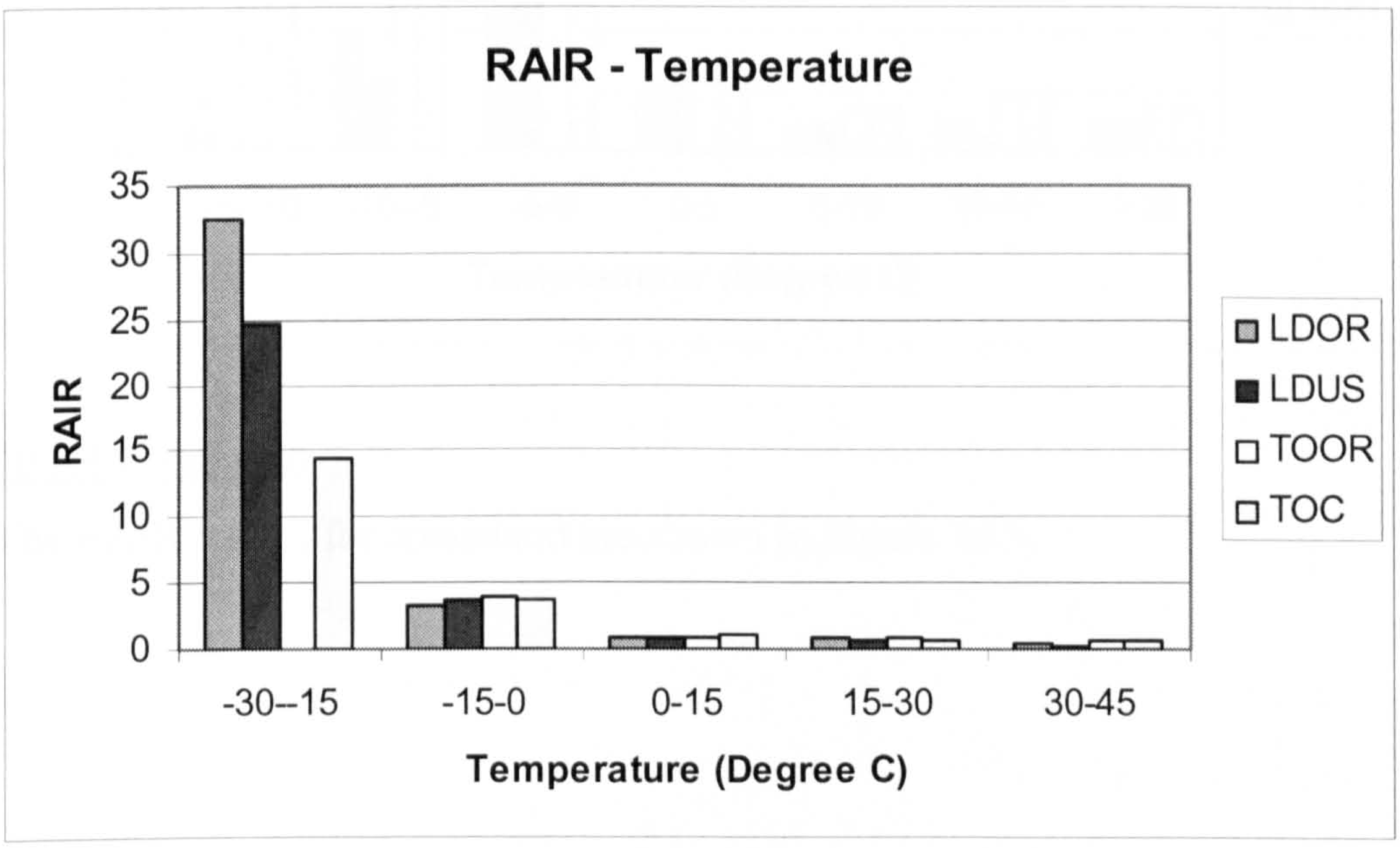
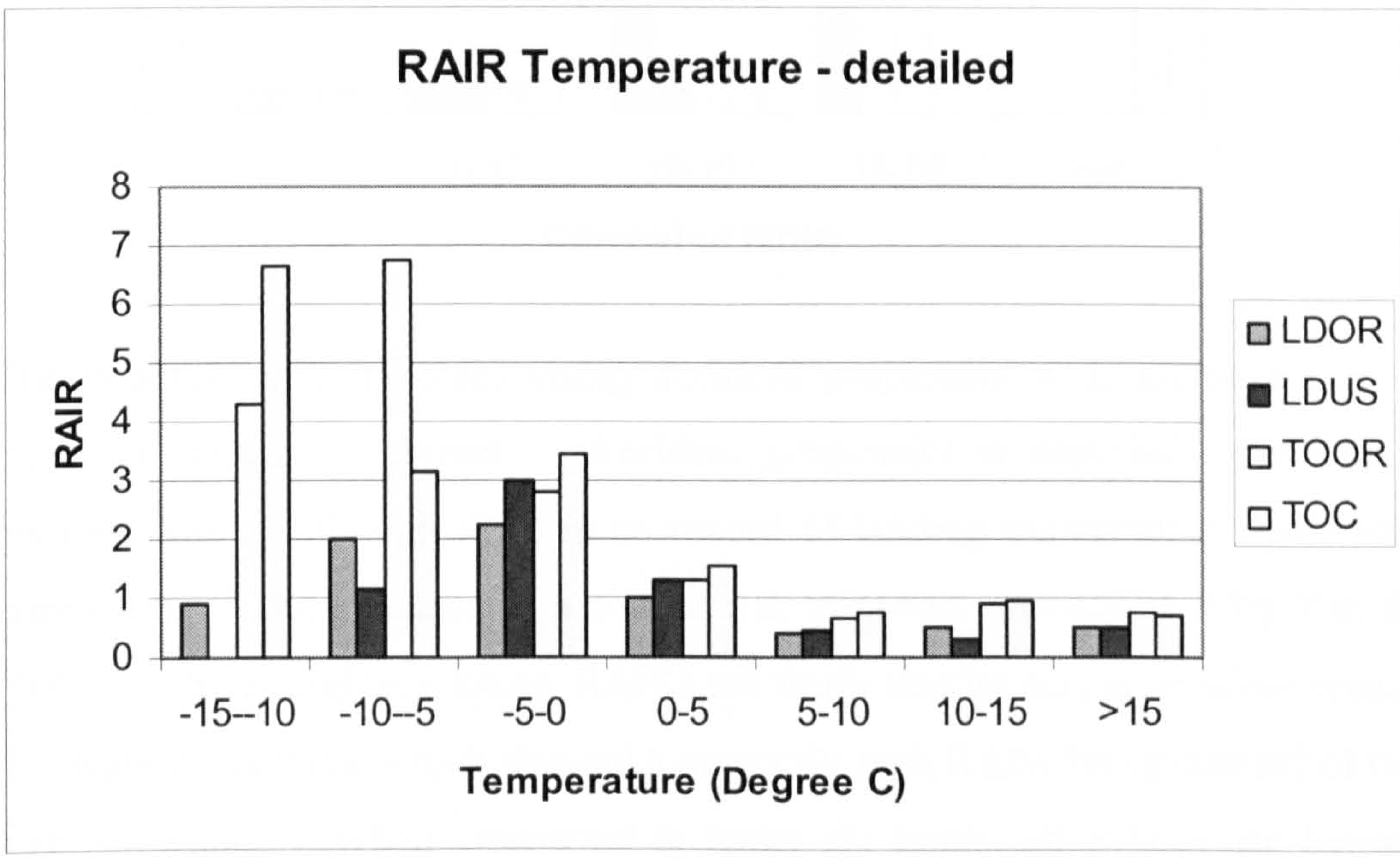


Figure 10.7 shows a more detailed investigation of RAIRs in the -15°C to 15°C temperature range. Within this range, the relatively small RAIR numbers suggest that accident propensity is somewhat less sensitive to temperature than to the range of visibility or ceiling height considered. This confirms the findings of the t-tests where temperature showed smaller effect sizes compared to the other two parameters.

Overall, high accident propensity is generally associated with lower temperatures but the trend is not as uniform between accident types as with ceiling height and visibility.

Between -15°C and 15°C, accident propensity clearly peaks around the freezing point for landing accidents. This is not apparent for take-off accidents, the propensity of which continues to rise below freezing point. This indicates that even different levels of the same risk factor affect accident propensity to varying degrees according to accident type. Nonetheless, RAIRs of all accident types fall below unity when temperature reaches 5°C.

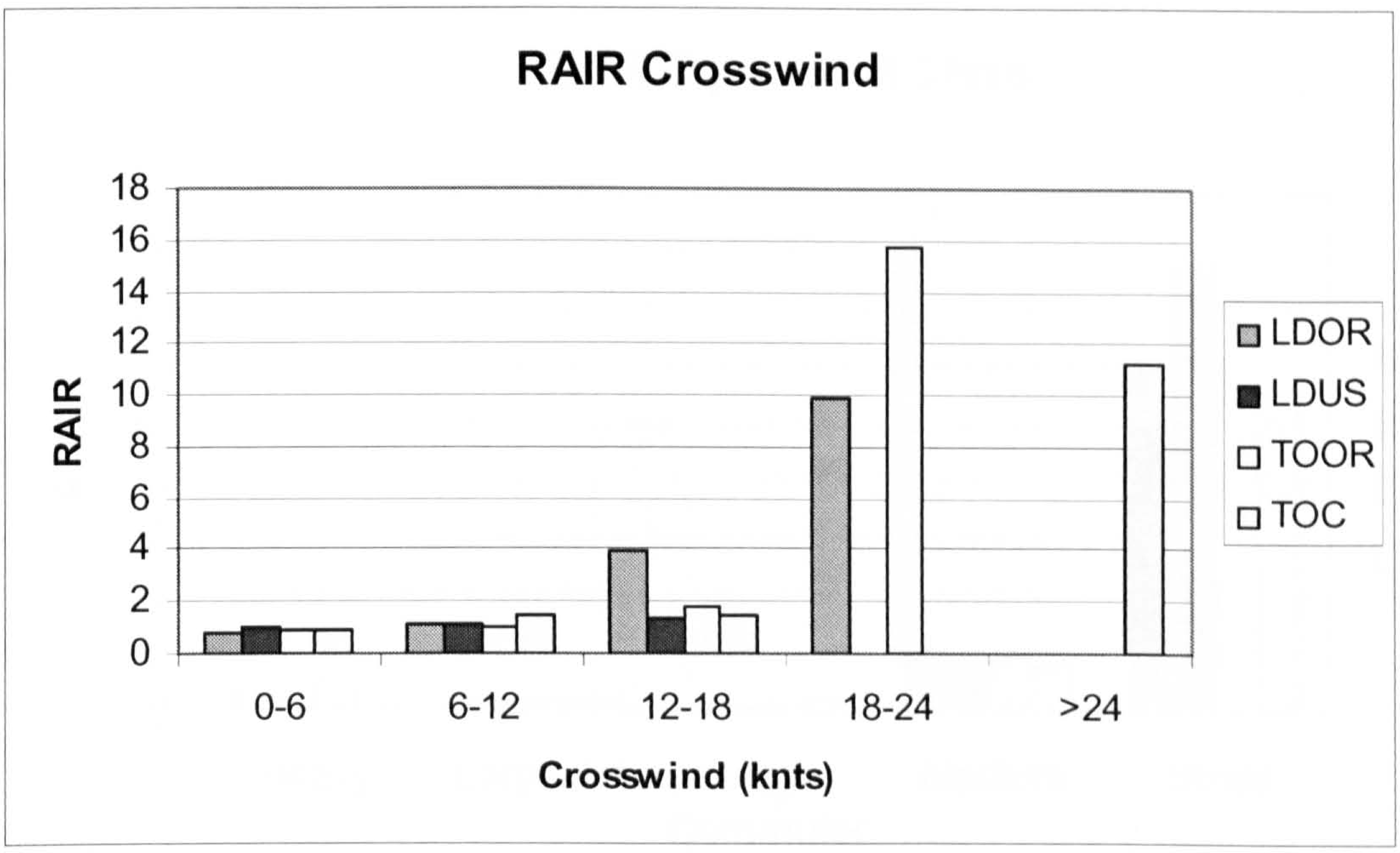
Figure 10.7 Temperature RAIRs detailed



10.5.4 Crosswind

The RAIR results for crosswind are shown in Figure 10.8.

Figure 10.8 Crosswind RAIRs

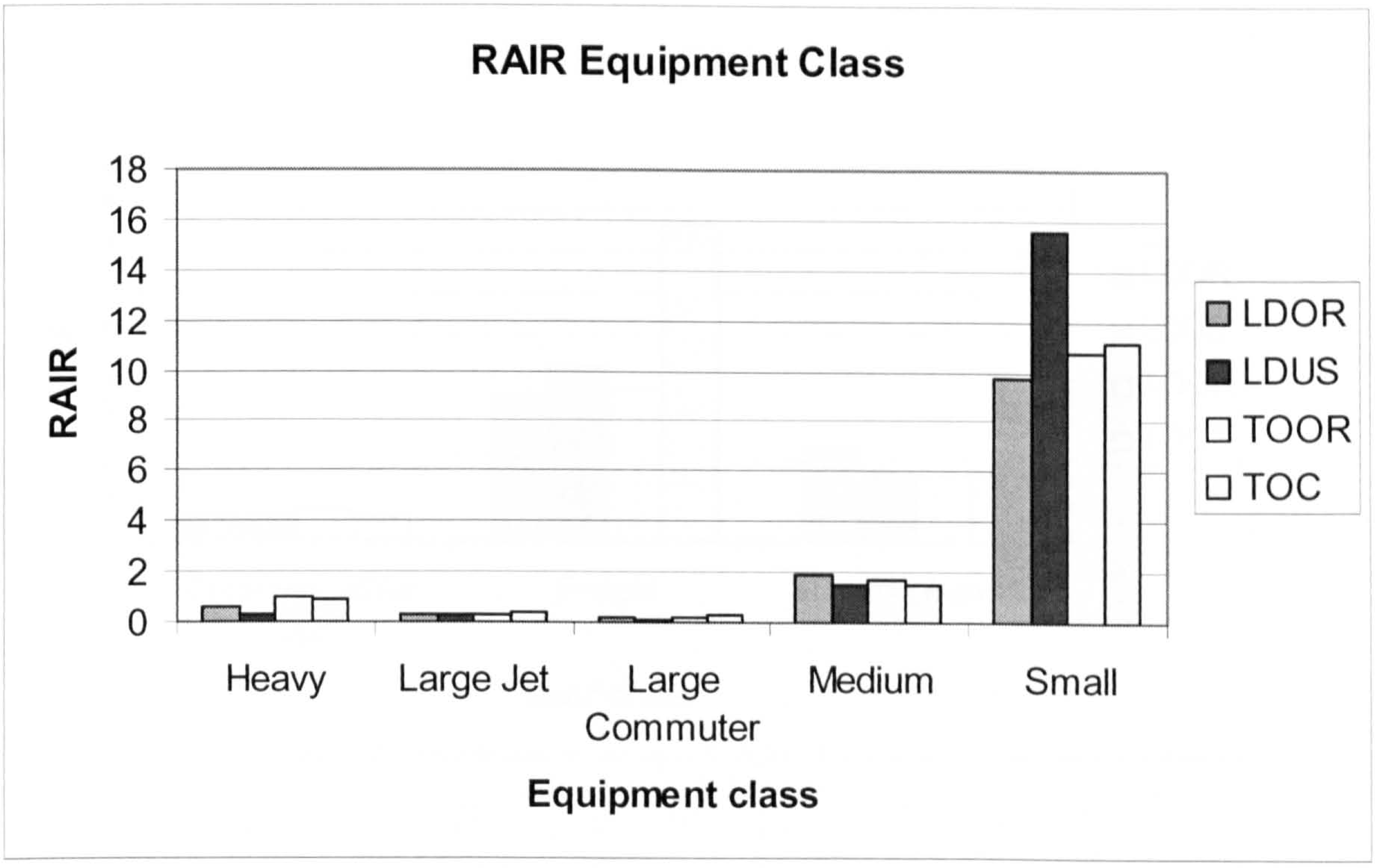


The general trend indicates rising accident propensity with increasing crosswind, which is intuitively correct. Accident propensity is especially elevated beyond eighteen knots, although there is no record of landing undershoots under such high crosswinds. The presence of a similar risk threshold was reported by Van Es et al. (2001). Under eighteen knots, RAIRs are fairly similar across accident types except for landing overruns, which showed a distinctly high RAIR for crosswind of twelve to eighteen knots. When crosswind is under six knots, all RAIRs are below unity, suggesting that crosswind only contributes to increased accident likelihood above approximately six knots.

10.5.5 Equipment class

The predominance of small aircraft is evident in the RAIR results for equipment class displayed in Figure 10.9. Accident propensity of small aircraft, i.e. those under 12,500lbs, is several times higher than other aircraft types. The average RAIR for medium aircraft is 1.65 while heavy aircraft, large jets and large commuters all have RAIRs at or under unity. There are no significant disparities between the accident types, except for a particularly strong association between small aircraft and landing undershoots.

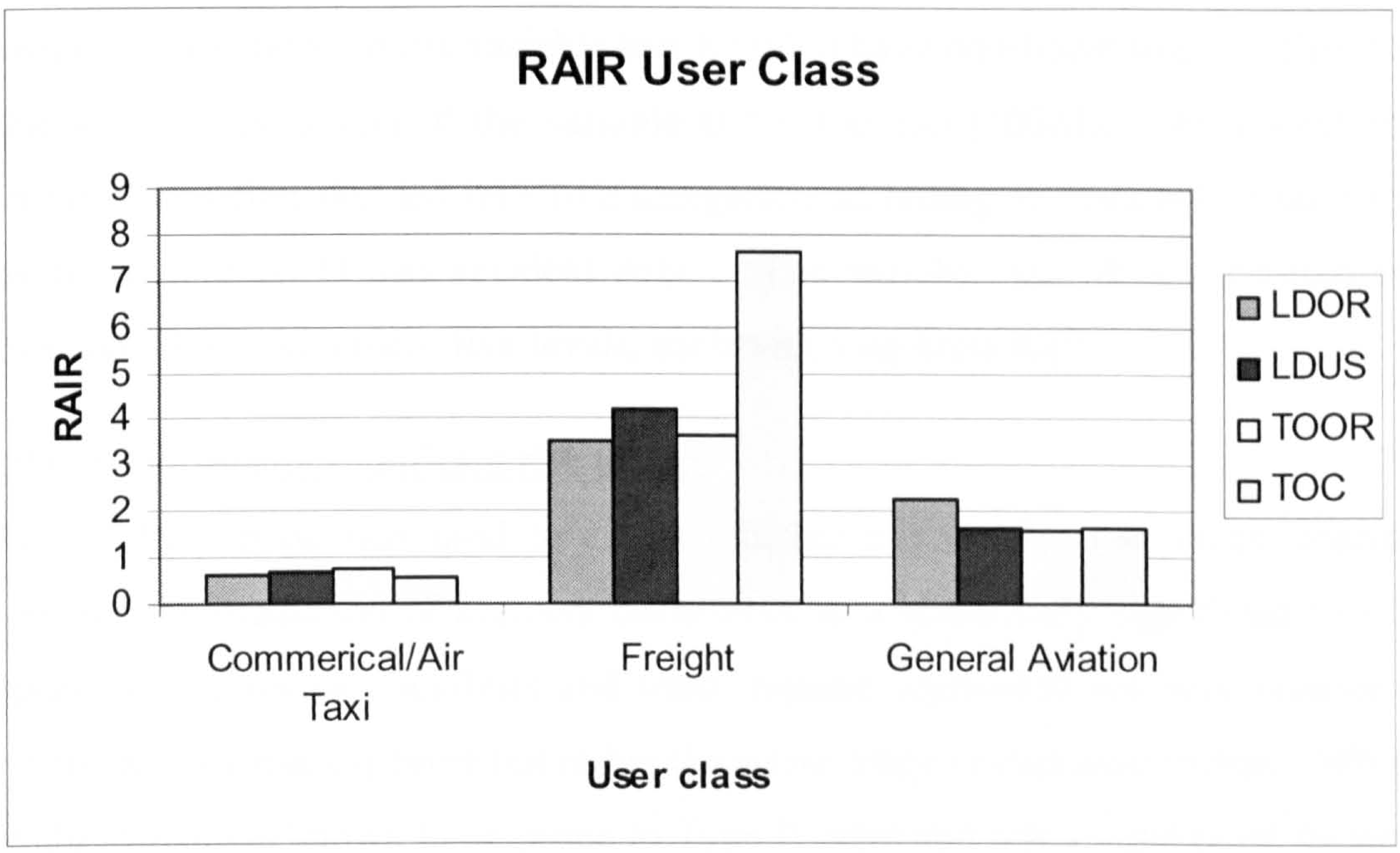
Figure 10.9 Equipment class RAIRs



10.5.6 User class

Considering user class, accident propensity is concentrated in freight and general aviation operations, especially the former. Figure 10.10 also shows that all RAIRs related to commercial/air taxi operations are under unity, suggesting that accidents of this category of operations are relatively unlikely. The largest inconsistency across accident types is the distinctly elevated accident propensity associated with freight operations and crashes after take-off. This is in line with the large number of cases where crashes after take-off resulted from freighters with improper loadings and centres of gravity observed when developing the accident database.

Figure 10.10 User class RAIRs



10.6 Bivariate Logistic Regression

The final stage of the bivariate analysis involved conducting individual logistic regressions on all risk factors. This firstly allows a formal statistical assessment of the significance of the risk factors' contribution towards the prediction of accident occurrence. Secondly, it also provides the odds ratios, and thus risk ratios, for assessing the impact of the presence or increase of a particular risk factor on the likelihood of accident occurrence. Full results are presented in Appendix J and the following sections in this chapter consider the results from two points of view – statistical significance of risk factors and their effect sizes as measured by risk ratios. First, however, the assumptions concerning logistic regression are discussed.

10.6.1 Assumptions check

Before the 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 2007). This involved adding to the model interaction terms that are the crossproduct of each independent times its natural logarithm [(X)ln(X)]. The logit linearity assumption is violated if these terms are significant. In the current analysis, only the visibility variable was found to have non-linear logits. This may be due to the constraining of the variable at the top end (10SM). As a solution, the variable was first divided into five categories according to standard equal intervals using landing NOD and accident data. The variable was then converted into a categorical one with these five levels, each with a separate logit.

10.6.2 Statistically significant risk factors

The Wald statistic was used to assess whether a particular risk factor contributes towards the prediction of accident occurrence in a statistically significant way. As opposed to chi-square analysis and t-test, logistic regression not only considers the mean value of risk exposure but rather the entire range of exposure values. While the Wald statistic is known to be prone to Type II error and reject significant factors, the change in -2LL (-2 x Log likelihood) was also inspected to ensure that all significant factors were identified (Pampel 2000). For factors found to be significant predictors of specific accidents, their risk ratios were calculated and shown in Table 10.3. Regarding multi-category discrete variables, risk ratios were calculated for the specific categories that were identified as significant. The level used as the indicator or reference level is marked by "Ref". By examining the populated fields of Table 10.3, then, the significant factors could be identified.

The majority of factors were found to be significant predictors of accident occurrence for all accident types. These include aircraft and operational factors such as equipment class (medium & small), turboprop aircraft, user class (freight & general aviation) and non-hub airport. Meteorological conditions such as ceiling height, visibility (<2SM), fog, rain, temperature, icing conditions, frozen precipitation and snow were also found to be significant for all accident types.

Two categories of multi-category discrete variables were found to be significant predictors for none of the accident types. They are equipment class (large commuters) and visibility (4-6SM). This may be due to the lack of data points belonging to these categories.

The remaining factors were identified as significant only for particular accident types. Visibility (2-4SM) and electric storm were only significant factors for predicting the occurrence of landing overruns and undershoots but not take-off accidents. Crosswind and foreign origin/destination only implicated landing and take-off overruns. Terrain was found to be significant only for landing undershoots, which is in line with expectations. The majority of these findings agree with respective t-test and chi-square analysis results.

Table 10.3 Bivariate logistic regression risk ratios

Variable	LDOR	LDUS	TOOR	TOC
Eqpt_class Heavy			3.50	
Eqpt_class Large jet	Ref	Ref	Ref	Ref
Eqpt_class Large commuter				
Eqpt_class Medium	5.51	5.28	5.36	3.35
Eqpt_class Small	28.18	52.97	30.64	22.67
Eqpt_type Turboprop	3.77	6.79	2.84	3.55
User_class Commercial/Air Taxi	Ref	Ref	Ref	Ref
User_class Freight	5.64	5.94	4.80	13.88
User_class General Aviation	3.68	2.33	2.07	3.00
Ceiling 1800Ft	Ref	Ref	Ref	Ref
Ceiling 1200Ft	1.76	1.89	1.33	1.57
Ceiling 600Ft	3.11	3.55	1.78	2.46
Ceiling 200Ft	4.53	5.41	2.15	3.31
Ceiling 0Ft	5.46	6.67	2.37	3.85
Visband <2 SM	19.99	23.99	5.68	10.72
Visband 2-4 SM	3.53	5.66		
Visband 4-6 SM				
Visband 6-8 SM	2.29			
Visband 8+ SM	Ref	Ref	Ref	Ref
Fog	12.04	12.63	4.67	6.99
Dawn/Dusk	1.91			2.27
Crosswind 0Knts	Ref	Ref	Ref	Ref
Crosswind 5Knts	1.45		1.51	
Crosswind 10Knts	2.09		2.27	
Crosswind 15Knts	3.03		3.42	
Rain	3.70	3.37	2.35	2.66
Electric storm	6.05	6.62		
Temperature -10°C	2.81	3.31	2.29	2.51

Temperature -5°C	2.17	2.46	1.86	2.00
Temperature 0°C	1.68	1.82	1.51	1.59
Temperature 5°C	1.29	1.35	1.23	1.26
Temperature 10°C	Ref	Ref	Ref	Ref
Temperature 15°C	0.77	0.74	0.81	0.79
Icing	42.57	72.62	14.45	70.32
Frozen precipitation	25.65	21.24	23.80	94.15
Snow	20.35	27.13	22.80	19.86
Terrain		1.66		
Non-hub airport	4.71	4.27	3.57	1.90
Foreign Origin/Destination	0.20		2.45	

10.6.3 Effect size of risk factors

A key output of the logistic regression is the odds ratio. Odds ratio is obtained by the exponentiation of the variable's logistic regression coefficient. The ratio indicates the change in odds of accident occurrence given a unit change in the predictor variable. In other words, the odds ratio is the number by which one multiplies the odds of accident occurrence for each one-unit increase in the independent variable[7]. Appendix J details the calculated odds ratios.

Although the odds ratio is useful for interpreting the relationship between the dependent and independent variables, it is often misinterpreted as the risk ratio, which is the ratio of two probabilities and more intuitively indicates relative risk (Menard 2001). In the current study, an extra step was taken to calculate the risk ratios for all statistically significant predictor variables as identified by the Wald statistic (Table 10.3). For a categorical risk factor, the risk ratio compares the relative risk of accident occurrence in the presence and absence of the factor. For example, a risk ratio of five for a categorical risk factor indicates that the risk of accident occurrence is five times greater in the presence of the factor than in its absence. Regarding risk factors measured as continuous variables, the risk ratio compares the probability of accident occurrence of several selected indicative levels with that of a reference level. For instance, a risk ratio of 0.2 for a risk factor measured as a continuous variable

[7] Odds is the probability divided by one minus the probability.

implies that accident risk at that level is a fifth of that at the reference level. So not only does the risk ratio quantify the magnitude of a risk factor's effect on accident likelihood, it also indicates the direction of the relationship. This adds a critical dimension to the understanding of risk factor criticality.

A number of risk factors consistently feature very large risk ratios for most accident types. Small aircraft (compared to large jets), visibility under two statute miles (compared to 8+ SM), fog, icing conditions, frozen precipitation and snow mostly have risk ratios above ten. This suggests that accident risk is ten times greater in the presence of these risk factors. Another set of risk factors have risk ratios between five to ten for landing accidents. They include medium aircraft (compared to large jets), freight operations, ceiling height 0ft (compared to 1800ft), and electric storm.

Several trends could be observed concerning notable risk ratio differences between accident types. A number of meteorological risk factors pose greater risk to landing accidents than take-off accidents. This confirms the findings of the previous stages of bivariate analysis and provides additional quantification of the phenomenon. Figures 10.11 to 10.15 compare the risk ratios for these factors between the accident types. Ceiling height, visibility, fog, rain as well as temperature tend to increase risk to a greater extent for landing occurrences than take-off ones. On average, fog increases the risk of landing accidents by 12.3 times but only 5.8 times for take-off accidents. The impact of fog on landing risk is hence twice that of take-off. For factors measured as continuous variables such as ceiling and temperature, the disparity in effect size on landing and take-off accidents grows as the risk factor level increases.

Figure 10.11 Ceiling height risk ratios

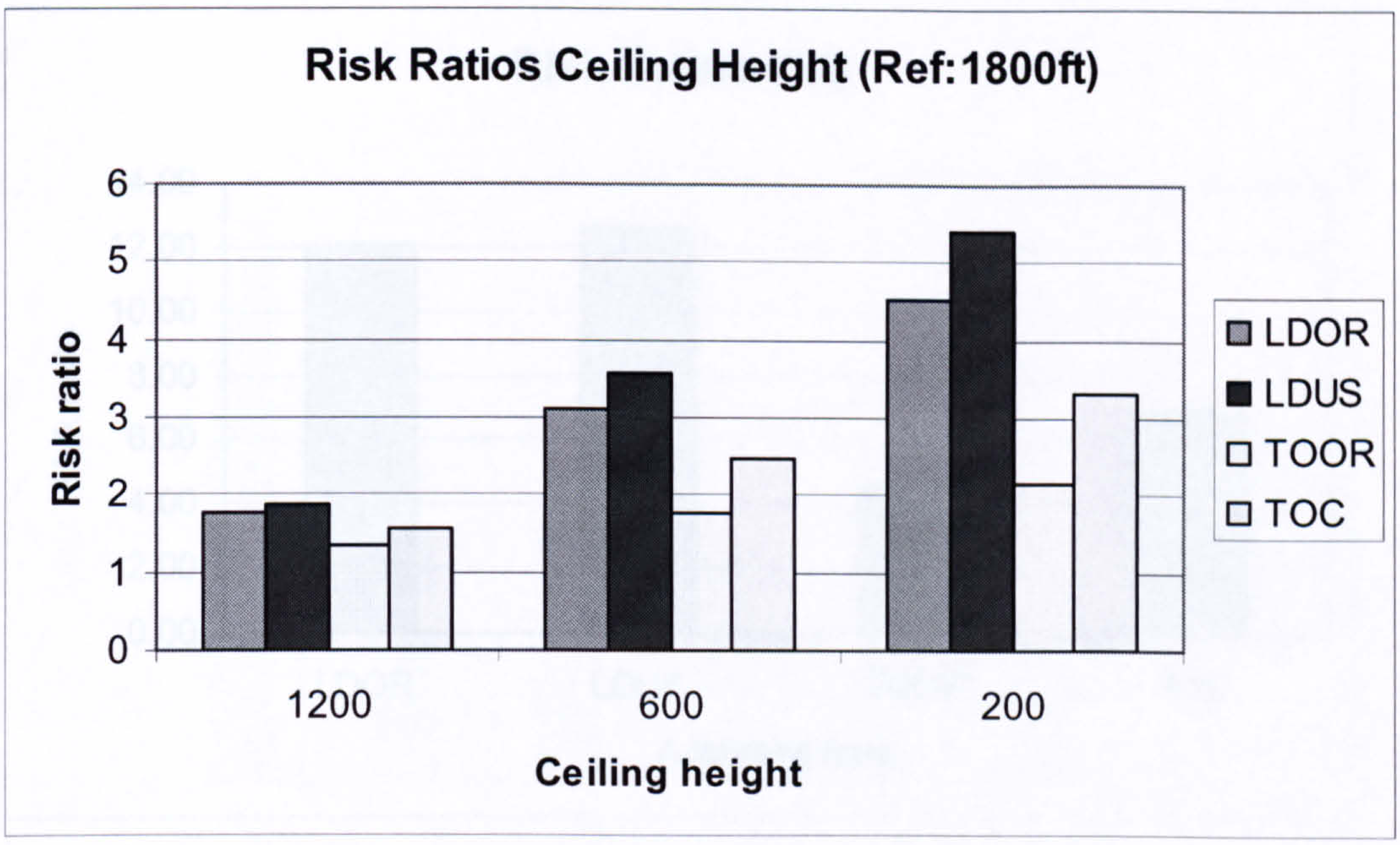


Figure 10.12 Visibility risk ratios

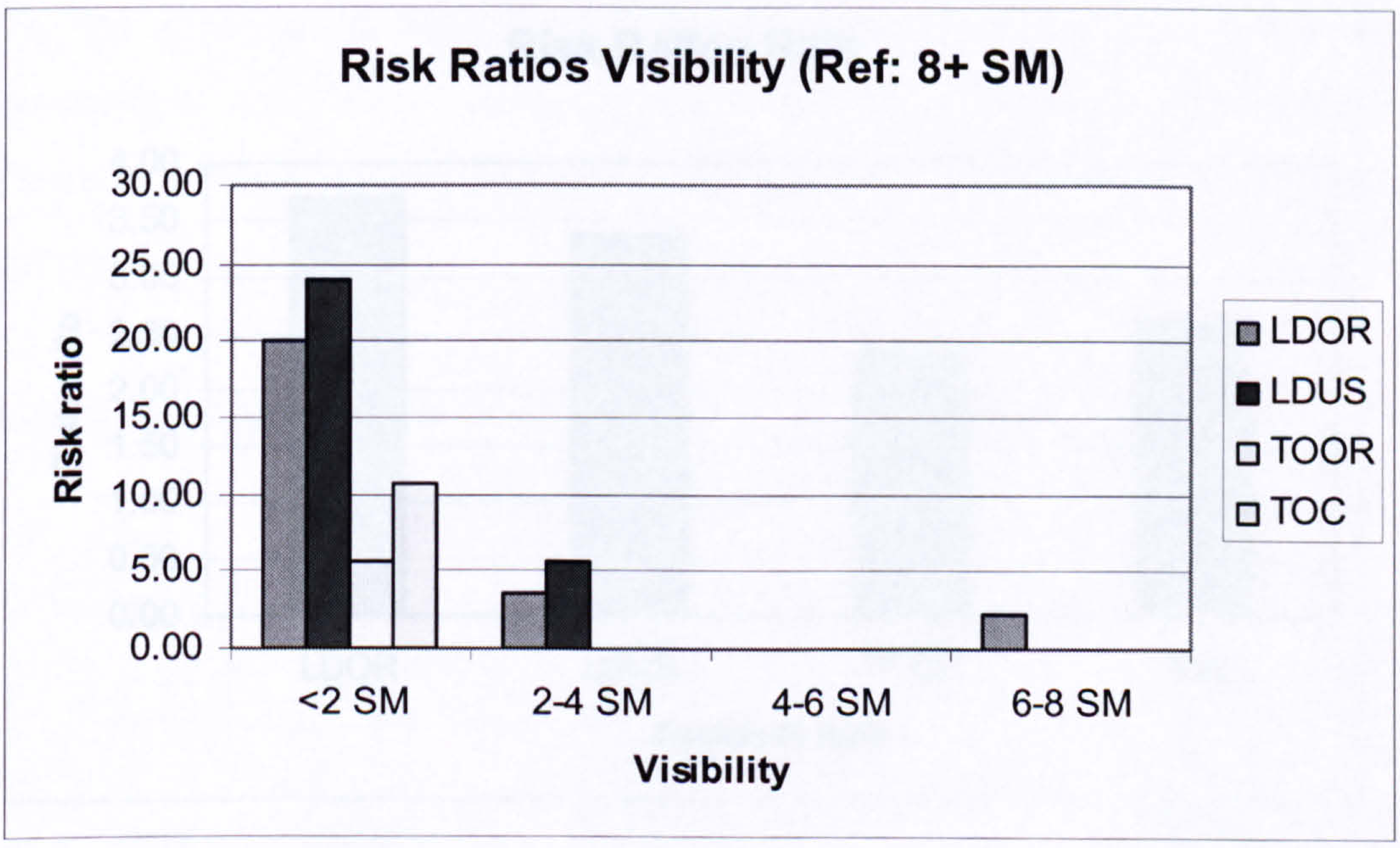


Figure 10.13 Fog risk ratios

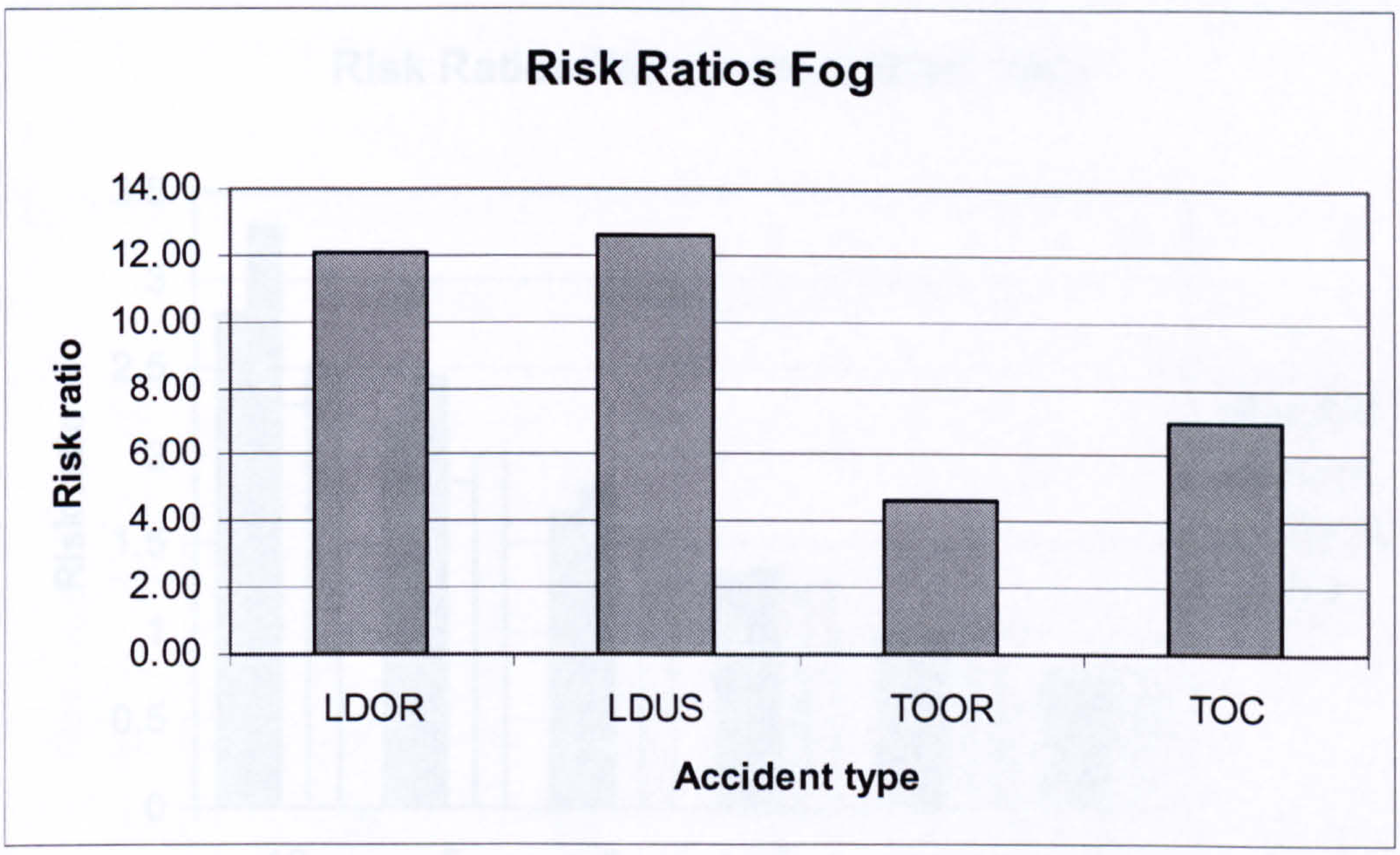


Figure 10.14 Rain risk ratios

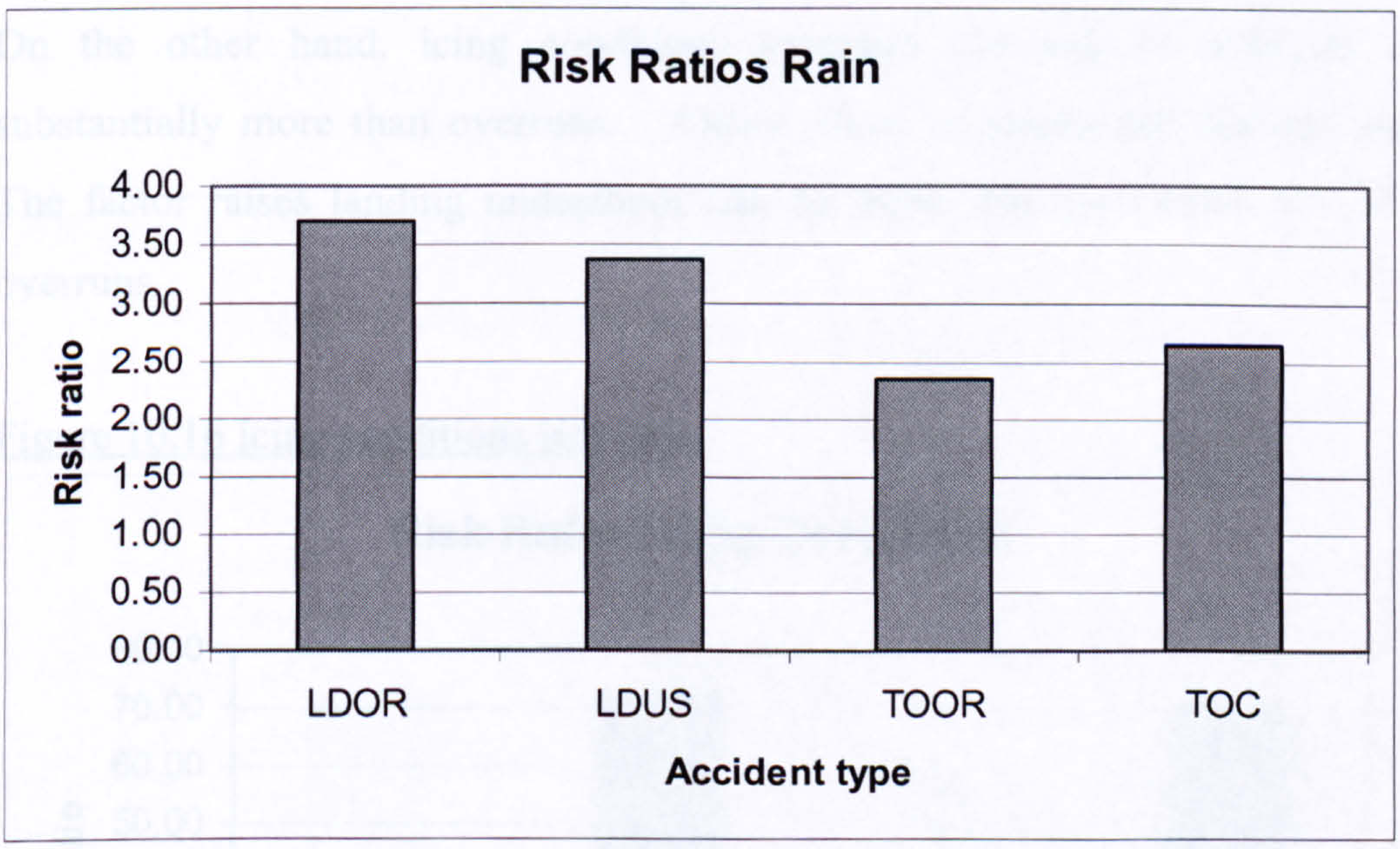
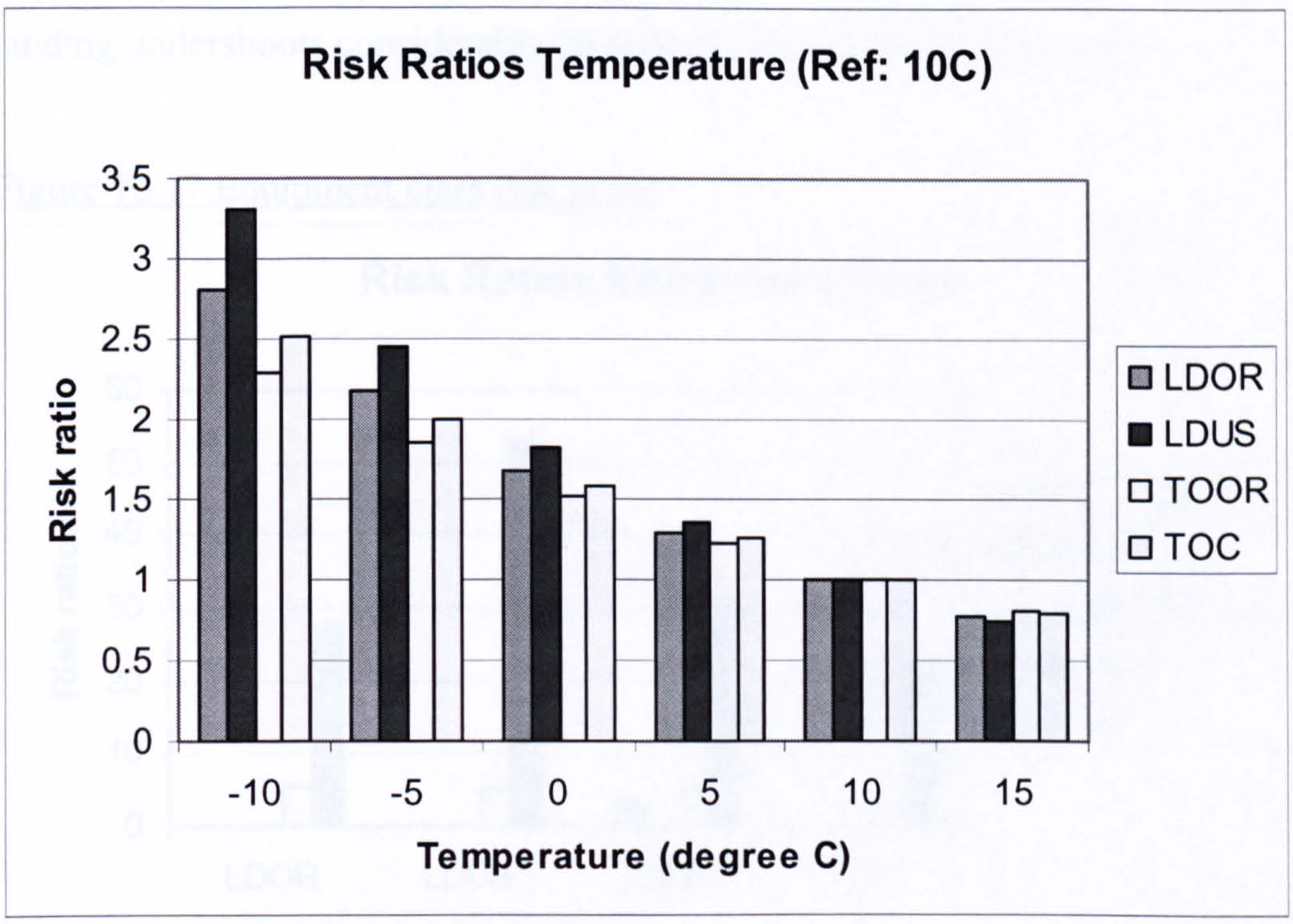
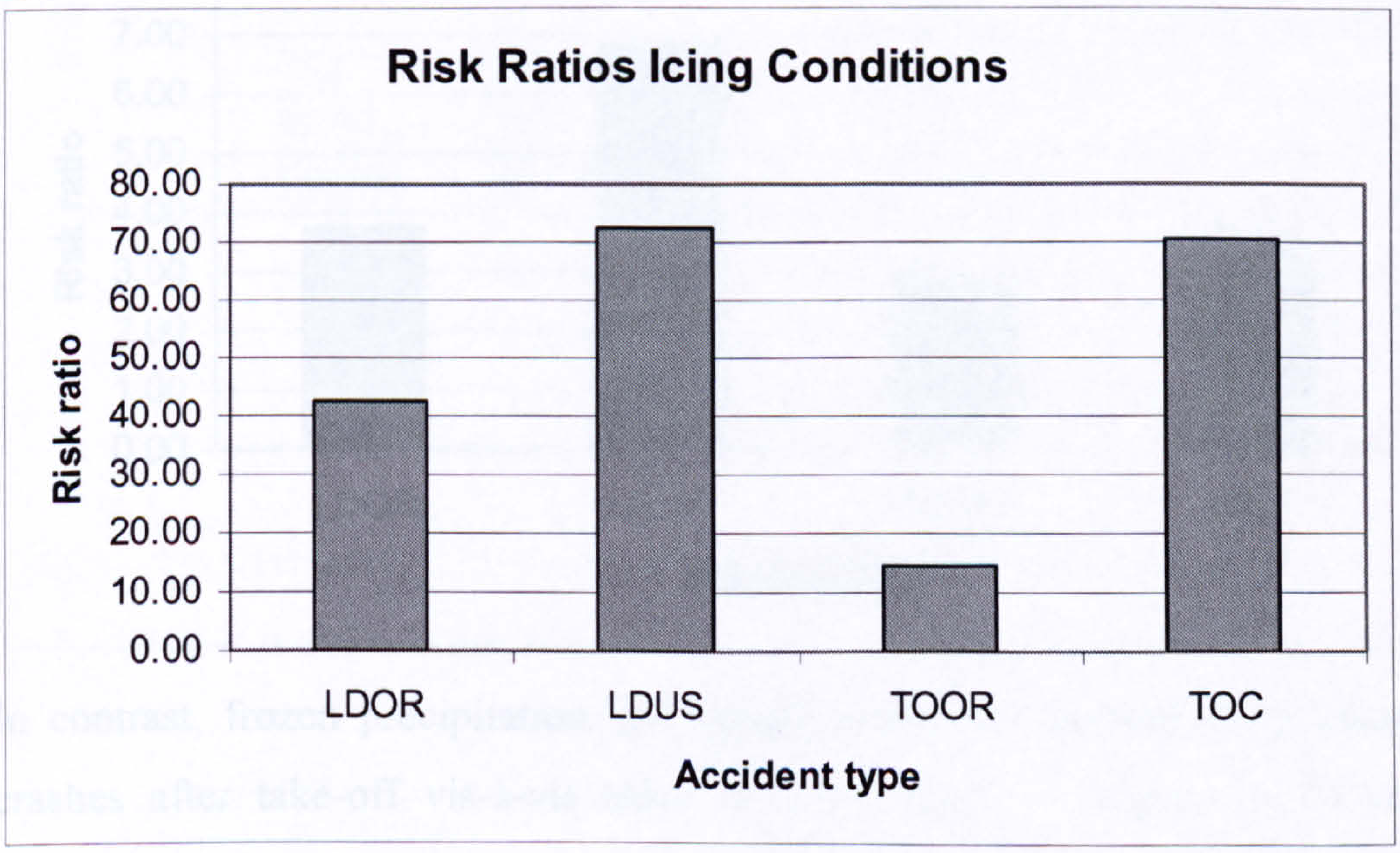


Figure 10.15 Temperature risk ratios



On the other hand, icing conditions increases the risk of airborne accidents substantially more than overruns. Figure 10.16 compares the relevant risk ratios. The factor raises landing undershoot risk by more than five times that of take-off overruns.

Figure 10.16 Icing conditions risk ratio



Certain accident types stand out to be especially vulnerable to specific risk factors. Landing undershoot is particularly susceptible to a number of operational features.

Figures 10.17 and 10.18 show that small and turboprop aircraft increase the risk of landing undershoots considerably more than other types of occurrences.

Figure 10.17 Equipment class risk ratios

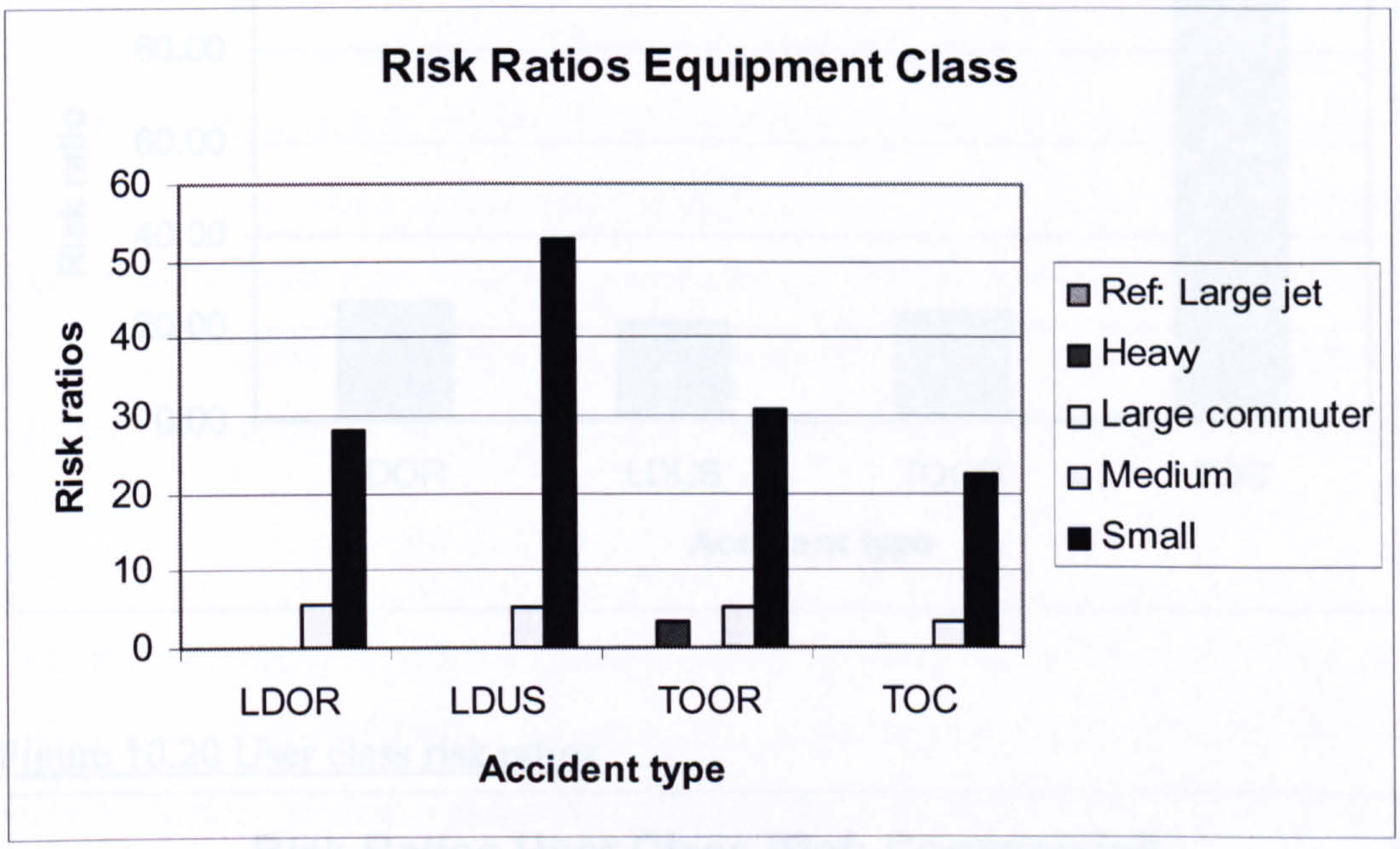
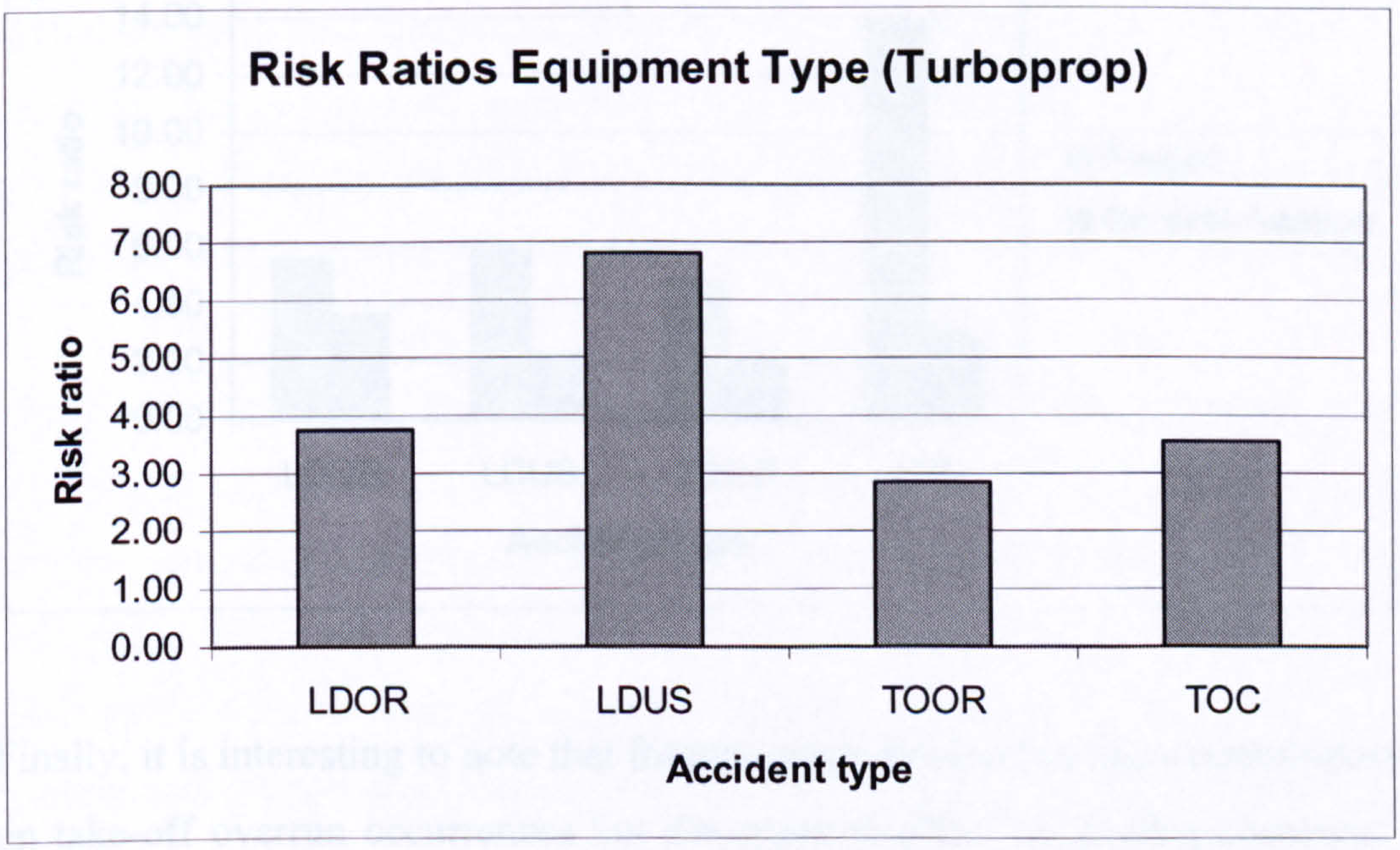


Figure 10.18 Equipment type risk ratios



In contrast, frozen precipitation and freight operations present the greatest risk to crashes after take-off vis-à-vis other accident types. Figures 10.19 and 10.20 compare the pertinent risk ratios. The increase in risk is two to four times greater for crashes after take-off two than other accident types.

Figure 10.19 Frozen precipitation risk ratios

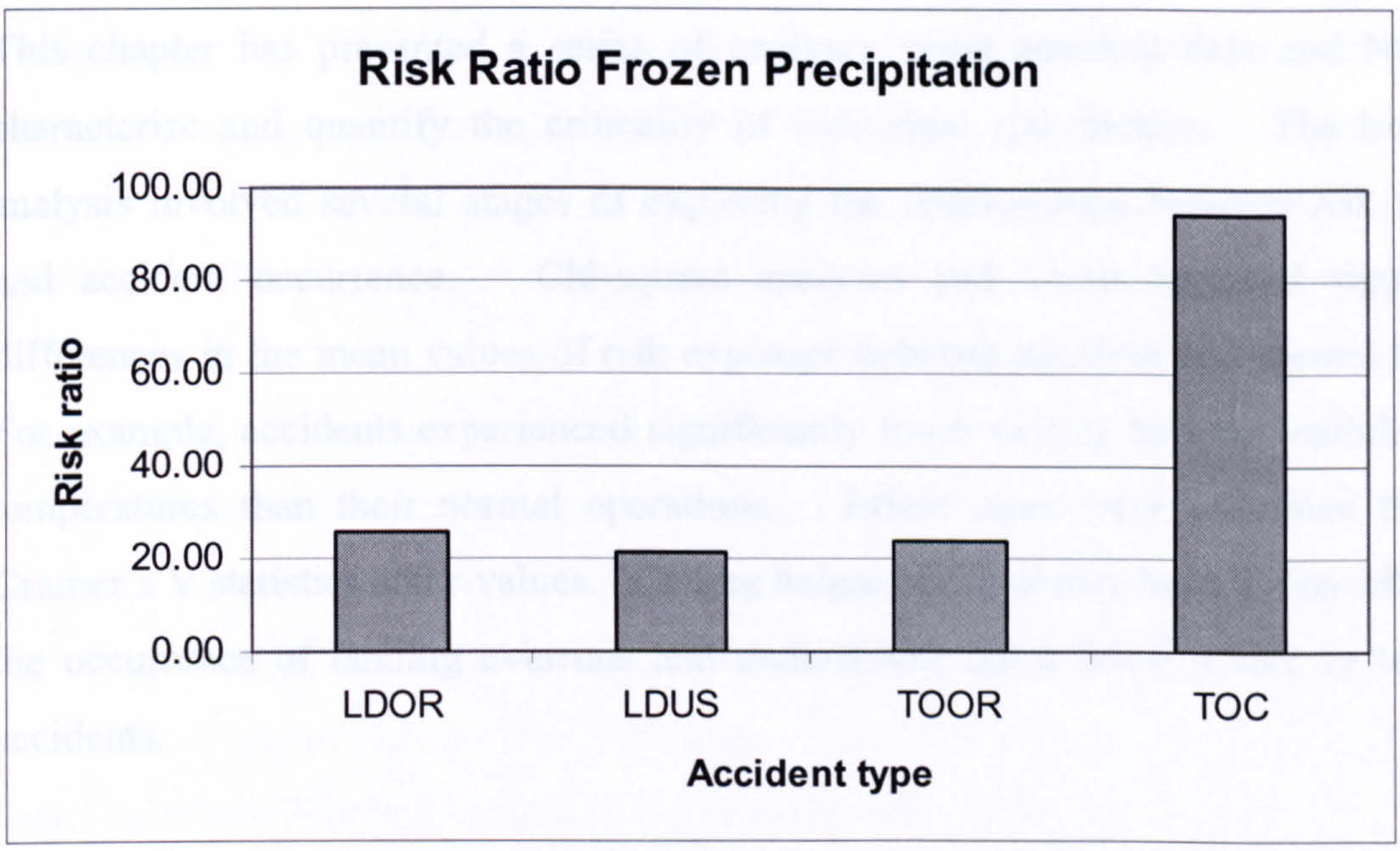
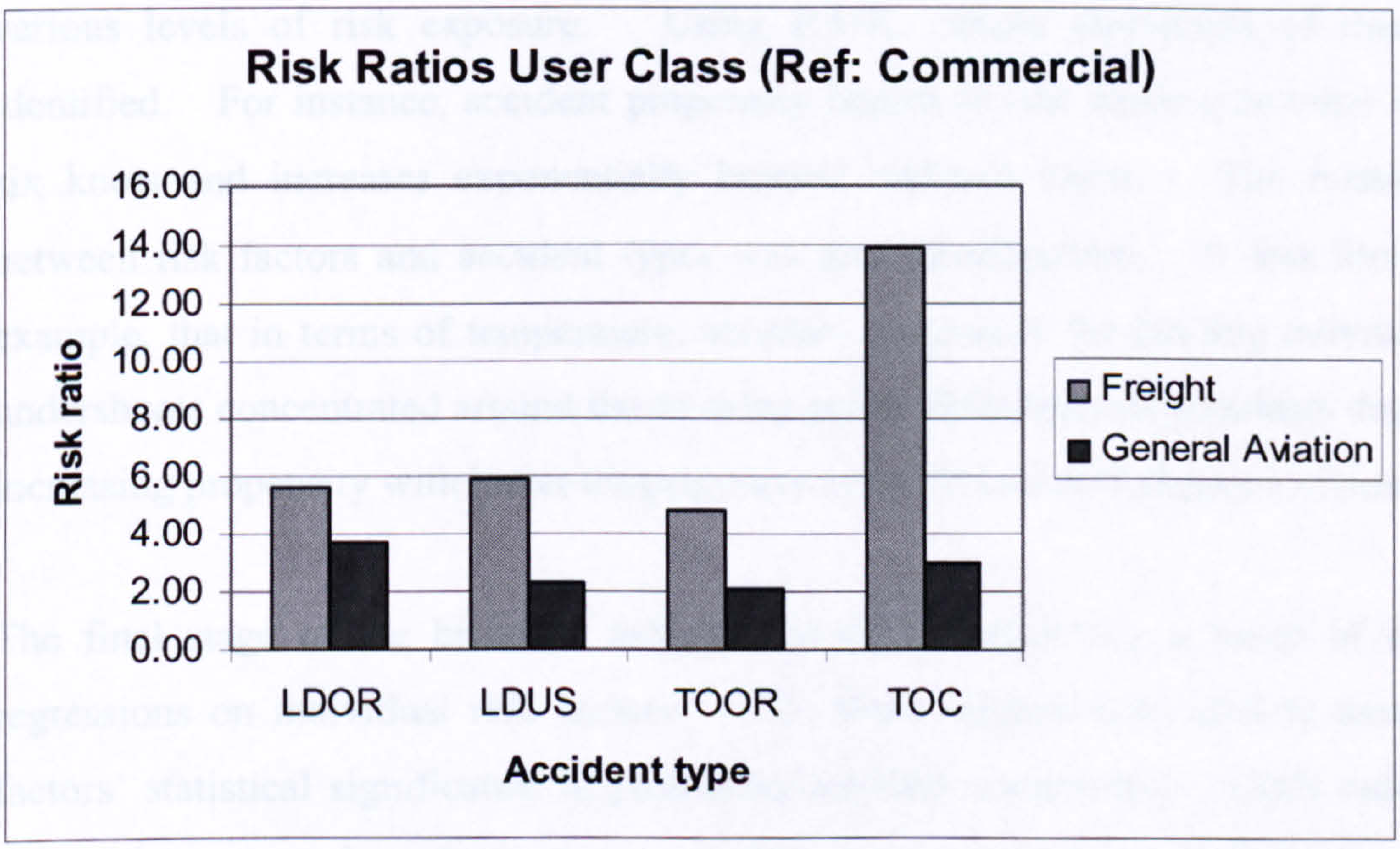


Figure 10.20 User class risk ratios



Finally, it is interesting to note that foreign origin/destination has a contributory effect on take-off overrun occurrences but the opposite effect on landing overruns. This reflects the dominance of landing overruns by local flights in the accident database and the reverse for take-off overruns.

10.7 Summary of Findings

This chapter has presented a series of analyses using accident data and NOD to characterise and quantify the criticality of individual risk factors. The bivariate analysis involved several stages of exploring the relationships between risk factors and accident occurrence. Chi-square analyses and t-tests revealed significant differences in the mean values of risk exposure between accident and normal flights. For example, accidents experienced significantly lower ceiling heights, visibility and temperatures than their normal operations. Effect sizes were examined through Cramer's V statistics and r-values. Ceiling height and visibility have a large effect on the occurrence of landing overruns and undershoots but a lesser effect on take-off accidents.

The second stage of the bivariate analysis involved calculating Relative Accident Involvement Ratios (RAIR), which measure the accident propensity of flights under various levels of risk exposure. Using RAIR, certain thresholds of risk were identified. For instance, accident propensity begins to rise when crosswind is over six knots and increases exponentially beyond eighteen knots. The relationship between risk factors and accident types was also characterised. It was found, for example, that in terms of temperature, accident propensity for landing overruns and undershoots concentrated around the freezing point while take-off accidents displayed increasing propensity with lower temperatures even beyond zero degree Celsius.

The final stage of the bivariate analysis involved conducting a series of logistic regressions on individual risk factors. The Wald statistic was used to assess the factors' statistical significance in predicting accident occurrence. Odds ratios and risk ratios were also obtained to quantify the magnitude and direction of the relationship between risk exposure and accident likelihood. Amongst the results, landing undershoots were found to be especially sensitive to aircraft and engine type. Turboprops are 6.8 times more likely than jet aircraft to be involved in a landing undershoot whereas the average for the other accident types is only 3.4. How the presence of various weather conditions heightens the risk of accident occurrence was also quantified. Rain was found to increase accident risk by a factor of 2.4 to 3.7. By contrast, accidents are up to 27 times more likely to occur in snow.

Only a handful of aviation studies have previously employed the case-control methodology (NTSB 2005). Using the most comprehensive accident and normal operations databases to date, the case-control analysis presented here represent major advances in understanding the relationship between risk exposure and accident likelihood. The three stages of the bivariate analysis together offer in-depth profiles of the risk factors and the criticality of seventeen risk factors was quantified and characterised. Nonetheless, it should be noted again that the analysis is centred on establishing associations between risk exposure and accident occurrence without implying causality. Moreover, the risk ratios presented are derived from bivariate logistic regressions of individual risk factors and as such are not controlled for the joint influences of the various factors. The implications this has on accident frequency modelling is discussed in the next chapter.

CHAPTER 11 MULTIVARIATE ANALYSIS – ACCIDENT FREQUENCY MODELLING

This chapter details the development of multivariate models for the prediction of accident occurrence. The models take into account the risk factors studied in the bivariate analysis. The choice of the statistical procedure, the form and coefficients of the four risk models and their respective goodness-of-fit and predictive performance are discussed.

11.1 Need for Multivariate Models

While the bivariate analysis of the previous chapter revealed many new insights on the properties and criticality of a range of risk factors, the bivariate logistic regression models are of little use in terms of accident prediction. Each bivariate model only considers a single risk factor, similar to Kirkland's models on runway and weight criticality (Kirkland et al. 2003a). As such, it is not surprising that the predictive power of each individual bivariate model is limited on its own. Table 11.1 shows the models' respective Nagelkereke R^2 measures[8].

Table 11.1 Bivariate Logistic Regression Nagelkereke R^2

Bivariate model	LDOR	LDUS	TOOR	TOC
Equipment Class	0.093	0.141	0.077	0.071
Equipment Type	0.027	0.056	0.014	0.022
User Class	0.033	0.023	0.014	0.054
Ceiling Height	0.059	0.073	0.009	0.029
Visibility	0.083	0.092	0.016	0.039
Fog	0.063	0.062	0.014	0.028
Dawn/Dusk	0.003	0.000	0.001	0.004
Crosswind	0.006	0.000	0.006	0.002
Rain	0.020	0.016	0.006	0.009
Electric Storm	0.006	0.006	0.001	0.000
Temperature	0.020	0.026	0.011	0.014
Icing Conditions	0.025	0.045	0.004	0.034
Frozen Precipitation	0.010	0.007	0.005	0.031

[8] Nagelkerke R^2 is a pseudo measure of model substantive significance similar to R^2 in linear regression, varying between zero and one. Nagelkerke R^2 of 0.3 suggests that the model explains roughly 30 percent of the variance in the data.

Snow	0.038	0.050	0.032	0.028
Terrain	0.000	0.002	0.000	0.003
Hub NH	0.039	0.033	0.022	0.006
For OD	0.003	0.001	0.004	0.000

Not only is it clear from the small Nagelkereke R^2 measures that bivariate models are inadequate as predictive accident frequency models, their bivariate set-up also renders them difficult to use in conjunction with each other to obtain a total risk measure for a population of flights. Since independent variables are usually associated with one another, a series of bivariate models seldom provide an adequate analysis of the model data. In order to statistically adjust for the estimated effects of all risk factors, multivariate modelling is required (Hosmer & Lemeshow 2000).

11.2 Choice of Logistic Regression

A number of numerical techniques could be used to carry out the multivariate analysis. Logistic regression was the preferred statistical procedure for this study for a number of reasons. Firstly the technique is suited to models with a dichotomous outcome (accident and non-accident) with multiple predictor variables that include a mixture of continuous and categorical parameters. Logistic regression is also especially 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 allows the sampling fractions of accident flights and that of normal flights to be different. This property is not shared by most other types of regression analysis (Nagelkerke et al. 2005).

Discriminant analysis as well as probit analysis were also considered for model building. The former was not used because it involves numerous assumptions which logistic regression is free from, including requirements of the independent variables to be normally distributed, linearly related and equal variance within each group (Tabachnick & Fidell 1996). Logistic regression was chosen over probit analysis because the latter does not give the equivalent of odds ratio so changes in probability are harder to quantify (Pampel 2000).

Consideration was equally given as to whether data-mining techniques such as artificial neural networks (ANN) should be used in lieu of conventional statistical procedures. In terms of predictive power, previous research is not conclusive as to whether neural networks or methods such as logistic regression offer better solutions (Borque et al. 2001, Freeman et al. 2002, Eftekhar et al. 2005). However, one marked disadvantage of ANN is its "black box" approach. Data-mining is focused more on predictive application than identifying the specific relationships between variables. Valid predictions could therefore be generated without providing much additional insight on the effects that predictor variables have on the model outcome. In contrast, the standardised coefficients and odds ratios of logistic regression offer far greater interpretability (Tu 1996, Duh et al. 1998, Ohno-Machado & Rowland 1999). This is an important advantage for its use in risk assessment and safety management.

11.3 Assumptions Check

As with bivariate logistic regression, it was ensured that all assumptions for the statistical technique were met. Visibility was again entered into the model as a five-level categorical variable in order to meet the logit linearity assumption as described in Chapter 10. An additional test required for multivariate logistic regression is that of multicollinearity. Collinearity among the predictor variables was assessed by conducting linear regression analyses to obtain the relevant tolerance and VIF values. None of the tolerance values were smaller than one and no VIF value was greater than ten, suggesting that collinearity among the variables is not serious (Myers 1990, Menard 2001). Kendall's tau was also used to assess potential correlations between predictor variables that are likely to be related. Three pairs of variables had Kendall's tau correlation coefficient between 0.5 and 0.65, indicating moderate correlation. They were equipment class with user class, 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.

11.4 Logistic Regression Setup & Results

Backward stepwise logistic regression was used to calibrate the risk models because of the predictive nature of the research. The selected technique is able to identify relationships missed by forward stepwise logistic regression (Hosmer & Lemeshow 2000, Menard 2001). The predictor variables were entered by blocks, each consisting of related factors, as shown in Table 11.2, such that the change in the model's substantive significance could be observed as the variables were included. Due to the more stringent data requirements of multivariate regression, cases with missing data were replaced by their respective series means. This only concerned the parameters of ceiling height (47 accidents), crosswind (14 accidents) and temperature (21 accidents). The most severely affected case was ceiling height for take-off overruns, for which 15.4% of accidents had no data and were replaced by the series mean.

Table 11.2 Blocks of variables

Block	Variables Entered
Block 1	Equipment class, Equipment type
Block 2	User class, Foreign origin/destination
Block 3	Ceiling height
Block 4	Visibility, Fog, Dawn/dusk
Block 5	Crosswind
Block 6	Rain, Electric storm
Block 7	Temperature, Icing conditions, Frozen precipitation, Snow
Block 8	Airport hub size
Block 9	Significant terrain

The results of the final models for each accident type are found in Appendix K, including the model coefficients, and adjusted risk factor odds ratios[9].

11.5 Accident Frequency Models

With the model coefficients, the probability formula for accident occurrence could be obtained.

[9] The adjusted odds ratios take into account potential confounders among risk factors included in the analysis. As such, they are closer to the risk factors' true effect on the likelihood of accident occurrence than the odds ratios obtained by bivariate analyses. However, the latter are relatively straightforward comparisons of risk exposure and are thus more directly interpretable.

For each accident model,

$$P(AccidentOccurrence) = \frac{1}{1+e^{-z}}$$

where

$$z = b_0 + b_1(Variable_1) + b_2(Variable_2) + ... + b_n(Variable_n)$$

where b_0 is the constant and b_1 to b_n are the corresponding parameter coefficients.

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 & Lemeshow 2000):

$$b*_0 = \ln(t_1 / t_0) + b_0$$

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.

t_1 is one since all relevant accidents have been sampled. 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 operations. That is 44.78 percent of the period's total itinerant operations excluding military operations. From the Terminal Area Forecasts, 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. 44.78 percent of the latter equates 630,792,133 movements. 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 could be calculated:

$$b*_0 = \ln(t_1 / t_0) + b_0 = \ln(1/3.843x10^{-4}) + b_0 = 7.864 + b_0$$

Table 11.3 shows the original and adjusted intercepts.

Table 11.3 Original & adjusted risk model equation intercepts

Model	Original intercept	Adjusted intercept
LDOR	-8.431	-16.295
LDUS	-8.911	-16.775
TOOR	-9.281	-17.145
TOC	-9.540	-17.404

With the adjusted intercept term, the z for the landing overrun probability formula is:

$$z = -16.295 + 0.486(HeavyAcft) - 1.631(L\arg eCommuterAcft) + 0.893(MediumAcft) + 1.951(SmallAcft)$$
$$+ 1.050(TurbopropAcft) + 0.934(FreightOp) + 0.835(GAOp) - 1.565(ForeignOD) - 0.014(CeilingHeight00ft)$$
$$+ 1.443(Visibility < 2SM) - 0.239(Visibility2 - 4SM) - 1.429(Visibility4 - 6SM) + 0.276(Visibility6 - 8SM)$$
$$+ 2.437(Fog) + 0.486(DawnDusk) + 0.089(Crosswindknts) + 2.164(IcingConditions) + 1.860(Snow)$$
$$+ 0.588(NonhubApt) + 0.417(SignificantTerrain)$$

The z for the landing undershoot probability formula is:

$$z = -16.775 + 0.139(HeavyAcft) - 2.017(L\arg eCommuterAcft) + 1.457(MediumAcft) + 2.932(SmallAcft)$$
$$+ 1.086(TurbopropAcft) + 0.894(FreightOp) + 0.610(GAOp) - 0.017(CeilingHeight00ft) + 1.881(Visibility < 2SM)$$
$$+ 0.446(Visibility2 - 4SM) - 0.234(Visibility4 - 6SM) + 0.321(Visibility6 - 8SM) + 1.738(Fog) + 0.043(Crosswindknts)$$
$$+ 3.775(IcingConditions) - 2.562(Frozen\Pr ecipitation) + 2.011(Snow) + 0.819(SignificantTerrain)$$

The z for the take-odd overruns probability formula is:

$$z = 17.145 + 1.157(HeavyAcft) - 0.485(L\arg eCommuterAcft) + 2.082(MediumAcft) + 3.860(SmallAcft)$$
$$+ 0.968(ForeignOD) - 0.008(CeilingHeight00ft) + 0.320(Visibility < 2SM) - 2.077(Visibility2 - 4SM)$$
$$- 0.470(Visibility4 - 6SM) - 0.544(Visibility6 - 8SM) + 1.847(Fog) + 0.093(Crosswindknts)$$
$$- 0.254(Temperature) + 2.932(Snow)$$

The z for the crashes after take-off probability formula is:

$$z = -17.404 + 0.760(HeavyAcft) - 0.776(L\arg eCommuterAcft) + 1.251(MediumAcft) + 2.842(SmallAcft)$$
$$+ 0.934(TurbopropAcft) + 2.049(FreightOp) + 1.316(GAOp) - 0.003(CeilingHeight00ft) + 1.307(Visibility < 2SM)$$
$$- 0.790(Visibility2 - 4SM) - 1.104(Visibility4 - 6SM) + 0.178(Visibility6 - 8SM) + 1.753(Fog) + 0.683(DawnDusk)$$
$$+ 0.074(Crosswindknts) + 2.246(IcingConditions) - 2.188(Frozen\Pr ecipitation) + 2.561(Snow) - 0.734(NonhubApt)$$
$$- 1.213(SignificantTerrain)$$

It can be seen that the four formula do not contain identical parameters. The stepwise regression procedure has eliminated parameters that are not significant for the particular risk models. For example, foreign origin/destination only features in the formula for landing overruns and take-off overruns. Moreover, their signs are also different. Foreign operation is negative in the landing overrun formulae and positive in the take-off overrun one. This indicates that the factor contributes to accident risk for take-off overruns but has the opposite effect on landing overruns. This is in line with the findings of the bivariate analysis. The great majority of factors, however, bear the same sign for all accident types. The size of the factors' coefficients also differs between the four formula. The coefficients for fog, for instance, vary from 1.738 (landing undershoot) to 2.437 (landing overrun). This reflects the degree to which the factor increases accident risk. Appendix L explains the exponential functional form of the models.

11.6 Assessing Goodness-of-fit

11.6.1 Nagelkerke R2

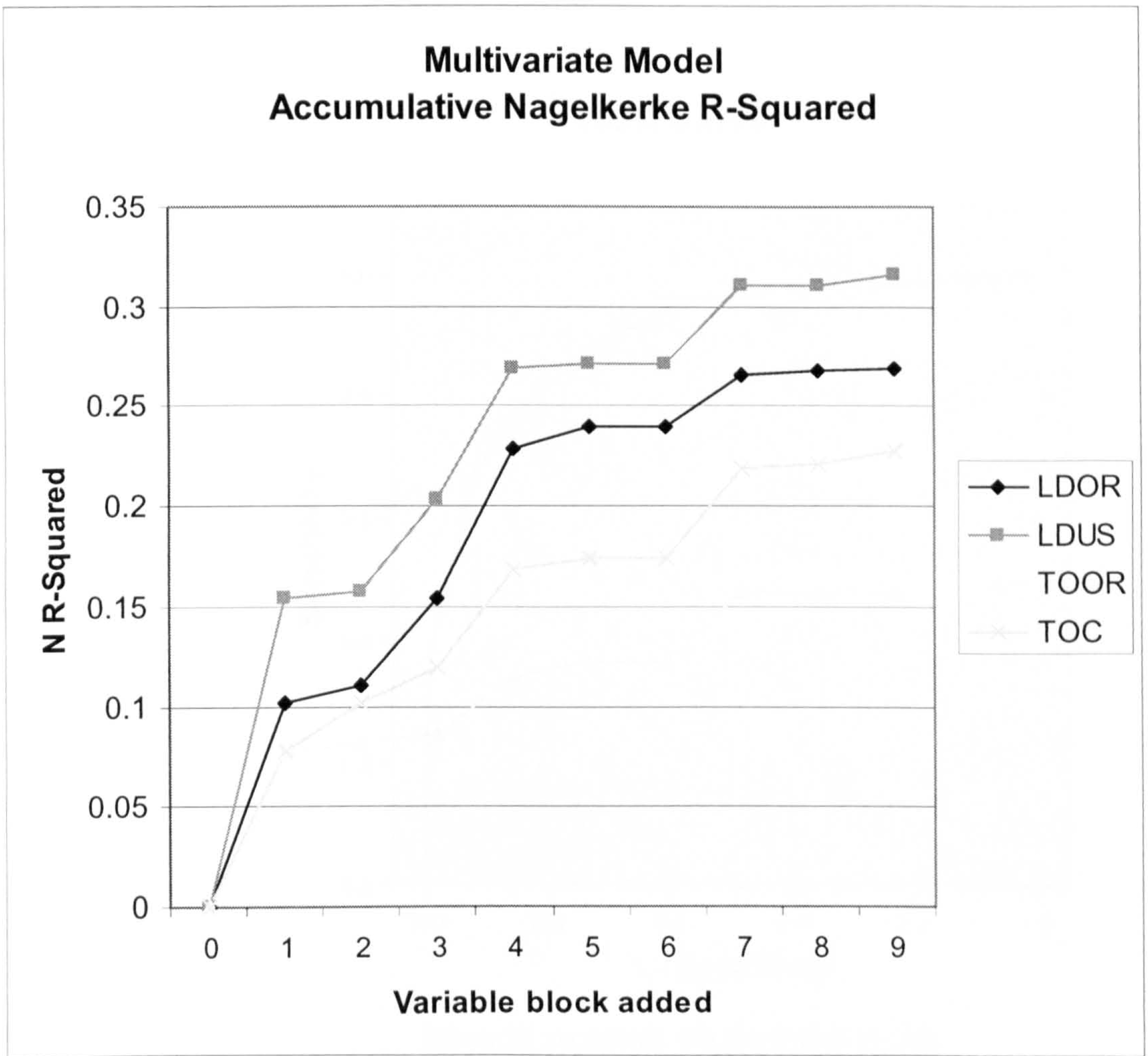
The Nagelkerke R^2 measures of the multivariate models are shown in Table 11.4.

Table 11.4 Multivariate Logistic Regression Nagelkerke R^2

Model	**Nagelkerke R^2**
Landing Overrun	0.269
Landing Undershoot	0.316
Take-off Overrun	0.157
Crash after Take-off	0.227

The multivariate models clearly perform much better in explaining the variations in the data compared to bivariate models of the previous chapter (compare with Table 11.1). The model for landing undershoot occurrence is the most potent, explaining twice as much data variation than the model for take-off overruns, the worse-performing model. Relatively low R^2 values are the norm in logistic regression (Ash & Schwartz 1999) and they should not be compared with the R^2 of linear regressions (Hosmer & Lemeshow 2000). Figure 11.1 shows how Nagelkerke R^2 increased as variables were added to the model.

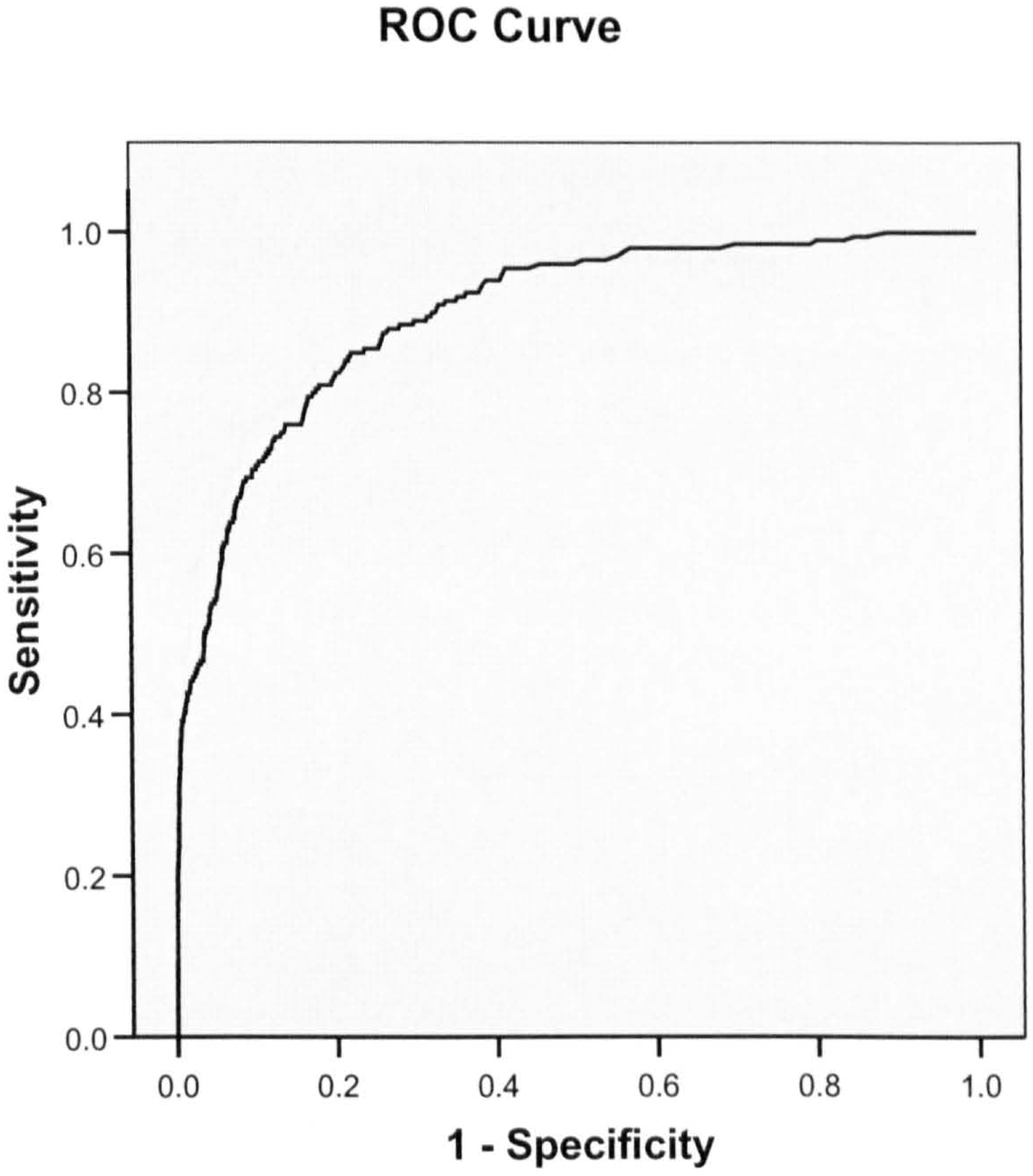
Figure 11.1 Multivariate model accumulative Nagelkerke R^2



11.6.2 Receiver operating characteristics curve

In order to assess how successful the models are in classifying flights correctly as "accident" or "normal" and to find the appropriate cut-off points for the logistic regression models, Receiver Operating Characteristics (ROC) Curves were used. The cut-off point is the critical probability above which the model will class an event as an accident. The ROC curve plots all potential cut-off points according to their respective True Positive Rates (percentage of accidents correctly classed as accidents) and False Positive Rates (percentage of normal flights incorrectly classed as accidents). The best cut-off point would have a optimally high TPR and low FPR. Figures 11.2 to 11.5 display the four models' ROC curves. TPR is labelled Sensitivity and FPR 1-Specificity.

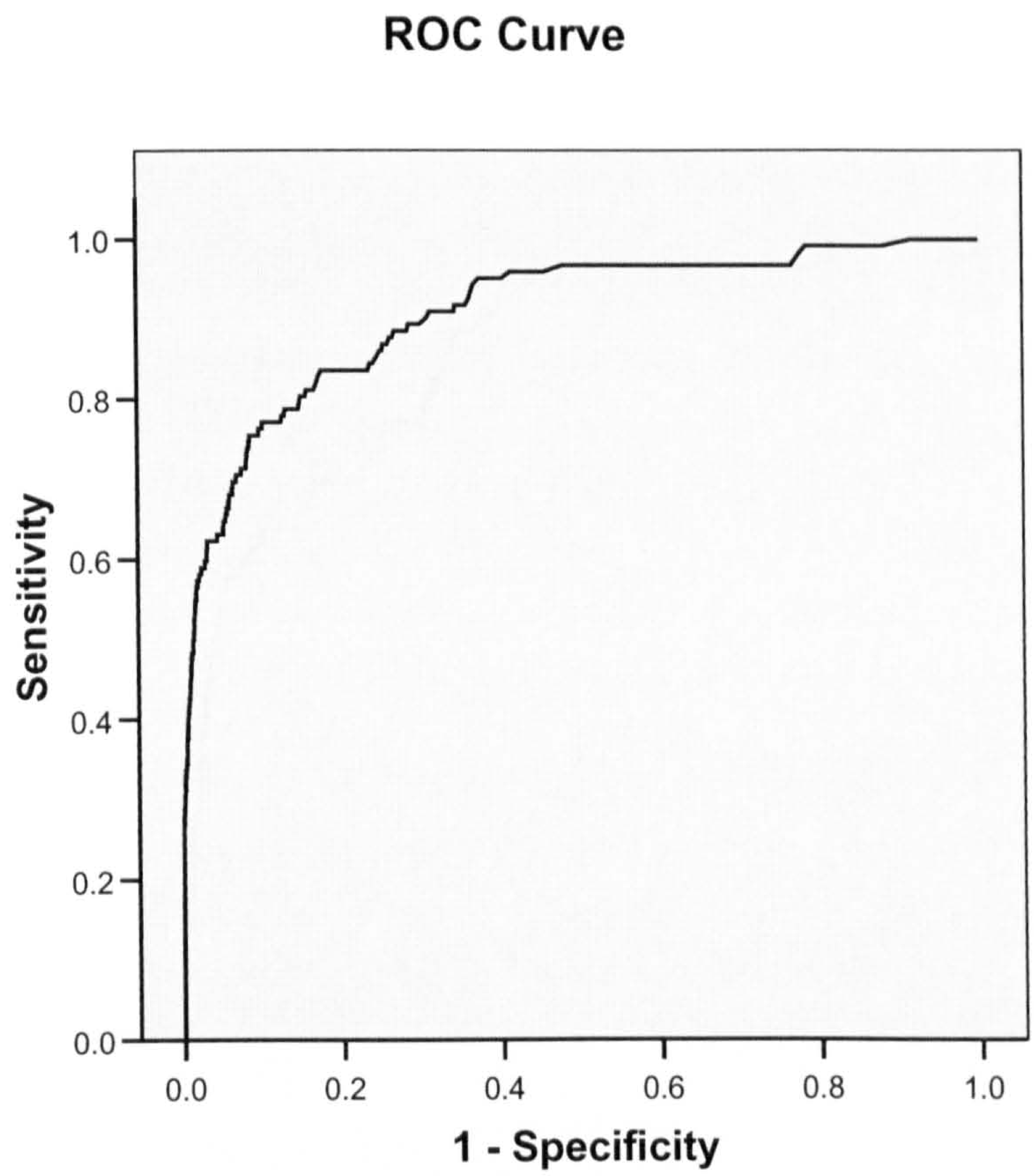
Figure 11.2 Landing overrun model ROC curve



Diagonal segments are produced by ties.

The ROC curve graphically presents the trade-off between TPR and FPR for all possible cut-off points, the best of which is likely to be the point closest to the top-left corner of the graph. The trade-off between TPR and FPR can be seen in Figure 11.2. As the TPR (sensitivity) rises, the FPR (1-specificity) also increases. The larger the area under the curve, the better the model is at identifying accidents from normal flights. Figures 11.3 to 11.5 are interpreted in the same way. It is clear that the landing accident models produced better results than the take-off models.

Figure 11.3 Landing undershoot model ROC curve



Diagonal segments are produced by ties.

Figure 11.4 Take-off overrun model ROC curve

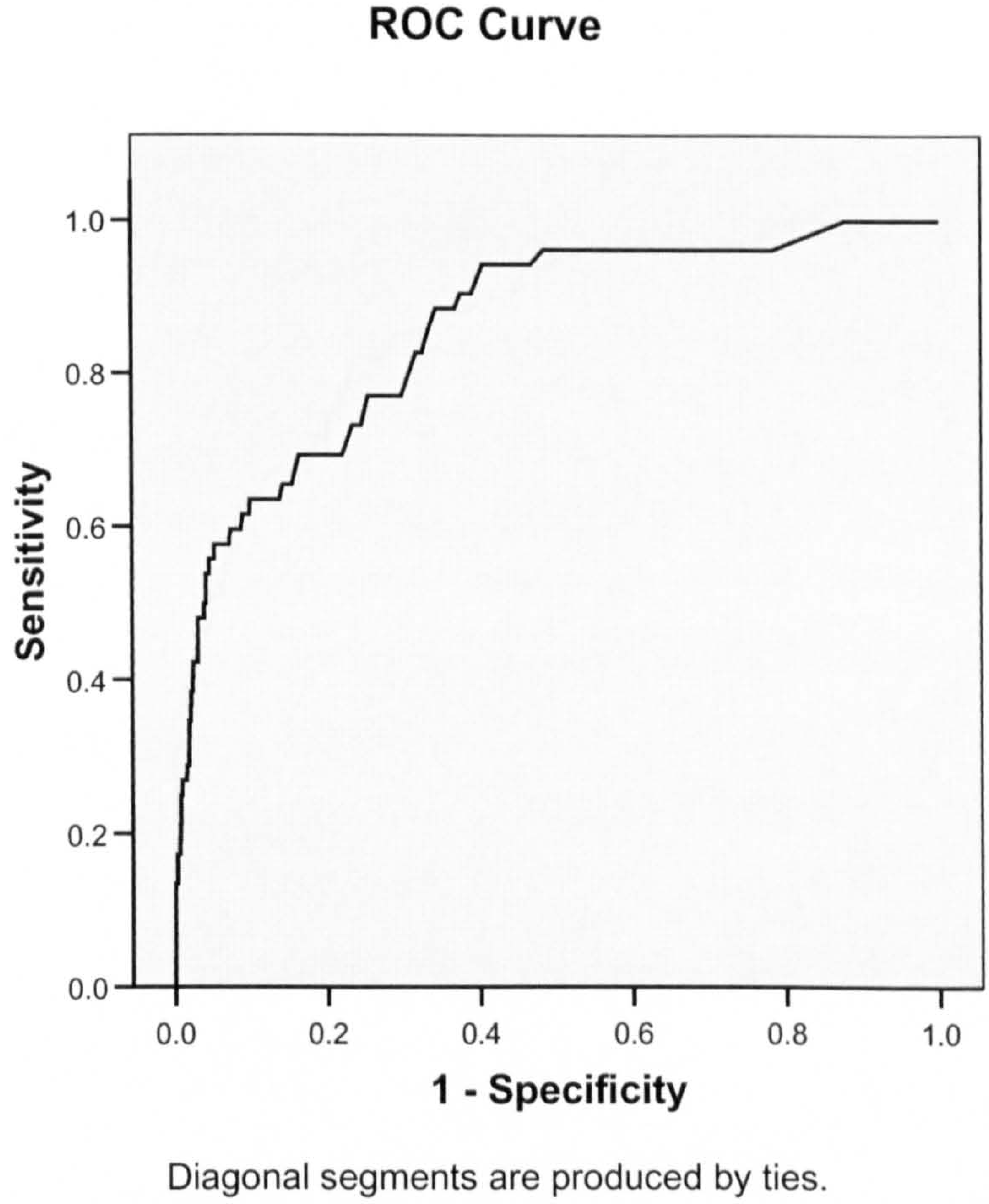
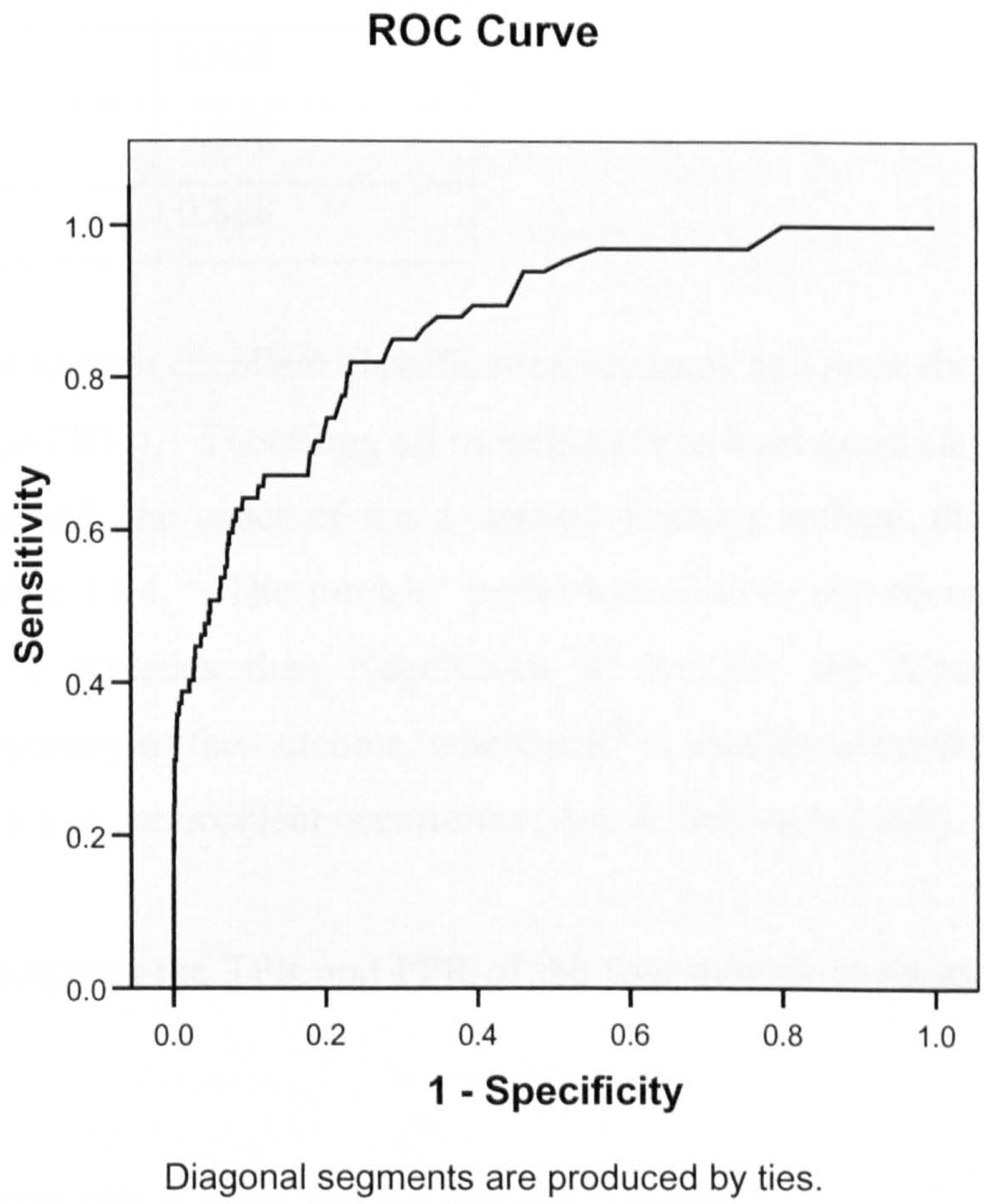


Figure 11.5 Crash after take-off model ROC curve



11.6.3 c statistic

The area under the ROC curve is quantified by the c statistic, which measures the discriminative power of the accident frequency models. The statistic varies between 0.5 (indicating that the model's predictions are no better than chance) and 1 (indicating a perfect classification model with 100 percent TPR and 0 percent FPR). Table 11.5 shows the c statistics for the four models.

Table 11.5 Model c statistics

Model	c statistic
Landing Overrun	0.897
Landing Undershoot	0.908
Take-off Overrun	0.858
Crash after Take-off	0.868

c statistics of over 0.9 suggest excellent classification accuracy and ones above 0.8 are considered good (Tape 2007). Therefore, all models have at least good classification accuracy. As expected, the order of the c statistic findings reflects those of the Nagelkerke R^2 in Table 11.4. The models' performance seem significantly better when measured by c statistics than Nagelkerke R^2 because the former is not dependent on the frequency of the outcome, whereas R^2 is smaller when the outcome is infrequent, which is true for accident occurrence (Ash & Schwartz 1999).

Table 11.6 further compares the TPR and FPR of the four models at selected cut-off points.

Table 11.6 True positive rate & false positive rate comparison

Model	Cut-off point	TPR	FPR
Landing Overrun	0.00000052127	0.849	0.221
Landing Undershoot	0.00000024800	0.844	0.237
Take-off Overrun	0.00000010955	0.846	0.330
Crash after Take-off	0.00000009420	0.851	0.290

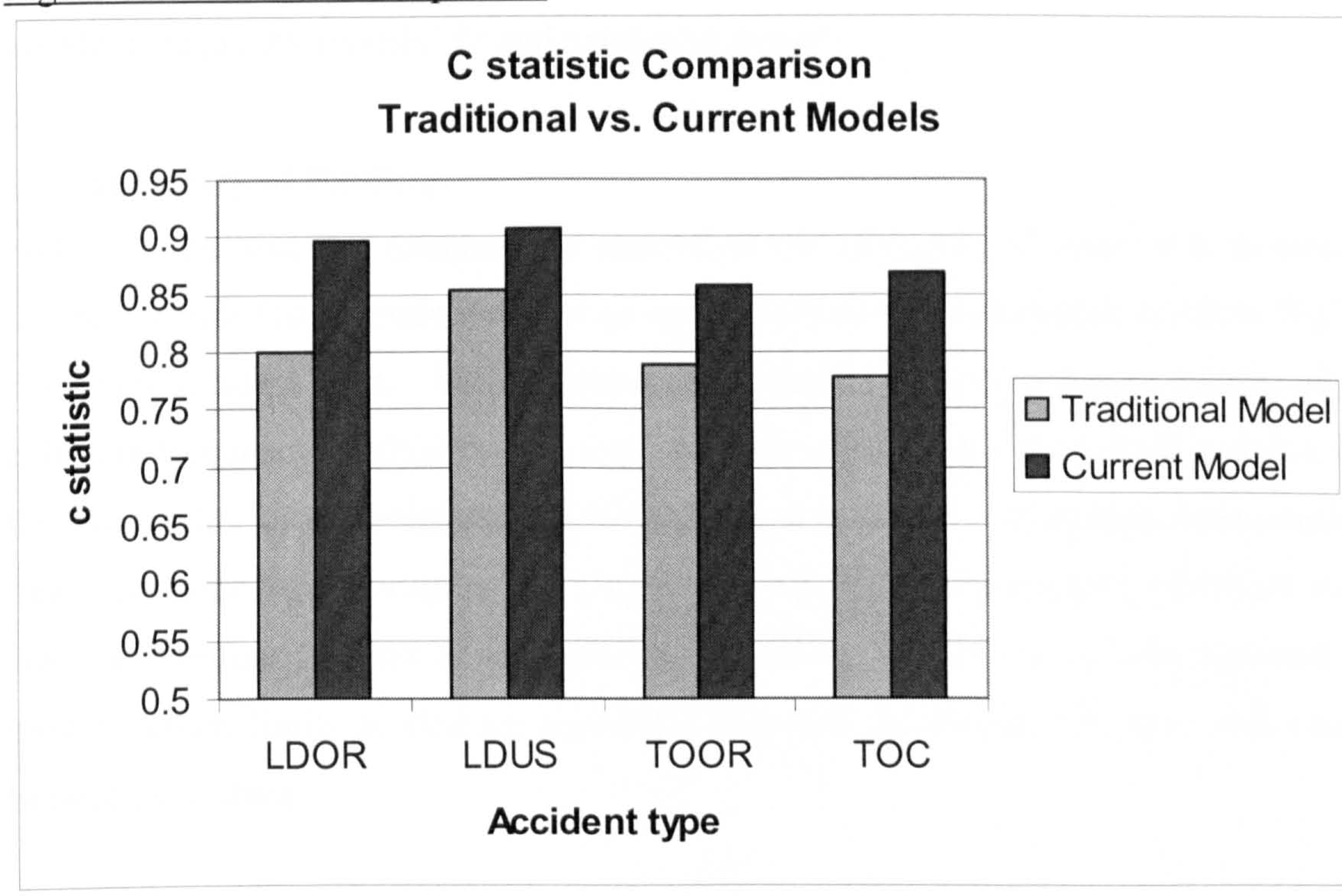
For the landing overrun model, then, a cut-off point of 0.00000052127 yields 84.9 percent of accidents being correctly classed as such and 22.1 percent of normal flights falsely classified as accidents. The latter could in fact be interpreted as high risk but incident-free operations. Depending on the objective of the risk assessment exercise, a relatively conservative or risk-tolerant cut-off point could be chosen.

11.7 Comparison with Traditional Risk Assessment Models

The improvements achieved by this research in terms of the risk models' goodness-of-fit and predictive power ought to be examined. As discussed in Chapter 5, most traditional risk assessments for airport safety areas rely on simple crash rates according to general groupings of aircraft type when considering accident frequency. It is evident from Figure 11.1 that the final models' substantive significance as measured by Nagelkerke R^2 are considerable improvements upon models based only on Block 1 parameters (aircraft size and type). The results also compare favourably with Kirkland's landing overrun model based on excess runway distance, which only explained 11 percent of risk determinants (Kirkland 2001a).

Figure 11.6 shows the difference in terms of c statistics between traditional models and the current ones. Gains in goodness-of-fit and predictive power were observed for models of all accident types.

Figure 11.6 C statistic comparison



Finally Table 11.7 contrasts the models' predictive accuracy by comparing their respective false positive rates at cut-off points with similar true positive rates.

Table 11.7 False positive rate comparison

Model	Traditional Model TPR	Current Model TPR	Traditional Mode FPR	Current Model FPR
Landing Overrun	0.844	0.849	0.395	0.221
Landing Undershoot	0.852	0.844	0.299	0.237
Take-off Overrun	0.846	0.846	0.405	0.330
Crash after Take-off	0.821	0.851	0.405	0.290

At similar TPRs, the FPR of the current models are significantly lower than that of the traditional models for all accident types. For example, at a true positive rate of 84.6 percent, the model of take-off overruns using the conventional predictor variables incorrectly classed 40.5 percent of normal operations as accidents. In contrast, the equivalent for the model developed in the present study is 33.0 percent. The models' increased ability in discriminating between safe and accident flights are important steps towards better airport risk assessment. From the various measures, then, it is clear that important gains have been made by the current research in improving the accident frequency models' fit and predictive power.

11.8 Summary of Findings

Although the bivariate analysis has quantified the criticality of many risk factors, a series of single factor models cannot be used to effectively distinguish accident flights from non-accident ones. Multivariate logistic regression was therefore conducted to calibrate frequency models for the four accident types. This was made possible by the availability of multidimensional normal operations data. This represents another major breakthrough in airport risk assessment because where normal operations data was used before (Enders et al. 1996, Kirkland 2001a), it was one-dimensional in nature, which limits modelling capability and fails to account for joint influences between variables.

Multivariate modelling using the range of risk factors available vastly improved predictive power compared to previous methodologies, including Kirkland et al. (2003a), and traditional methods that only considered aircraft and engine types. Nagelkerke R^2 and the c statistic were used to assess the goodness-of-fit and predictive ability of the models. On average, the models developed in this study explained 14 percentage points more data variation than conventional models. Traditional techniques that only included aircraft and engine type had an average c statistic of 0.81 across the accident types, whereas the new models averaged 0.88. Significant improvements in model sensitivity and specificity were also observed.

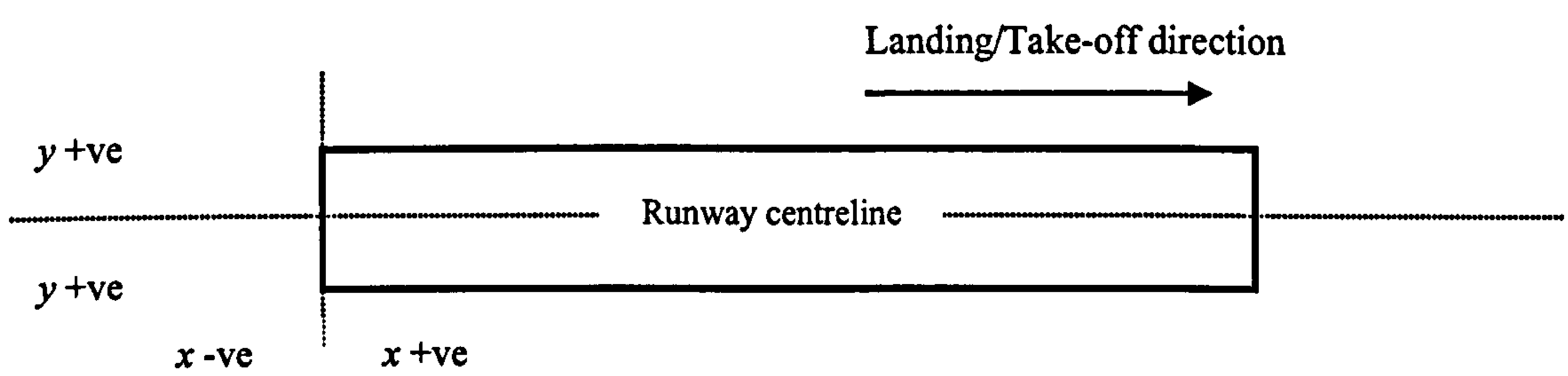
CHAPTER 12 ACCIDENT LOCATION ANALYSIS

The core contribution of this thesis concerns the first part of the three-step airport risk assessment, i.e. the frequency modelling of ASA-related aircraft accidents. Nonetheless, advances were also made in the second component of risk assessment regarding accident locations. With the comprehensive accident database developed, a more complete understanding of accident locations could be obtained. This chapter describes the relevant analyses and findings. The purpose of the analysis is to support the demonstration application of the accident frequency models in the next chapter.

12.1 Location Coordinate System

The accidents' crash locations were recorded using a coordinate system as shown in Figure 12.1.

Figure 12.1 Location coordinate system



The origin of the coordinate system is where the runway centreline intersects the runway threshold for landing accidents and the start-of-roll threshold for take-off accidents. Positive x is the distance from the threshold towards the end of the runway and negative x is the distance before the runway threshold. y measures the distance from the runway centreline. The measurement system is similar to those used by most risk assessment studies in the area, such as the British NATS and FAA's crash location studies (Cowell et al. 1997, David 1990).

A number of Dutch studies such as (Ale & Piers 2000a) referenced accident locations to flight paths rather than the extended centreline. Although intuitively more accurate, the lack of relevant flight path information and hence lower statistical confidence as well as the tendency of landing aircraft to align with the extended runway centreline at considerable distance from the threshold limit the benefits of referencing accident locations to flight paths (Davies & Quinn 2004b).

12.2 Point of First Impact

Another innovation of the current research involves recording the point of first impact (POFI) for landing undershoots and crashes after take-off in addition to their final wreckage sites. For these classes of accidents, there is often a significant distance between the location where an ASA was first challenged, e.g. obstacle hit before the runway threshold, and the final wreckage site. If only the latter was considered, the dimensional needs of ASAs would be substantially underestimated. When considering the longitudinal ASA dimensional needs for landing undershoots and crashes after take-off, then, the concept of the 'critical x distance' was used. The critical x distance is the larger of the x distances as measured from the final wreckage site and the POFI. This allows a better assessment of true ASA infringements and needs. When only POFI or final wreckage location was known, it was treated as the critical x distance. The equivalent critical y distances were computed for landing undershoots and crashes after take-off correspondingly.

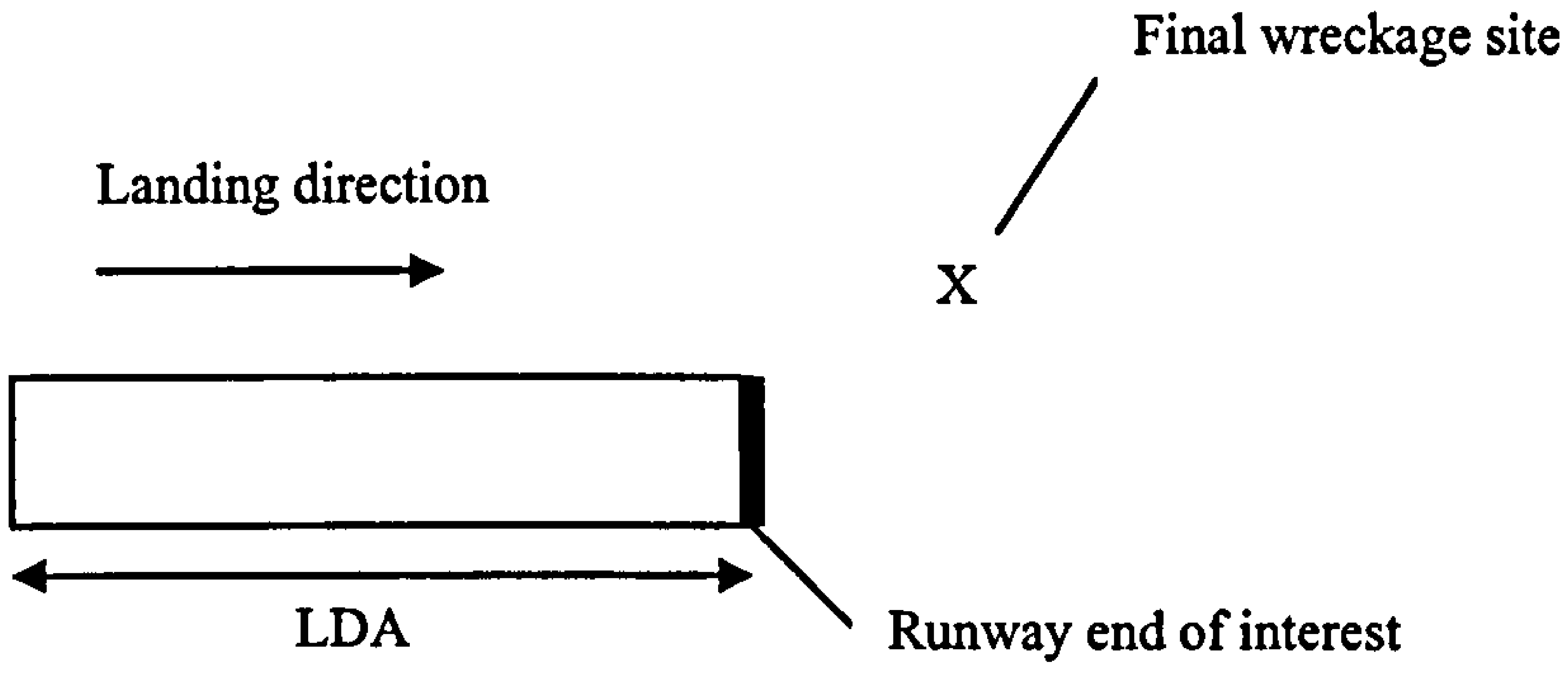
12.3 Crash Scenarios

The current analysis considered a total of six possible scenarios under which the longitudinal length of ASAs (x distance) could be challenged. These are explained in turn.

12.3.1 Scenario 1 – landing overrun

Figure 12.2 depicts accident location scenario 1. After a landing overrun, the aircraft's final wreckage site lies beyond the runway end.

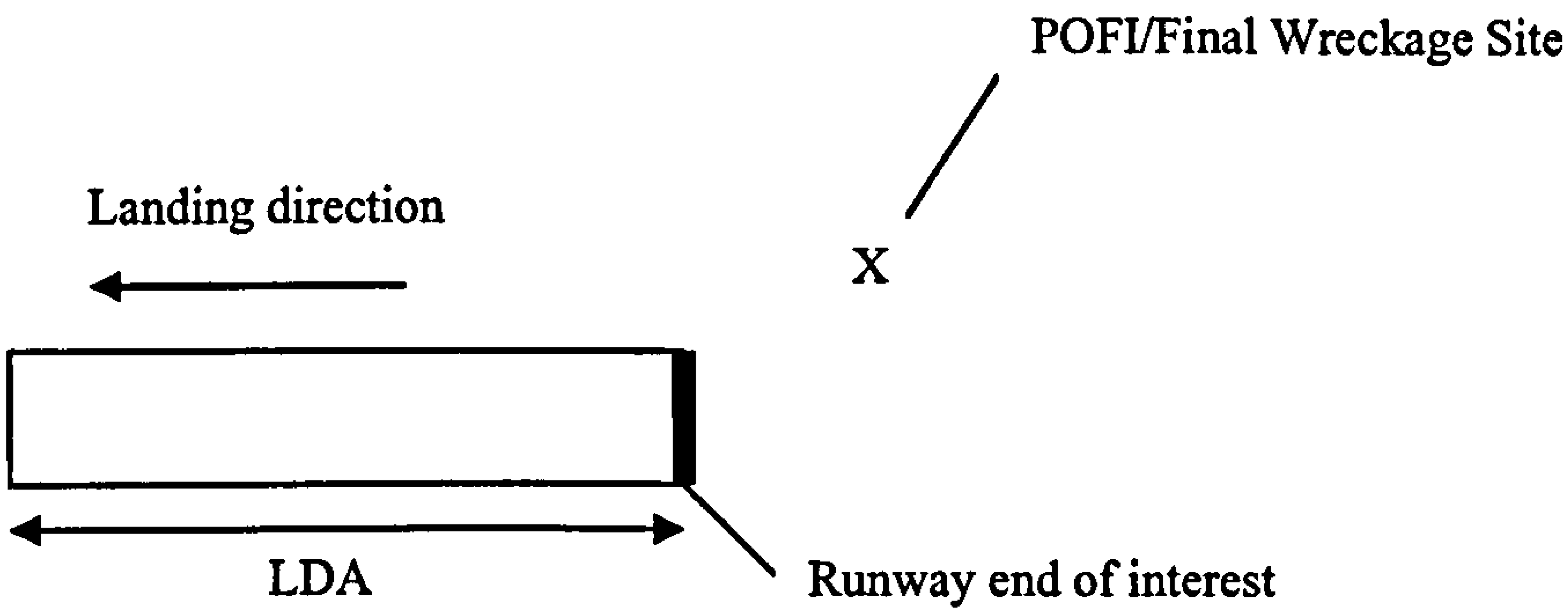
Figure 12.2 Scenario 1



12.3.2 Scenario 2 – landing undershoot

Figure 12.3 depicts accident location scenario 2. Before reaching the runway threshold, the aircraft undershoots and challenged an ASA. The x distances to the runway threshold from the POFI and final wreckage site were both measured. Critical x is the one with the largest negative x figure.

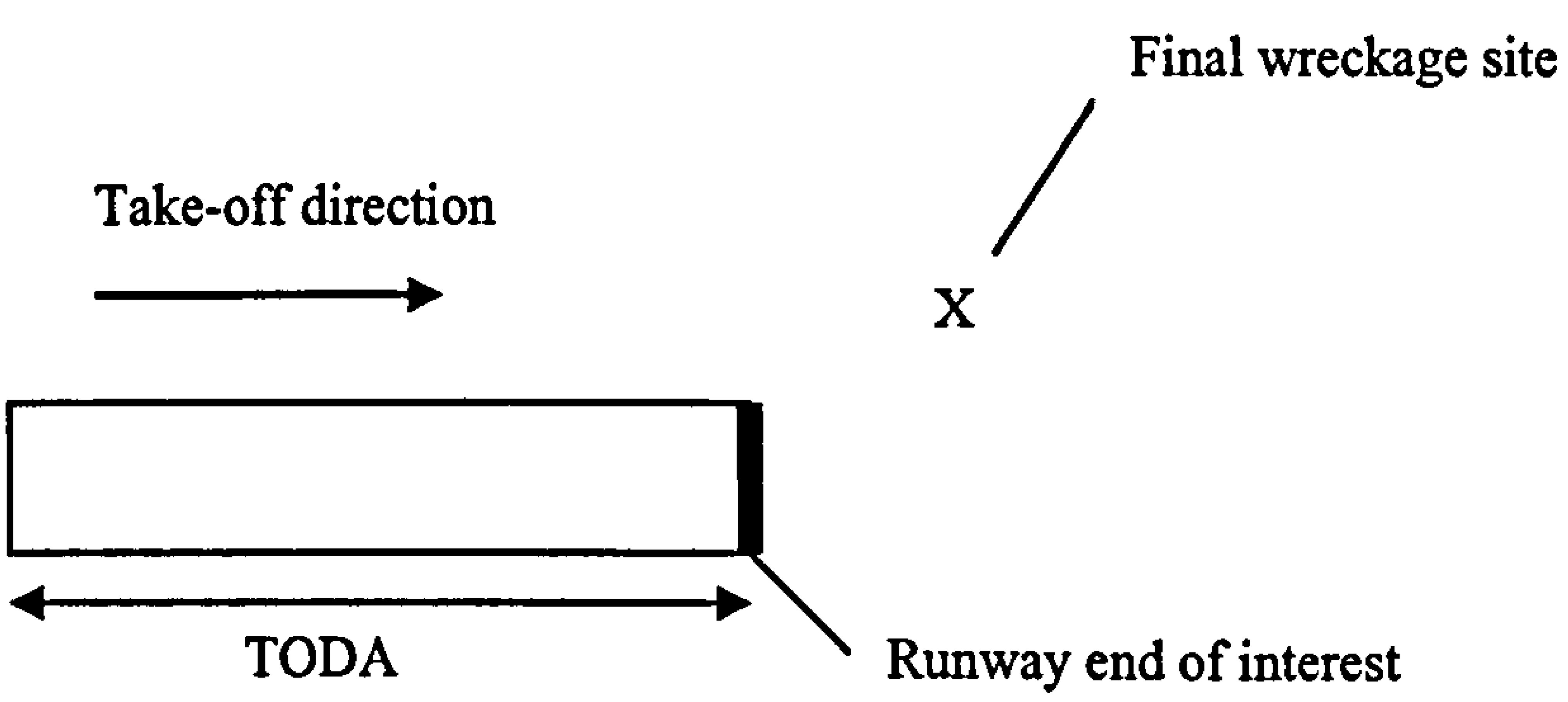
Figure 12.3 Scenario 2



12.3.3 Scenario 3 – take-off overrun

Figure 12.4 depicts accident location scenario 3. After a take-off overrun, the aircraft's final wreckage site lies beyond the runway end.

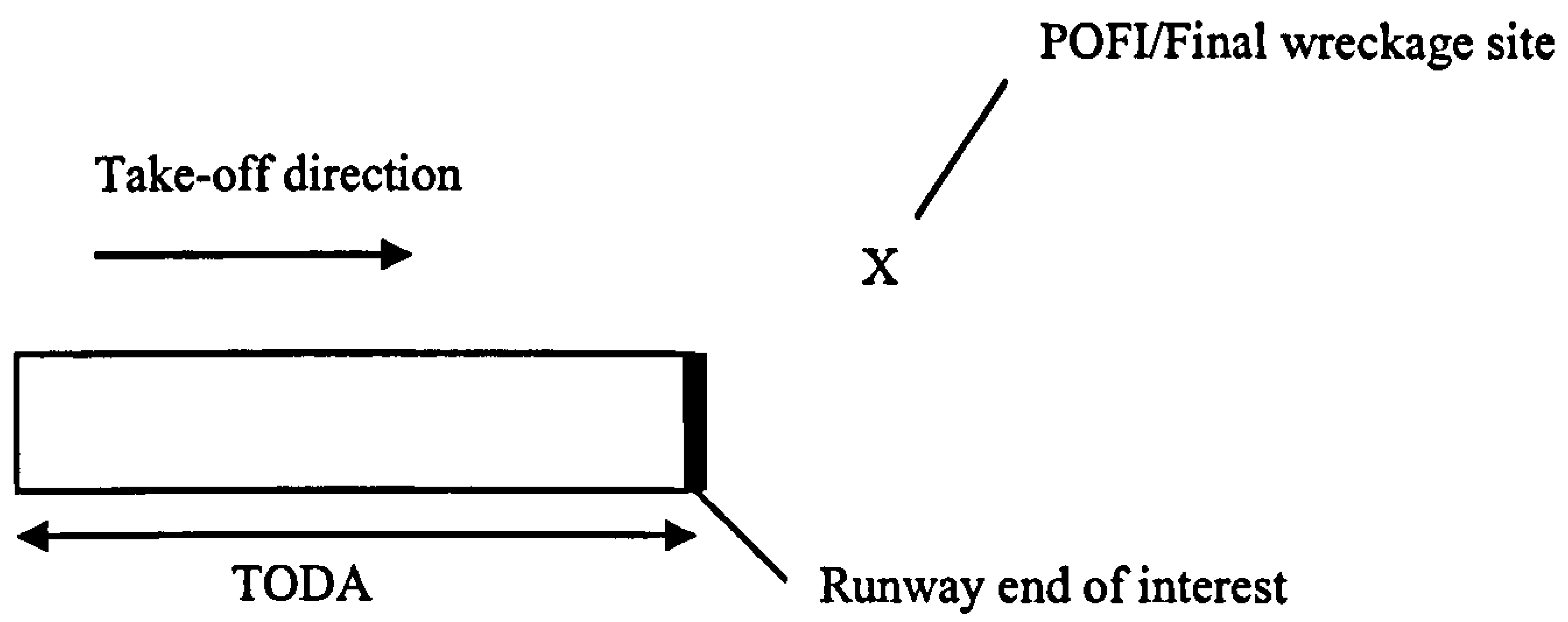
Figure 12.4 Scenario 3



12.3.4 Scenario 4 – crash after take-off

Figure 12.5 depicts accident location scenario 4. The x distances from the start-of-roll threshold to the POFI and final wreckage site were both measured. Critical x is the one with the largest x figure.

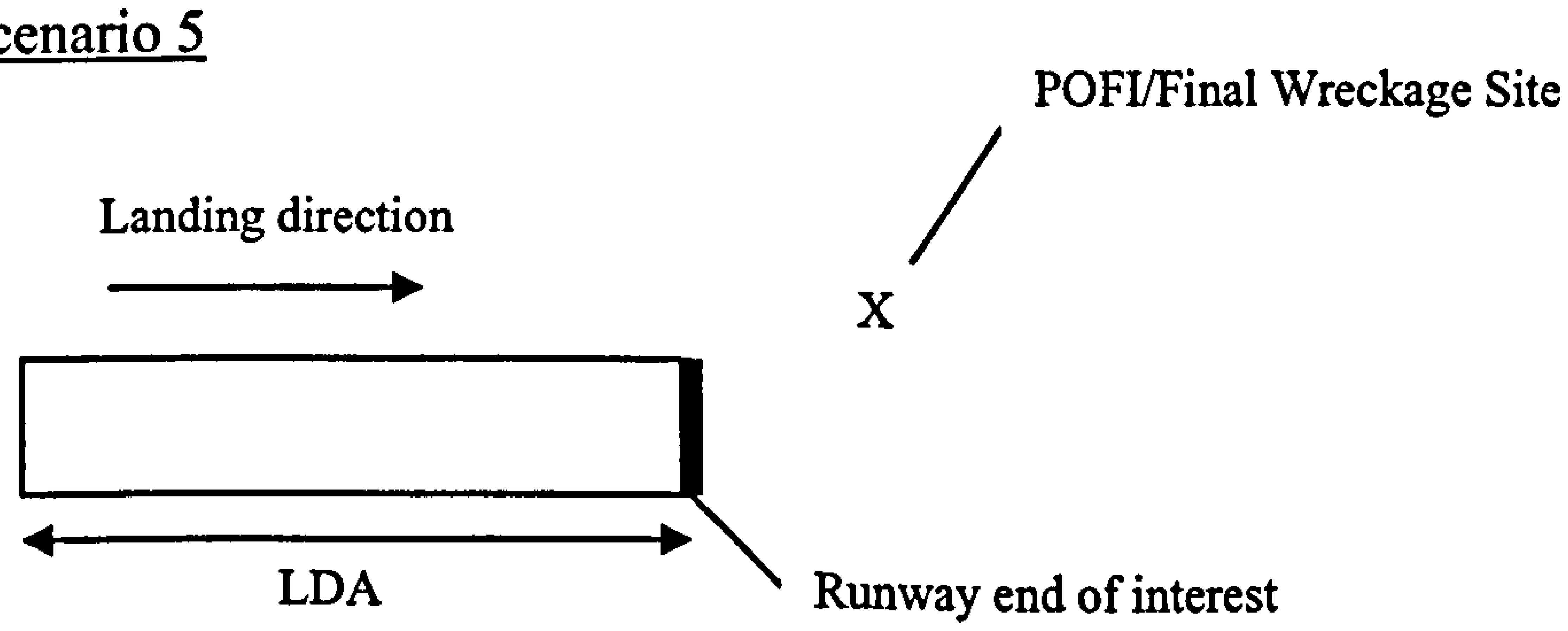
Figure 12.5 Scenario 4



12.3.5 Scenario 5 – landing undershoot (beyond runway end)

There are some cases of landing undershoots with POFIs and/or final wreckage sites beyond the runway threshold. These are classed as landing undershoots because their POFIs are off-runway. Scenario 5 considers such cases with POFIs or final wreckage locations beyond the runway end (Figure 12.6). This scenario also includes cases which, after a POFI before the runway threshold, the aircraft continued to a final wreckage site beyond the runway end.

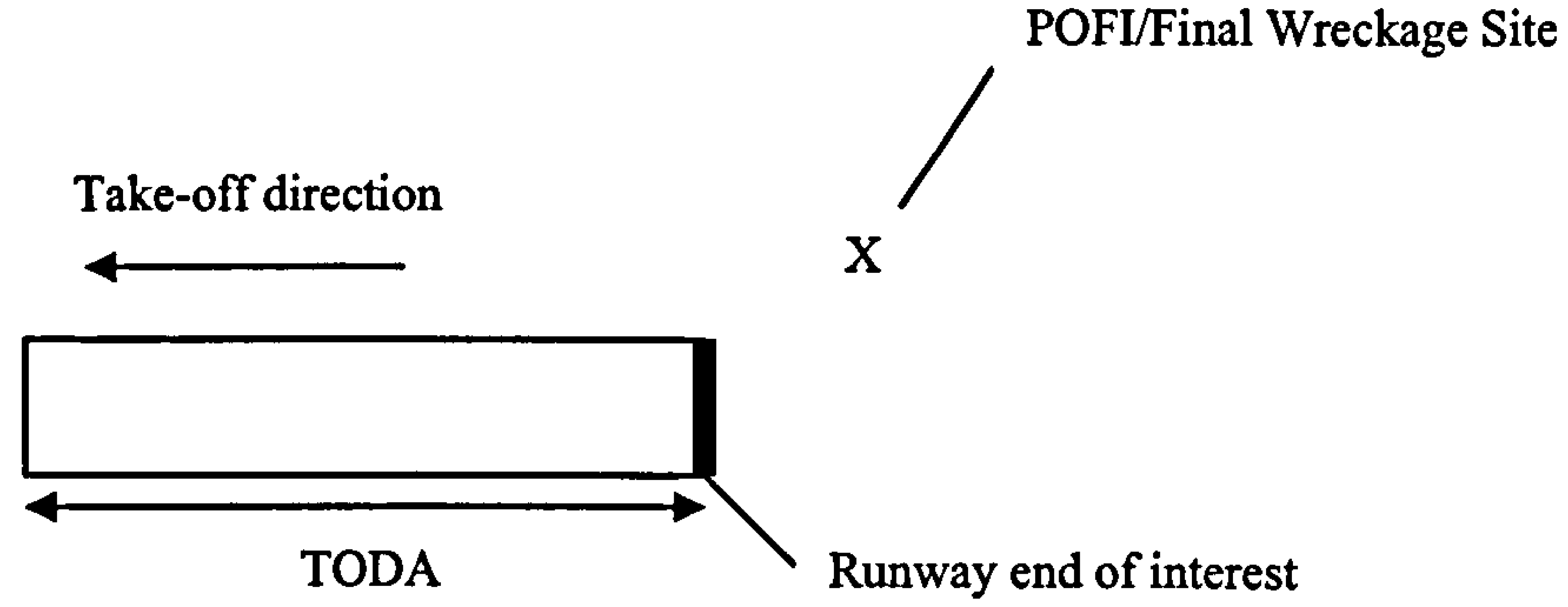
Figure 12.6 Scenario 5



12.3.6 Scenario 6 – crash after take-off (before start-of-roll threshold)

Depicted in Figure 12.7, there are potentially cases of crashes after take-off that have POFIs and/or final wreckage locations with negative x distances. This is likely for flights that have made a sharp turn after lift-off towards the start-of-roll runway threshold before crashing.

Figure 12.7 Scenario 6



12.4 Complementary Cumulative Probability Distributions

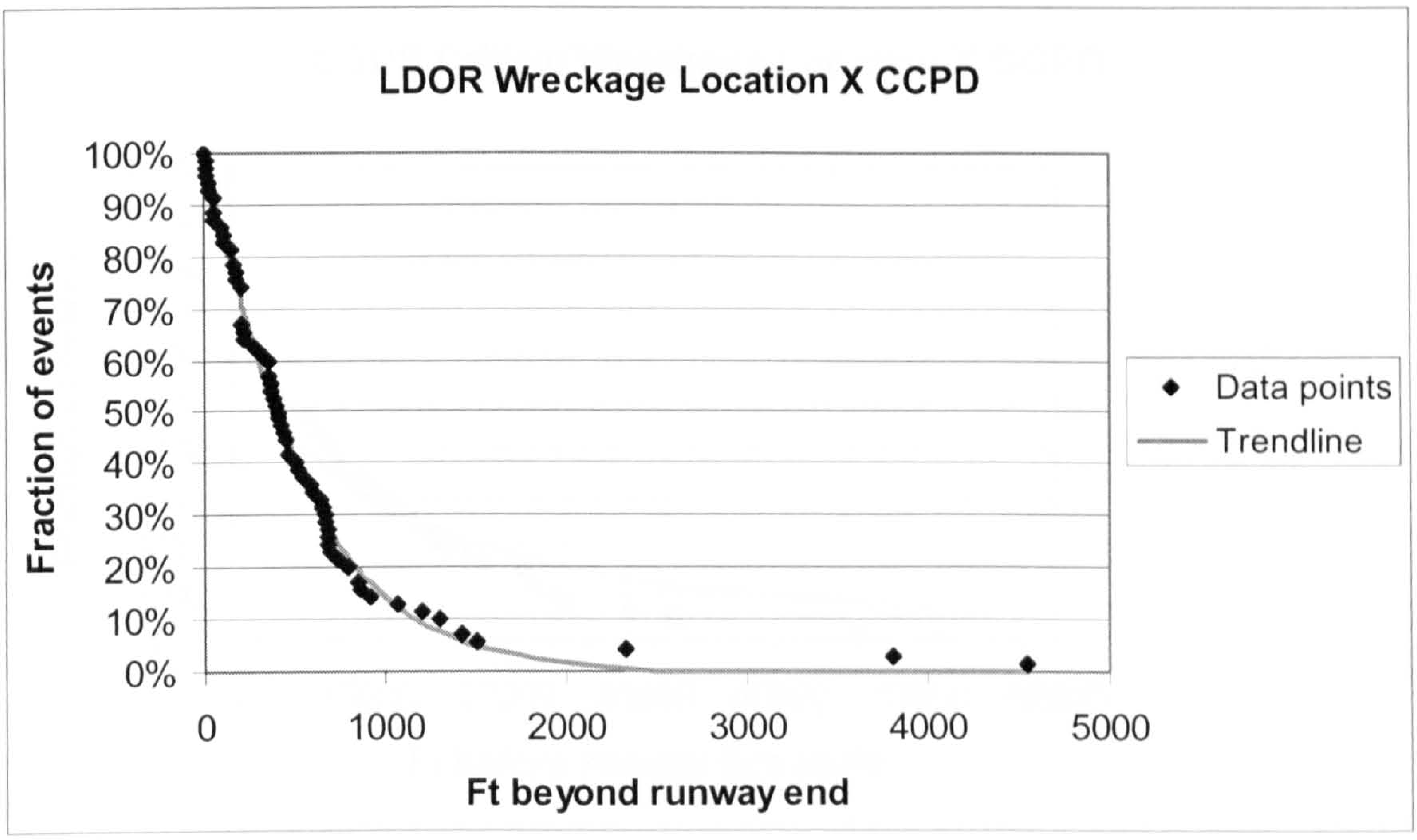
For each of the accident scenarios described above, complementary cumulative probability distributions (CCPD) of the relevant x and y distances were plotted[10]. Eddowes et al. (2001) also used CCPDs to analyse overrun and undershoot distances. These CCPDs are essential to the application of the accident frequency models as demonstrated in the next chapter. Details of how each CCPD was obtained are described in the following sections.

12.4.1 CCPD scenario 1 x distance

For scenario 1, the cases that challenge longitudinal ASAs are landing overruns with final wreckage sites beyond the runway end. Out of 133 landing overruns with known wreckage locations, 71 cases involved x locations beyond the runway end. The x distances from the runway end to the final wreckage sites were measured. One case that involved an x distance of over 19000ft was considered as an outlier and was removed. The remaining 70 cases were used to plot the CCPD, as shown in Figure 12.8.

[10] It is expected that the amount of lateral deviation would bear some relationship to the x distance involved. However, this has not been explored in the current thesis because location modelling is beyond the scope of this chapter, which aims to provide a simple analysis of accident locations for the purpose of demonstrating the application of the frequency models developed.

Figure 12.8 Scenario 1 x distance CCPD

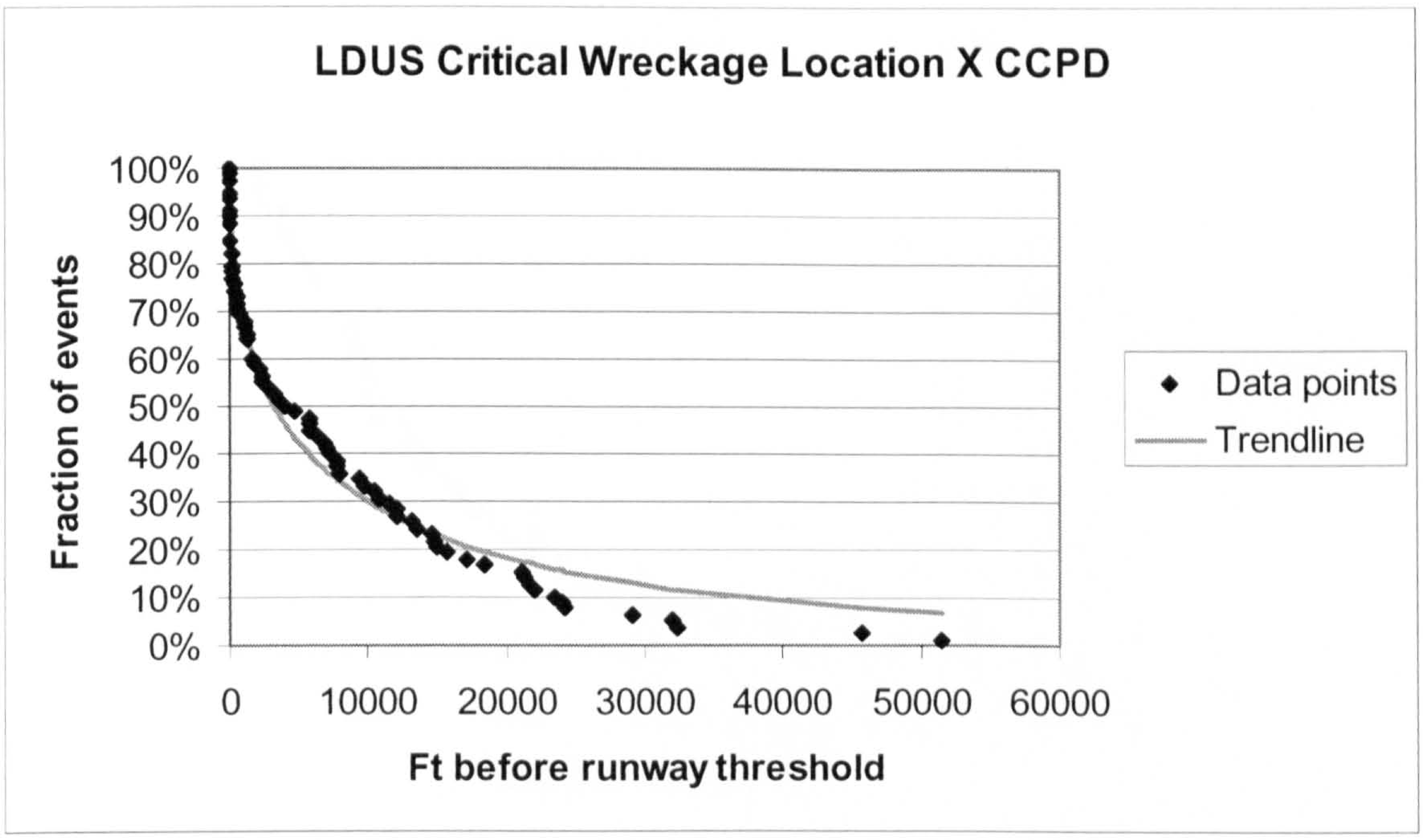


The CCPD shows that 80 percent of cases involve overrun distances of more than 150ft beyond the runway end. The plot also shows that 40 percent of cases involve overrun distances of 500ft or more beyond the runway end.

12.4.2 CCPD scenario 2 x distance

For scenario 2, the cases that challenge longitudinal ASAs are landing undershoots with POFIs and/or final wreckage sites before the runway threshold. Out of 105 landing undershoots with known wreckage information, 78 cases involved x locations beyond the runway end. The critical x distances from the POFI/final wreckage site to the runway threshold were measured. All 78 cases were used to plot the CCPD, as shown in Figure 12.9.

Figure 12.9 Scenario 2 x distance CCPD

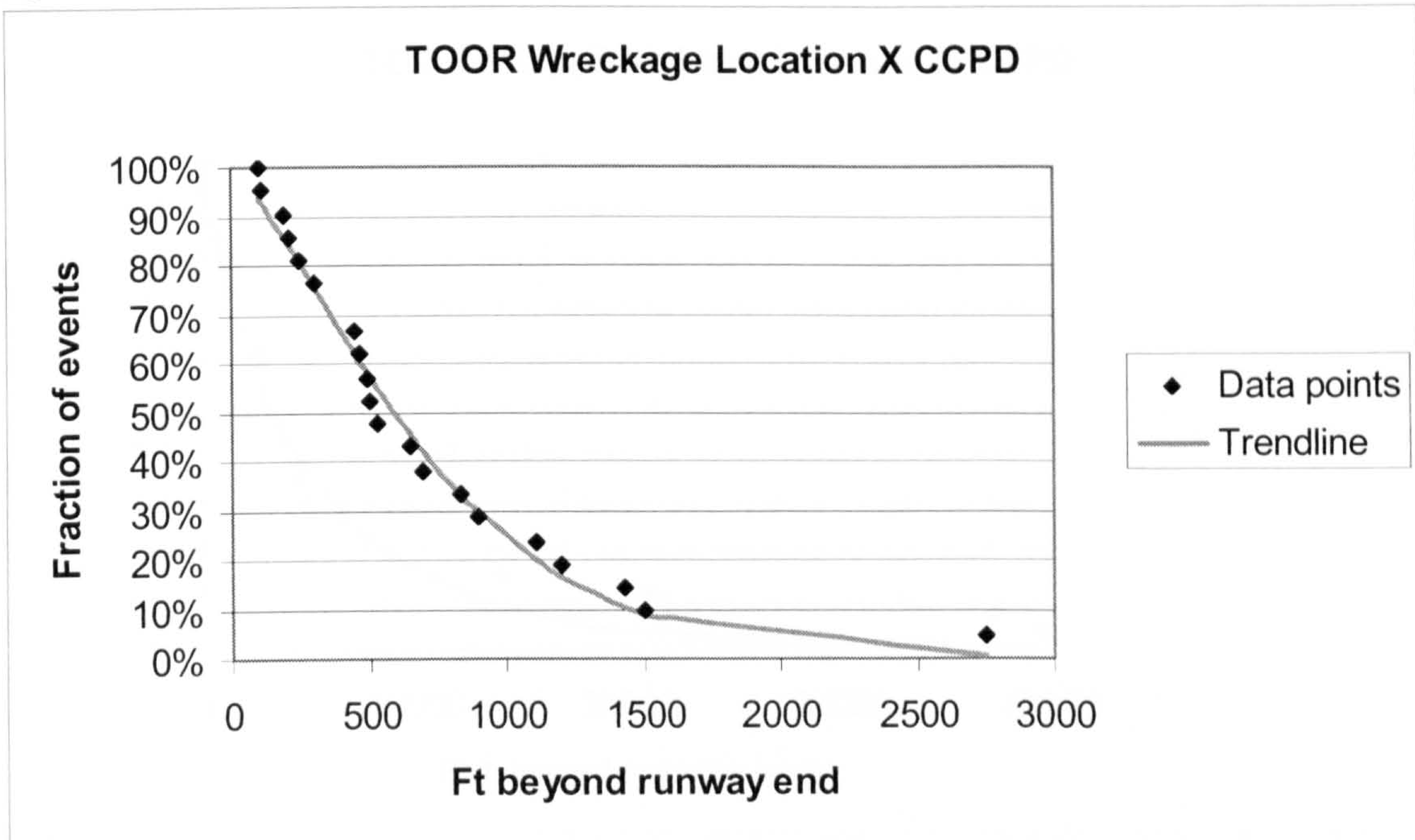


The CCPD shows that approximately 80 percent of cases involve undershoot distances of more than 100ft from the runway threshold. The plot also shows that a significant proportion of cases involve very large x distances. Roughly a third of cases involve undershoot distances of 10,000ft or more. The greater x distances compared to landing overruns were expected due to the airborne nature of undershoots.

12.4.3 CCPD scenario 3 x distance

For scenario 3, the cases that challenge longitudinal ASAs are take-off overruns with final wreckage sites beyond the runway end. Out of 37 take-off overruns with known wreckage locations, 21 cases involved x locations beyond the runway end. The x distances from the runway end to the final wreckage sites were measured and used to plot the corresponding CCPD (Figure 12.10).

Figure 12.10 Scenario 3 x distance CCPD

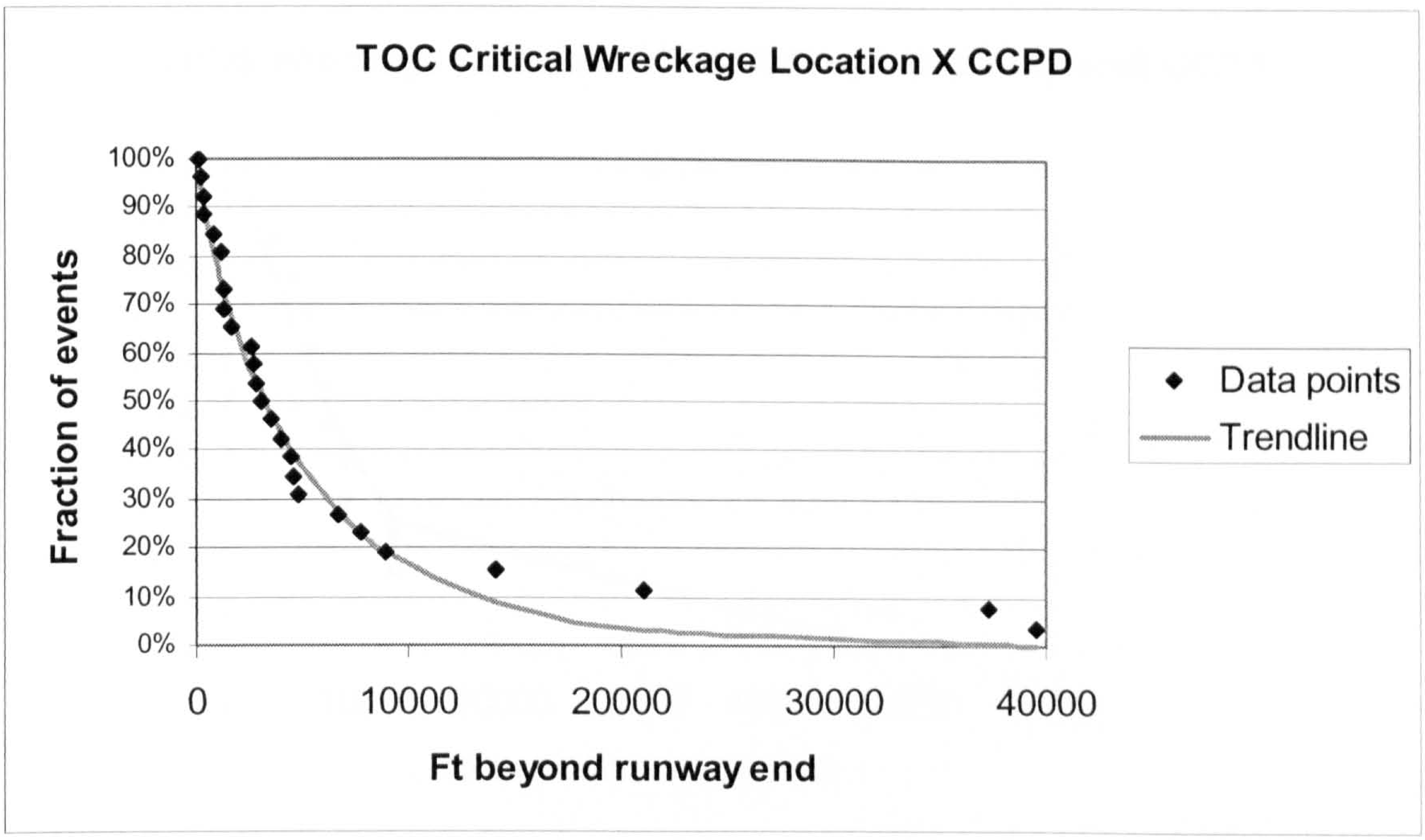


The CCPD shows that 80 percent of cases involve overrun distances of more than 245ft beyond the runway end. The greater overruns distances compared to landing overruns are probably due to the high energy nature of many take-off overruns. The plot also shows that roughly half of all cases involve overrun distances of 500ft or more.

12.4.4 CCPD scenario 4 x distance

For scenario 4, the cases that challenge longitudinal ASAs are crashes after take-off with POFIs and/or final wreckage sites beyond the runway end. Out of 57 crashes after take-off with known wreckage information, 26 cases involved x locations beyond the runway end. The critical x distances from the runway end to the POFI/final wreckage site were measured. Figure 12.11 shows the corresponding CCPD.

Figure 12.11 Scenario 4 x distance CCPD

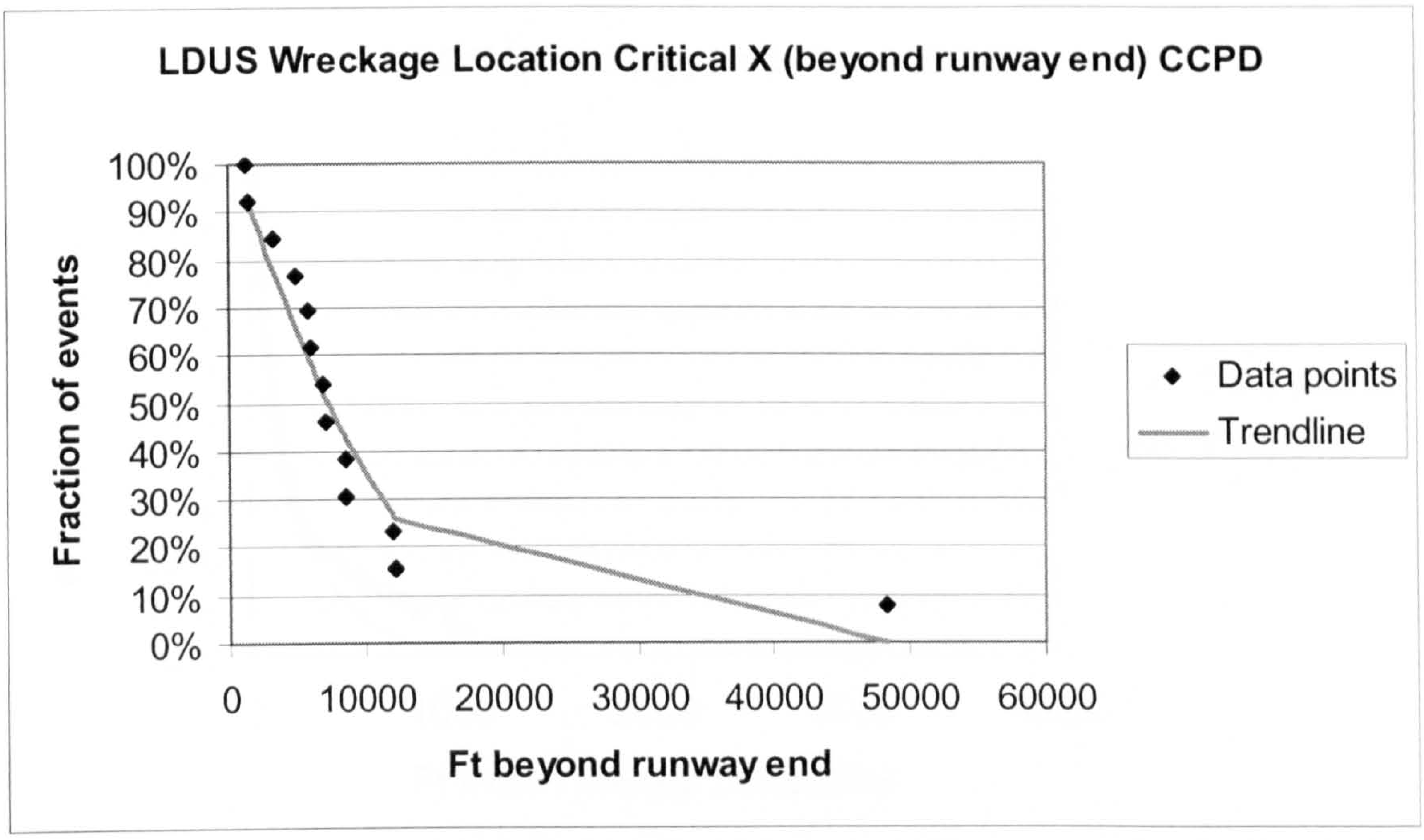


The CCPD shows that 80 percent of cases involve x distances of more than 1180ft beyond the runway end. Similar to landing undershoots, the plot also shows a significant proportion of accidents involve very large x distances. Roughly 15.4 percent of cases involve undershoot distances of 10,000ft or more. The greater x distances compared to take-off overruns were expected due to the airborne nature of crashes after take-off.

12.4.5 CCPD scenario 5 x distance

For scenario 5, the cases of concern are landing undershoots with positive x distances beyond the runway end. Out of 105 landing undershoots with known wreckage information, thirteen cases fall into this category. The critical x distances from the POFI/final wreckage site to the runway end were measured and used to plot the corresponding CCPD (Figure 12.12).

Figure 12.12 Scenario 5 x distance CCPD



The CCPD shows that approximately 80 percent of cases involve x distances of more than 3300ft beyond the runway end. The large x distances suggest that the majority of the cases involve occurrences far from the airports' immediate surroundings, where both POFIs and final wreckage sites are a distance away from the runway.

12.4.6 CCPD scenario 6 x distance

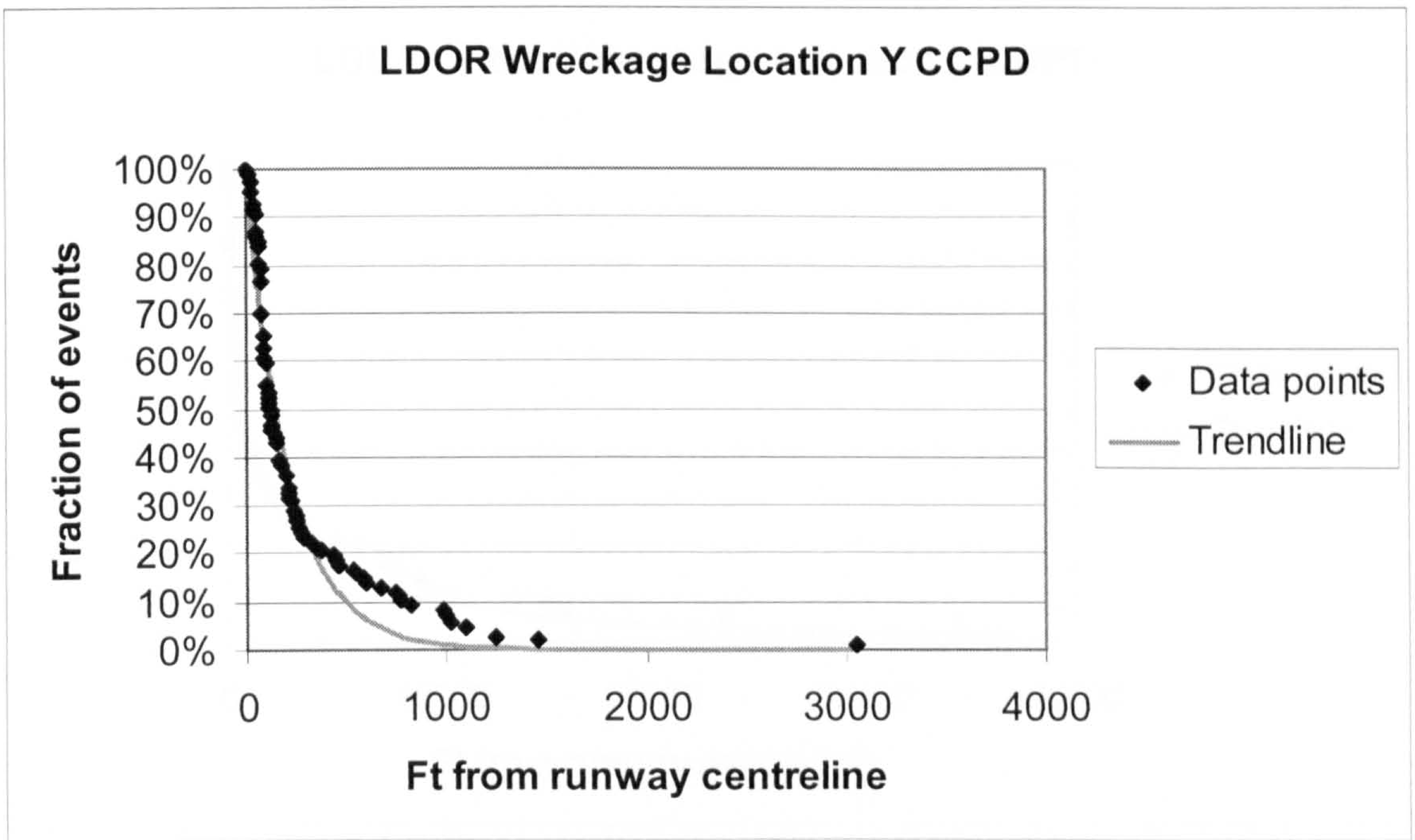
For scenario 6, the cases of concern are crashes after take-off with negative x distances, i.e. POFIs and/or final wreckage sites before the start-of-roll runway threshold. Out of 57 crashes after take-off with known wreckage information, only two cases fall into this category. Their critical x distances are 3252ft and 9504ft respectively from the runway threshold. The large distances again suggest that the events were altogether removed from the immediate surroundings of the airport. The small number of data points prevents a CCPD to be plotted with confidence.

12.4.7 CCPD landing overrun y distance

The lateral deviations of all landing overruns were plotted in a single CCPD. Of the 133 cases with known y distances, 26 were recorded as zero[11]. These were removed for the purpose of plotting the CCPD. The plot, based on the remaining 107 cases, is shown in Figure 12.13.

[11] A disproportionate number of cases recorded zero lateral deviation due to the lack of accurate data in the accident files. Cases believed to involve minimal lateral deviation were entered as y=0. Where such an assumption could not be confidently made, y was considered unknown.

Figure 12.13 Landing overrun y distance CCPD



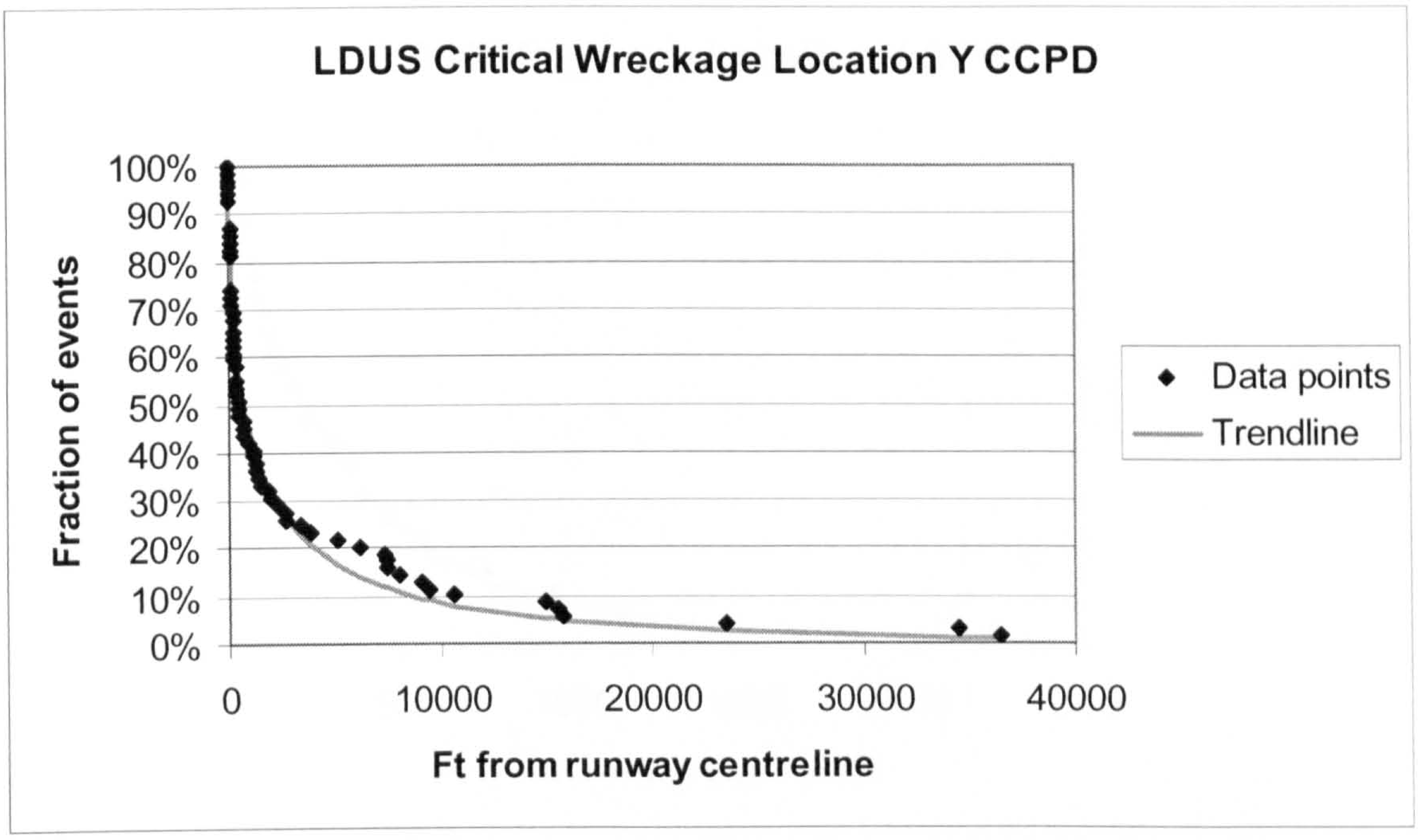
The CCPD shows that 80 percent of cases involve lateral deviations exceeding 65ft from the runway centreline. For a runway 150ft wide, the plot shows that 76.6 percent of landing overruns have final wreckage sites beyond the widths of the runway, i.e. y distances of over 75ft[12].

12.4.8 CCPD landing undershoot y distance

The lateral deviations of all landing undershoots were plotted in a single CCPD. Of the 91 cases with known y distances, 22 were recorded as zero. These were removed for the purpose of plotting the CCPD. The critical y distances were identified and based on 69 cases the CCPD was obtained, as shown in Figure 12.14.

[12] Many runways, however, are legitimately less than 150ft wide.

Figure 12.14 Landing undershoot y distance CCPD

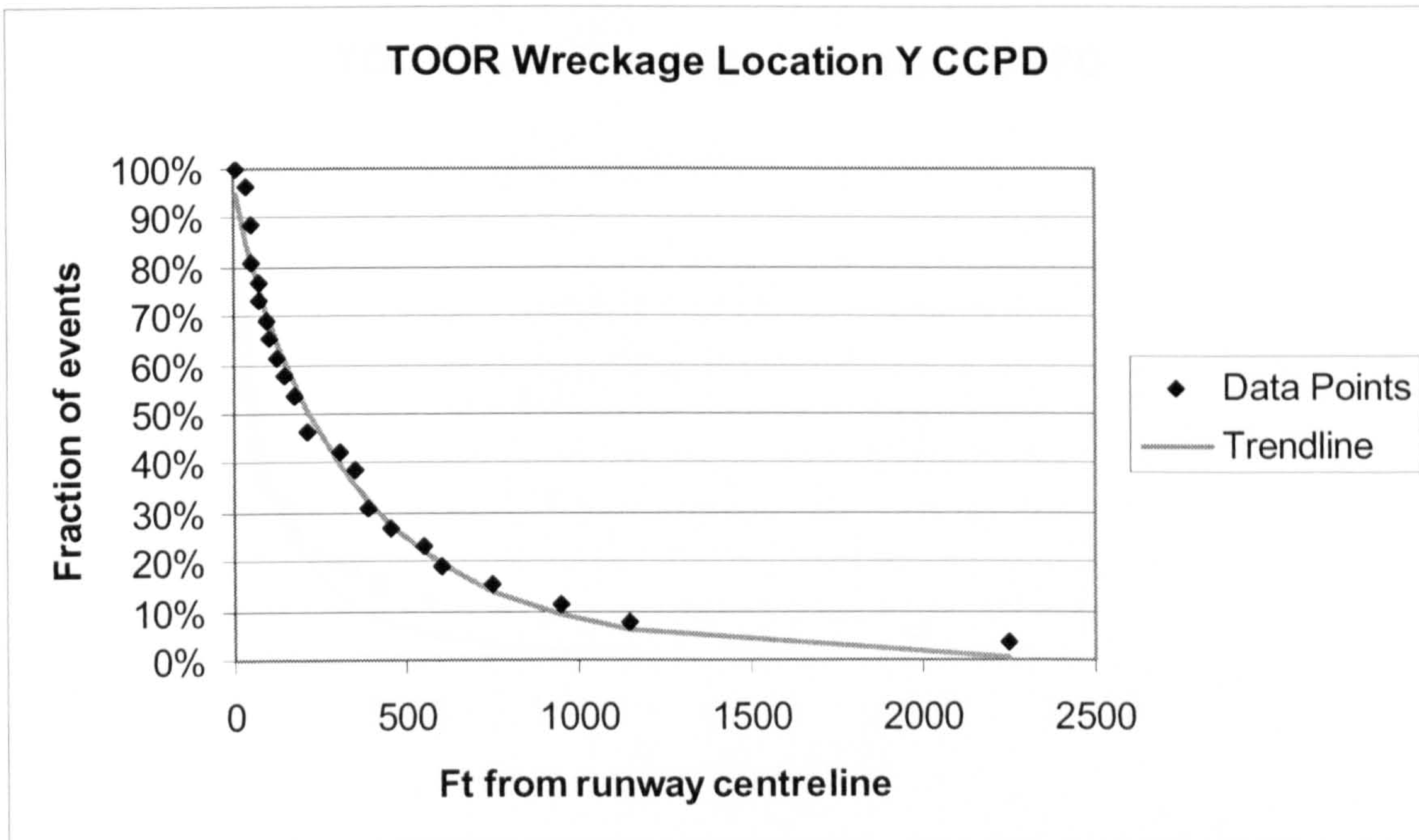


The CCPD shows that approximately 80 percent of cases involve lateral deviations exceeding 100ft from the runway centreline. For a runway 150ft wide, the plot shows that 85.5 percent of landing overruns have final wreckage sites beyond the widths of the runway. The greater lateral deviation of landing undershoots compared to overruns is in line with expectations.

12.4.9 CCPD take-off overrun y distance

The lateral deviations of all take-off overruns were plotted in a single CCPD. Of the 37 cases with known y distances, eleven were recorded as zero. These were removed for the purpose of plotting the CCPD. The plot, based on the remaining 26 cases, is shown in Figure 12.15.

Figure 12.15 Landing undershoot y distance CCPD

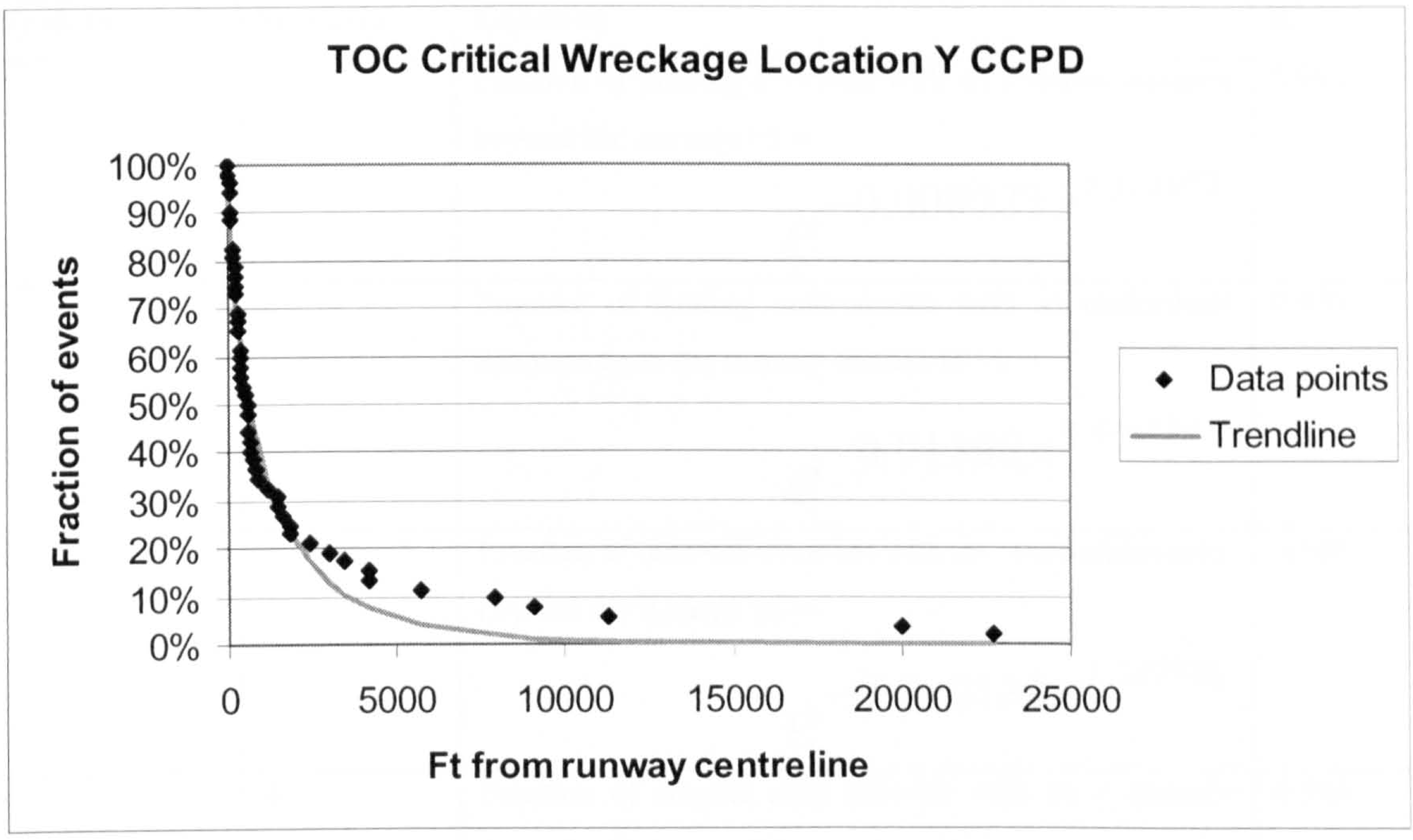


The CCPD shows that approximately 80 percent of cases involve lateral deviations exceeding 53ft from the runway centreline. For a runway 150ft wide, the plot shows that approximately 75.3 percent of landing overruns have final wreckage sites beyond the widths of the runway. The findings are broadly similar with those of landing overruns, albeit based on far fewer data points.

12.4.10 CCPD crash after take-off y distance

The lateral deviations of all crashes after take-off were plotted in a single CCPD. Of the 57 cases with known y distances, five were recorded as zero. These were removed for the purpose of plotting the CCPD. The critical y distances were identified and based on 52 cases the CCPD was obtained, as shown in Figure 12.15.

Figure 12.15 Landing undershoot y distance CCPD



The CCPD shows that approximately 80 percent of cases involve lateral deviations exceeding 150ft from the runway centreline. For a runway 150ft wide, the plot shows that approximately 94.2 percent of landing overruns have final wreckage sites beyond the widths of the runway. As such, crashes after take-off showed the largest lateral deviations. This is probably related to the high-energy and airborne nature of the accident type. Attempts to follow curved missed approach procedures may be a factor too.

12.5 CCPD Equations

The various CCPDs could be fitted into exponential functions as listed in Table 12.1. Their corresponding R^2 values are also indicated. The functions are also plotted in the relevant graphs (Figures 12.8-12.15) and labelled as 'Trendline'.

Table 12.1 CCPD Equations

x/y distance	Scenario	Equation	R^2
x	1	Fraction of landing overruns with an overrun distance beyond the runway >x = $e^{-0.000923\,x^{1.107653}}$	0.993
x	2	Fraction of landing undershoots with an undershoot distance from the runway threshold >x = $e^{-0.01308\,x^{0.491355}}$	0.980
x	3	Fraction of take-off overruns with an overrun distance beyond the runway >x = $e^{-0.000132\,x^{1.342743}}$	0.986
x	4	Fraction of crashes after take-off with an x distance from the runway end >x = $e^{-0.000663\,x^{0.860267}}$	0.984
x	5	Fraction of landing undershoots with an x distance beyond the runway end >x = $e^{-0.000008\,x^{1.277474}}$	0.944
y	LDOR	Fraction of landing overruns with a y distance from the runway centreline >y = $e^{-0.006\,y^{0.965}}$	0.958
y	LDUS	Fraction of landing undershoots with a y distance from the runway centreline >y = $e^{-0.003\,y^{0.468}}$	0.975
y	TOOR	Fraction of take-off overruns with a y distance from the runway centreline >y = $e^{-0.008\,y^{0.840}}$	0.984
y	TOC	Fraction of crashes after take-off with a y distance from the runway centreline >y = $e^{-0.008\,y^{0.687}}$	0.970

Although the overall fit of the functions are good, all of them, except for scenario 2, underestimate the proportion of cases involving large deviations. It would therefore be more prudent to only use the fitted functions for small and moderate deviation estimates.

12.6 Normalisation of accident locations

The research also experimented with normalising accident location x distances by the associated runway lengths. This involves expressing x distances as a percentage of the runway distance available for the specific landing or take-off. The resulting CCPDs are presented in Appendix M and are broadly similar to those reported in this chapter.

CHAPTER 13 MODEL APPLICATION & CASE STUDIES

This chapter details how the accident frequency models could be used for practical airport risk assessment along with the accident location distributions. Two case studies were carried out based on New York LaGuardia Airport and Boca Raton Airport in Florida. Other than demonstrating the application of the novel risk assessment techniques, the exercise also revealed important findings on the need of ASAs at the two airports.

13.1 Complementary Cumulative Frequency Distributions

The previous chapter described the development of complementary cumulative probability distributions (CCPD) for accident locations. With CCPDs, the fraction of accidents involving locations exceeding a given distance from the runway end or threshold could 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. In other words, multiplying the CCPDs of Chapter 12 by the accident frequency models of Chapter 11 yields CCFDs with which ASA needs could be assessed. Eddowes et al. (2001) also used CCFDs to draw conclusions on Norwegian aerodrome design rules.

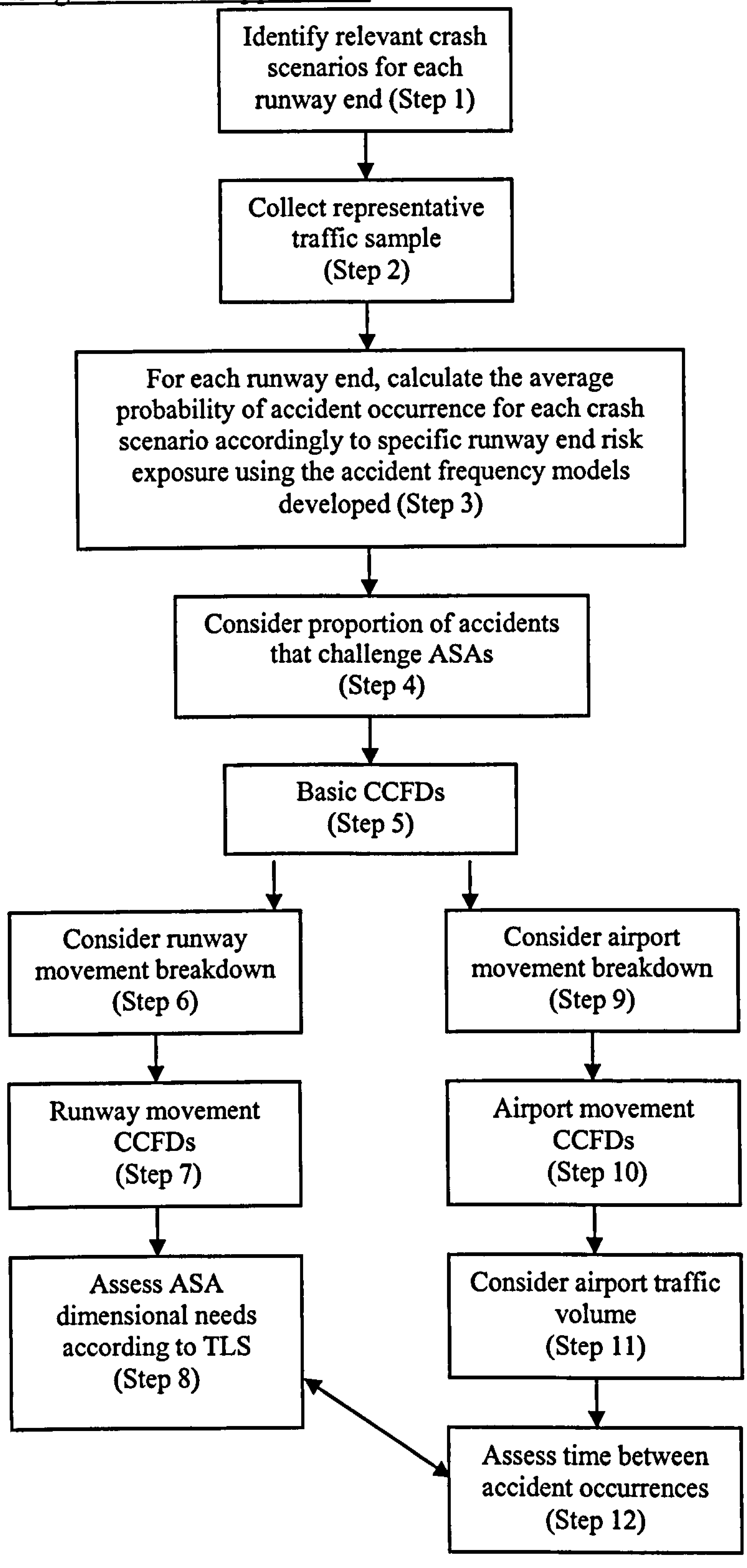
13.2 Case Study Airports

Two case studies were carried out to demonstrate the application of the overall risk assessment methodology developed in this thesis and to illustrate the difference in ASA needs at different airports and runways. New York LaGuardia Airport (LGA) and Boca Raton Airport in Florida (BCT) were selected for their contrasting characteristics. LGA is a two-runway primary commercial airport in the eastern region with 11,352,248 enplanements in 2001 and a FAA large hub. BCT is a non-hub, single-runway non-commercial service airport in the southern region mainly serving air taxi and general aviation services. Due to the differences in location, operational characteristics, traffic type and level, it is expected that the risk exposure of the two airports differ significantly, which should be reflected in ASA requirements.

13.3 Model Application Demonstration – ASA Length

The length of ASA needed for each runway end was considered in turn, taking into account their specific accident frequency risk exposure, runway use patterns as well as traffic levels. The various stages involved is summarised in Figure 13.1.

Figure 13.1 Stages in model application



The model application process is described in detail below for assessing the length of ASA at the end of runway 4 at LGA.

13.3.1 Identification of relevant crash scenarios (step 1)

In assessing the ASA needs of a specific runway end, each of the crash scenarios that challenge ASA length (described in section 12.3) should be taken into account. Table 13.1 shows the crash scenarios that should be considered for the end of runway 4.

Table 13.1 Relevant crash scenarios to end of runway 4 risk assessment

Crash Scenario No.	Crash Scenario
1	Overrun of landing on runway 4
2	Undershoot of landing on runway 22
3	Overrun of take-off on runway 4
4	Crash after take-off on runway 4
5	Undershoot of landing on runway 4 with location beyond runway
6	Crash after take-off on runway 22 with location behind start-of-roll threshold

13.3.2 Calculation of crash scenario probabilities (Step 2-4)

The average probability for each of these scenarios were then calculated. This involved applying the accident frequency models as defined in Chapter 11 to a representative sample of flights at the airport and runway concerned and finding the average probability per landing or take-off. In this case, the NOD sampled for model building was used, i.e. 5,758 landings and 5,796 take-offs at LGA and 160 landings and 191 take-offs at BCT.

Table 13.2 shows the relevant crash scenario probabilities. The probability of each crash scenario is the product of two distinct probabilities. The first is the probability of accident occurrence (the initial event) and the second is the probability of the specific ASA being challenged given the initial event occurred. The latter probability must be considered because the location CCPDs were calculated based only on cases that challenged ASAs, e.g. overrun wreckage sites beyond the runway end. Certain accidents would remain within the runway length, e.g. veer-offs with x distances smaller than the runway length.

Table 13.2 Crash scenario probabilities for ASA length assessment

Crash scenario No.	Initial event	Initial event probability	Location condition	Location probability	Scenario probability
1	Overrun of landing on runway 4	$1.188x10^{-6}$	x beyond LDA	0.534	**6.344×10^{-7}**
2	Undershoot of landing on runway 22	$5.904 x10^{-8}$	Negative x	0.743	**4.386×10^{-8}**
3	Overrun of take-off on runway 4	$1.423 x10^{-7}$	x beyond TODA	0.568	**8.074×10^{-8}**
4	Crash after take-off on runway 4	$1.315 x10^{-7}$	x beyond TODA	0.456	**5.999×10^{-8}**
5	Undershoot of landing on runway 4	$4.497 x10^{-7}$	x beyond LDA	0.124	**5.567×10^{-8}**
6	Crash after take-off on runway 22	$4.283 x10^{-8}$	Negative x	0.035	**1.503×10^{-9}**

It should be noted that the probabilities for each initial event take into account the particular risk exposure characteristics of the runway end concerned. For example, the average overrun probability of a landing on runway 4 is 1.188×10^{-6} whereas the equivalent for runway 22 is 1.291×10^{-7}. Further investigation suggests that the difference is due to the significant disparity in exposure to adverse weather conditions. There are notable discrepancies in terms of exposure to visibility, ceiling height and fog between landings on runway 4 and those on runway 22. For instance, over 30 percent of landings on runway 4 take place in visibility under 2SM compared to 1.67 percent on runway 22. In a related measure, almost 40 percent of landings on runway 4 experienced fog versus under 7 percent for runway 22. 39 percent of landings on runway 4 took place in ceiling height under 1000ft while the equivalent for runway 27 is only 3.9 percent. These differences are most likely to be related to LGA's runway use policy. In fact, data on LGA's runway usage patterns revealed that landings on runway 4 are relatively rare. There are over four times more landings on runway 22 than on runway 4. When runway 13/31 was considered as well, it becomes clear that runway 4/22 is used mainly for landing on runway 22. Only 14.5 percent of all landing operations at LGA used runway 4. It is hence reasonable to assume that runway 4 is used for landings only for exceptional circumstances, such as adverse wind conditions. This would also explain the discrepancy in risk exposure for landings on runway 4 and runway 22.

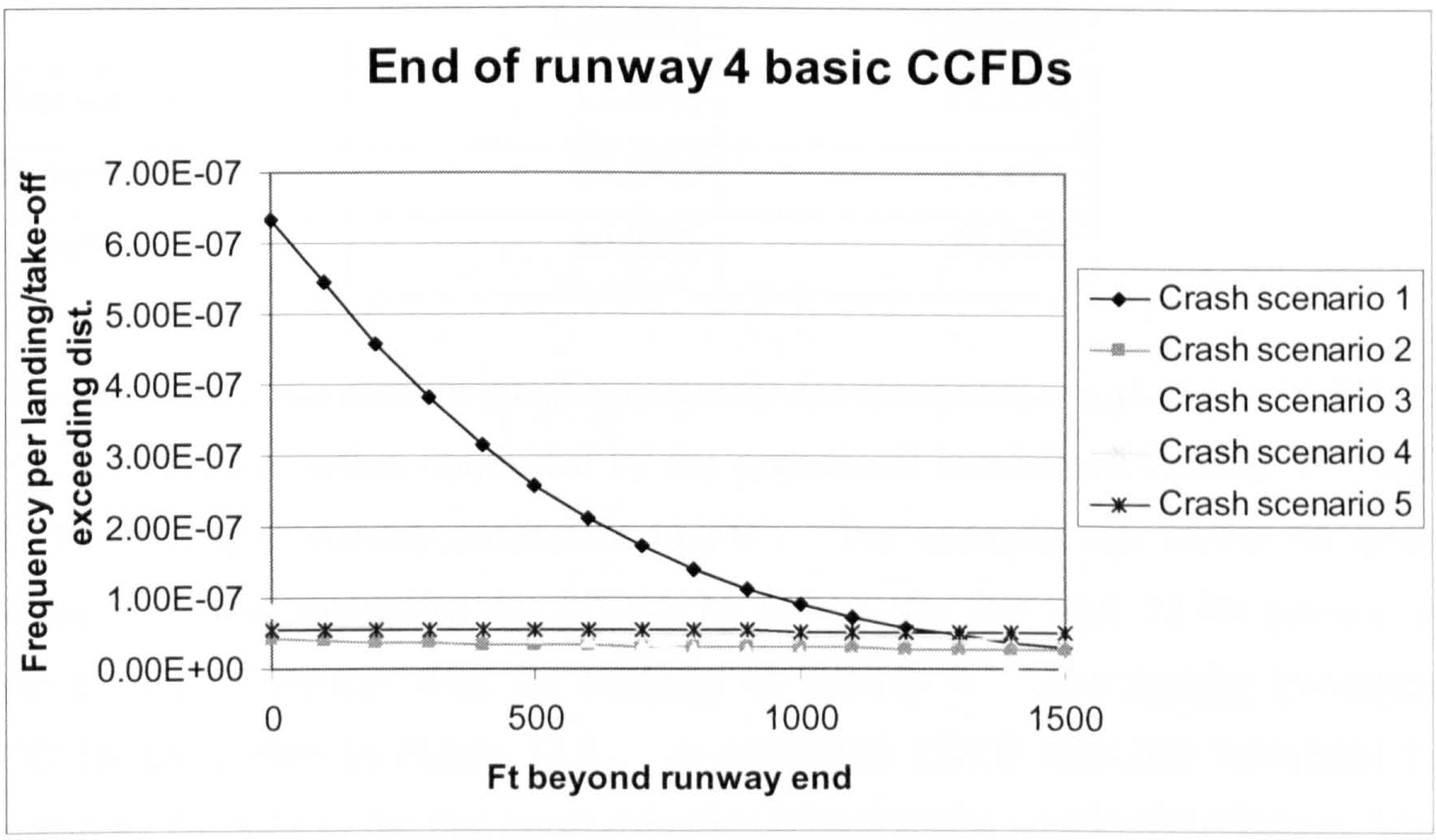
The above risk exposure breakdown by runway end was made possible by Aviation System Performance Metrics (ASPM) data identifying the take-off and landing runways in hourly segments. This information was coupled to the case study's traffic sample to identify the runway and direction used by each flight in the sample. The difference in risk exposure and accident probability between landings on runway 4 and runway 22 has highlighted the importance of differentiating risk at the runway end level, which has not been done in previous airport risk assessments. Unfortunately, ASPM only covers relatively large airports and so only average risks and probabilities could be calculated for BCT's runway ends. This would apply for any of the smaller airports not included in ASPM.

Due to the small probability of crash scenario 6 and the lack of related location distribution data (only two data points are available), crash scenario 6 was not considered hereafter.

13.3.3 Basic CCFD (Step 5)

To obtain the CCFD from which the frequency of accidents involving locations exceeding a given distance from the end of runway 4 could be derived, the CCPDs of the relevant accident scenarios (given in section 12.4) were multiplied by the corresponding crash scenario probabilities. For crash scenario 1, then, the CCFD is obtained by multiplying the CCPD equation $\exp(-0.000923x^{1.107653})$ by the crash scenario probability 6.344×10^{-7}. Figure 13.2 plots all the CCFDs related to the end of runway 4 up to a distance of 1500ft beyond the runway end.

Figure 13.2 End of runway 4 basic CCFDs



The frequencies depicted in Figure 13.2 relate to individual crash scenarios. Therefore, it is expected that an overrun of a landing on runway 4 entering the ASA beyond the runway end (crash scenario 1) occurs at a frequency of 6.34×10^{-7}. By inspecting the same plot, it is also estimated that a landing overrun on runway 4 in excess of 500ft occurs at a frequency of 2.58×10^{-7}. The other plots and frequencies are interpreted similarly. The graph also shows that the frequency of crash scenario 1 is several times higher than the other crash scenarios. The greater distances of airborne accidents such as undershoots and crashes after take-off are therefore overshadowed by the greater frequency of landing overruns on runway 4 as an initial event.

13.3.4 Runway movement CCFD (Step 6 & 7)

While Figure 13.2 reveals the CCFDs related to each of the crash scenarios affecting the end of runway 4, it does so without considering the runway use characteristics of runway 4/22 at LGA. Since runway 4/22 is principally used for landing on runway 22, the high frequency of landing overruns on runway 4 may not have as large an impact on the risk profile of the end of runway 4 as Figure 13.2 suggests. Table 13.3 shows the breakdown of operations on runway 4/22.

Table 13.3 Breakdown of runway 4/22 movements

	Landing	Take-off
Runway 4	12.85%	17.47%
Runway 22	56.24%	13.44%
Total	69.08%	30.92%

In order to take into account the above runway use characteristics, the basic CCFDs of Figure13.2 were further multiplied by the operational breakdown statistics of Table 13.3, yielding a 'runway movement CCFD'. For example, the CCFD for crash scenario 1 was multiplied by 0.1285 to reflect the fact that 12.85 percent of movements on runway 4/22 are landings on runway 4. The runway movement CCFDs are shown in Figure 13.3. A composite CCFD was also calculated by summing the risks of the five crash scenarios at each of the considered distances from the runway end.

Figure 13.3 End of runway 4 runway movement CCFDs

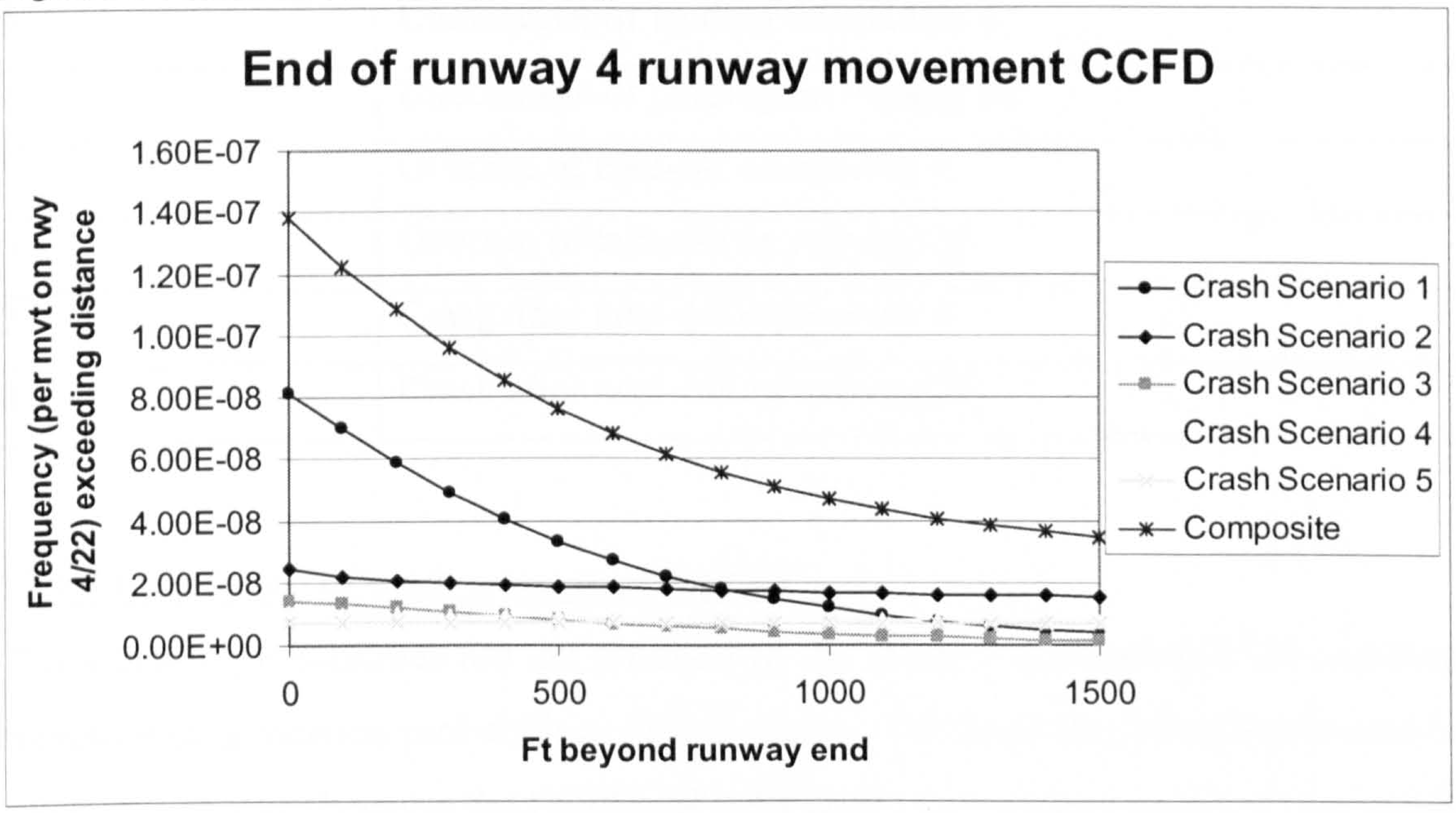


Figure 13.3 presents the CCFDs in the context of runway movements. These plots are more intuitive interpretations of the true risk posed by the crash scenarios. For instance, rather than noting the expected frequency of 2.58×10^{-7} for a landing overrun on runway 4 in excess of 500ft *per landing on runway 4*, Figure 13.3 provides the frequency of the same event *per movement on runway 4/22*, which is 3.31×10^{-8}.

By considering all scenarios which affect the end of runway 4, the composite plot could be used to determine the length of the ASA according to a predefined target level of safety. This is discussed in section 13.5 below.

13.4 Model Application Demonstration – ASA Width

The application of the risk models to determine ASA width is similar to the process described above for ASA length. The example for runway 4 at LGA is continued here.

13.4.1 Identification of relevant crash scenarios

The crash scenarios that affect the ASA width of runway 4 are listed in Table 13.4.

Table 13.4 Relevant crash scenarios to runway 4 width risk assessment

Crash Scenario No.	Crash Scenario
1	Overrun of landing on runway 4
2	Overrun of landing on runway 22
3	Undershoot of landing on runway 4
4	Undershoot of landing on runway 22
5	Overrun of take-off on runway 4
6	Overrun of take-off on runway 22
7	Crash after take-off on runway 4
8	Crash after take-off on runway 22

13.4.2 Calculation of crash scenario probabilities

The scenario probabilities are the products of the initial event probabilities and their corresponding location probabilities (Table 13.5). The location probabilities must be taken into account because the CCPDs of y distances were plotted based only on cases that diverged from the runway centreline, i.e. $y > 0$.

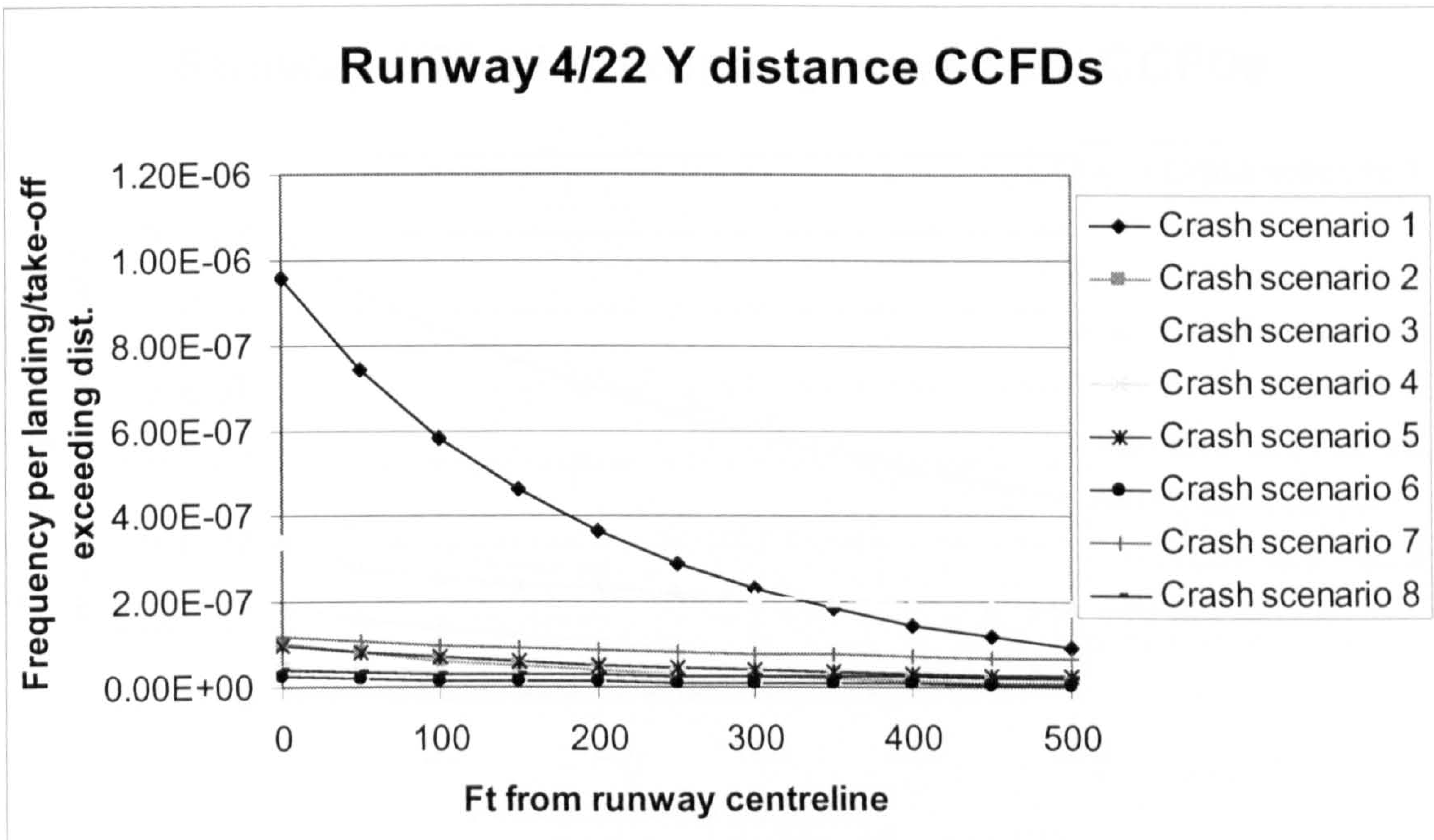
Table 13.5 Crash scenario probabilities for ASA width assessment

Crash scenario No.	Initial event	Initial event probability	Location condition	Location probability	Scenario probability
1	Overrun of landing on runway 4	1.188 x 10-6	y > 0	0.804511	**9.561×10^{-7}**
2	Overrun of landing on runway 22	1.291 x 10-7	y > 0	0.804511	**1.039×10^{-7}**
3	Undershoot of landing on runway 4	4.497 x 10-7	y > 0	0.758242	**3.410×10^{-7}**
4	Undershoot of landing on runway 22	5.904 x 10-8	y > 0	0.758242	**4.477×10^{-8}**
5	Overrun of take-off on runway 4	1.423 x 10-7	y > 0	0.702703	**9.997×10^{-8}**
6	Overrun of take-off on runway 22	3.671 x 10-8	y > 0	0.702703	**2.579×10^{-8}**
7	Crash after take-off on runway 4	1.315 x 10-7	y > 0	0.912281	**1.200×10^{-7}**
8	Crash after take-off on runway 22	4.283 x 10-8	y > 0	0.912281	**3.907×10^{-8}**

13.4.3 Basic CCFD

The basic CCFDs were then obtained by multiplying the y distance CCPDs in section 12.4 with the corresponding crash scenarios above. Figure 13.4 plots all the CCFDs related to the width of runway 4/22 up to a distance of 1500ft from the runway centreline.

Figure 13.4 Runway 4/22 width basic CCFDs

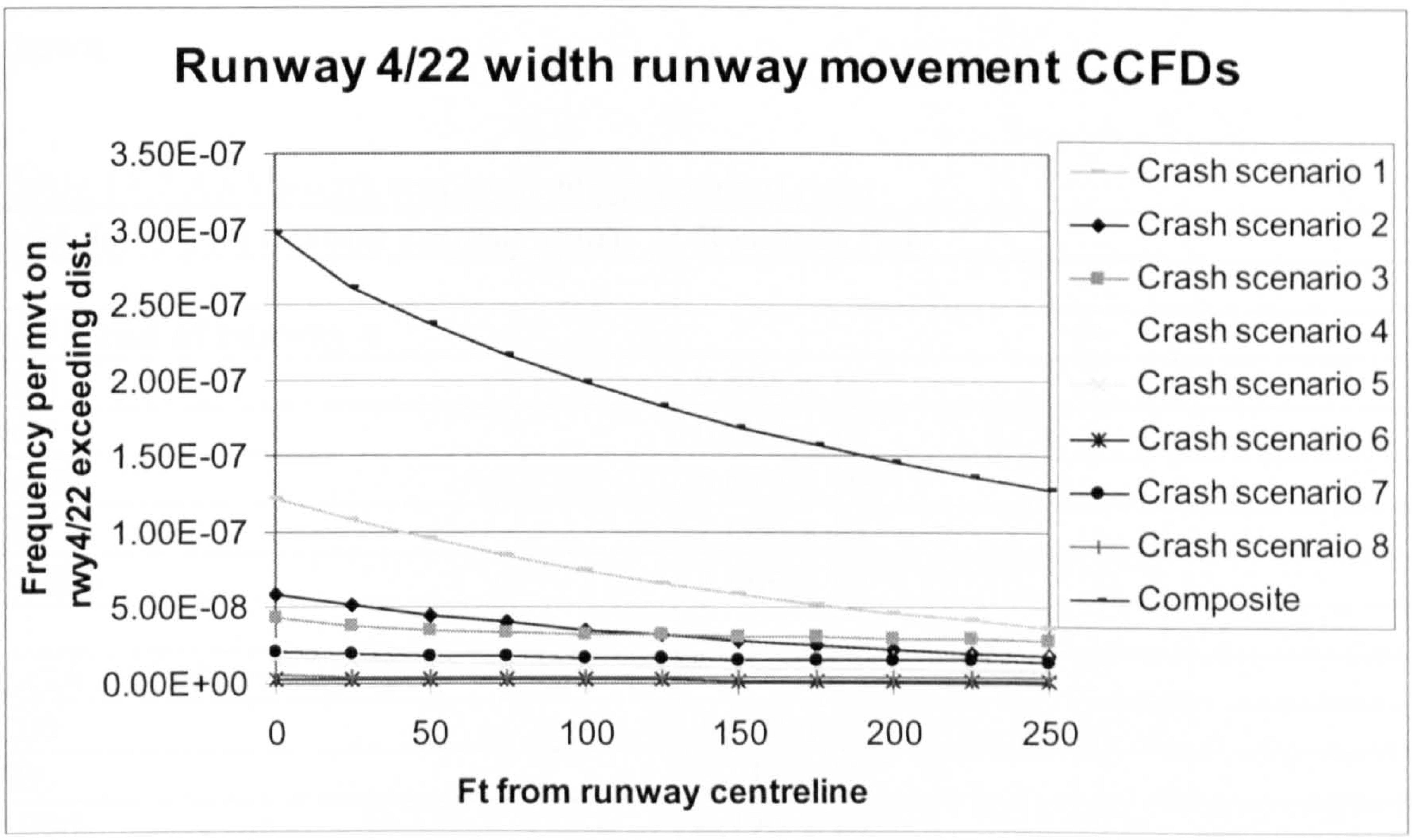


As for the ASA length assessment, the basic CCFDs relate to individual crash scenarios and are interpreted in the same way. For example, an overrun of a landing on runway 4 (crash scenario 1) that veers from the centreline in excess of 100ft is expected to occur at a frequency of 5.84×10^{-7}. The frequency for the same crash scenario but in excess of 300ft from the runway centreline is 2.31×10^{-7}. The graph also shows that the frequency of deviation from the centreline is considerably higher for crash scenario 1 up to 300ft when crash scenario 3 (undershoots of landings on runway 4) becomes the most likely to challenge ASA width. It should be noted that because y distances were recorded without discriminating between the two sides of the centreline, the frequencies of an event on one particular side of the centreline should be half of those cited above.

13.4.4 Runway movement CCFD

Runway movement CCFDs were again obtained by taking into account the runway use characteristics of the runway. These are shown in Figure 13.5.

Figure 13.5 Width of runway 4/22 runway movement CCFDs



The composite plot shows that the frequency of an accident veering from the centreline in excess of 100ft is 1.99 x 10^{-7} per runway movement. This equates to 1.00 x 10^{-7} per runway movement for each side of the centreline.

13.5 Setting the Size of ASAs

13.5.1 Target level of safety

Before the appropriate size of ASAs could be determined using the CCFDs obtained, a target level of safety (TLS) must be set. This is the safety level against which the size of ASAs are evaluated. In the assessment of Norwegian aerodrome design rules, the benchmark TLS of 10^{-7} per movement was used with the recommendation of improving upon this towards 10^{-8} per movement where practicable (Eddowes et al. 2001). The current study adopts the same standards. It should be stressed that the selection of an appropriate TLS is beyond the scope of risk assessment and concerns a socio-political process.

13.5.2 ASA lengths (Step 8)

With the methodology described above, the relevant CCFDs for all runway ends and widths at LGA and BCT were computed. Tables 13.6 highlights the residual risk at ASA lengths of 300ft, 600ft and 1000ft, which corresponds to the FAA Runway Safety Area length requirements for Airplane Design Groups II, III and IV respectively. The ASA lengths necessary to achieve a TLS of 10^{-7} and 10^{-8} are shown.

Table 13.7 ASA length requirements & residual risks

ASA length (ft beyond runway end)	Residual risk
LGA end of runway 4	
300	9.605×10^{-8}
600	6.807×10^{-8}
1000	4.676×10^{-8}
267	*1.000×10^{-7}*
11690	*1.000×10^{-8}*
LGA end of runway 22	
300	6.640×10^{-8}
600	5.216×10^{-8}
1000	4.124×10^{-8}
N.A.	*1.000×10^{-7}*
16303	*1.000×10^{-8}*
LGA end of runway 13	
300	8.713×10^{-8}
600	6.838×10^{-8}
1000	5.174×10^{-8}
130	*1.000×10^{-7}*
9872	*1.000×10^{-8}*
LGA end of runway 31	
300	3.156×10^{-8}
600	2.509×10^{-8}
1000	1.975×10^{-8}
N.A.	*1.000×10^{-7}*
4730	*1.000×10^{-8}*
BCT runway end (average)	
300	1.772×10^{-7}
600	1.311×10^{-7}
1000	9.500×10^{-8}
927	*1.000×10^{-7}*
25302	*1.000×10^{-8}*

The results show the ASA needs of each runway end differ significantly. The end of runway 22 and runway 31 at LGA exceed the TLS of 10^{-7} even without ASAs beyond the runway end due to the low risk exposure of its operations. Figure 13.6 compares the average probability of accident occurrence for all accident types and runway ends.

The principal crash scenarios that affect risk at the ends of runway 22 and 31, such as overruns of landings on runway 22 and 31 and undershoots of landings on runway 4 are all relatively low. The largest source of risk for the end of runway 31 is undershoots of landings on runway 13. However, this is offset by the rarity of landings on runway 13. Figure 13.7 shows the small proportion of landings that used runway 13 (0.73 percent).

Figure 13.6 Average accident occurrence probabilities

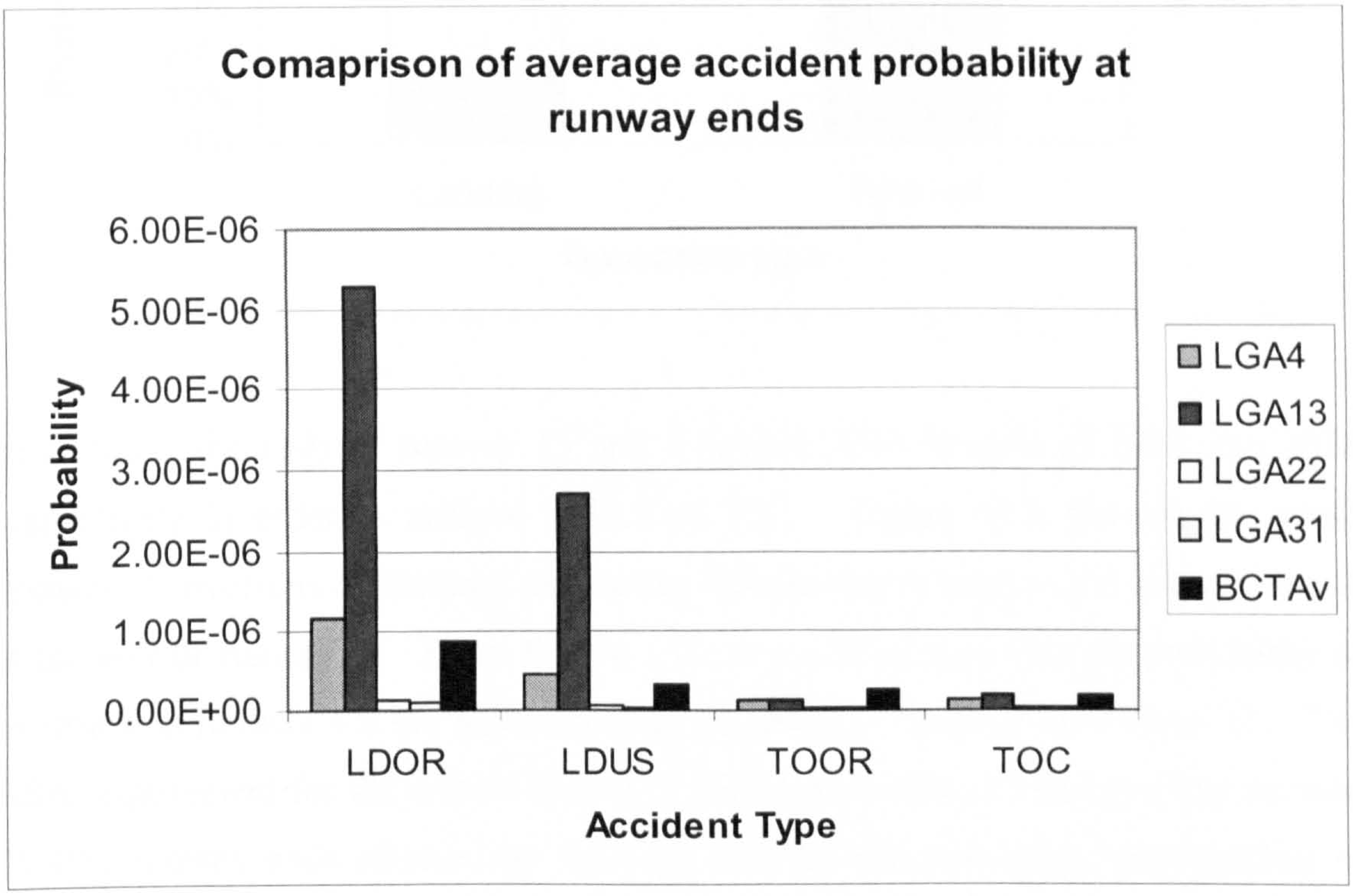
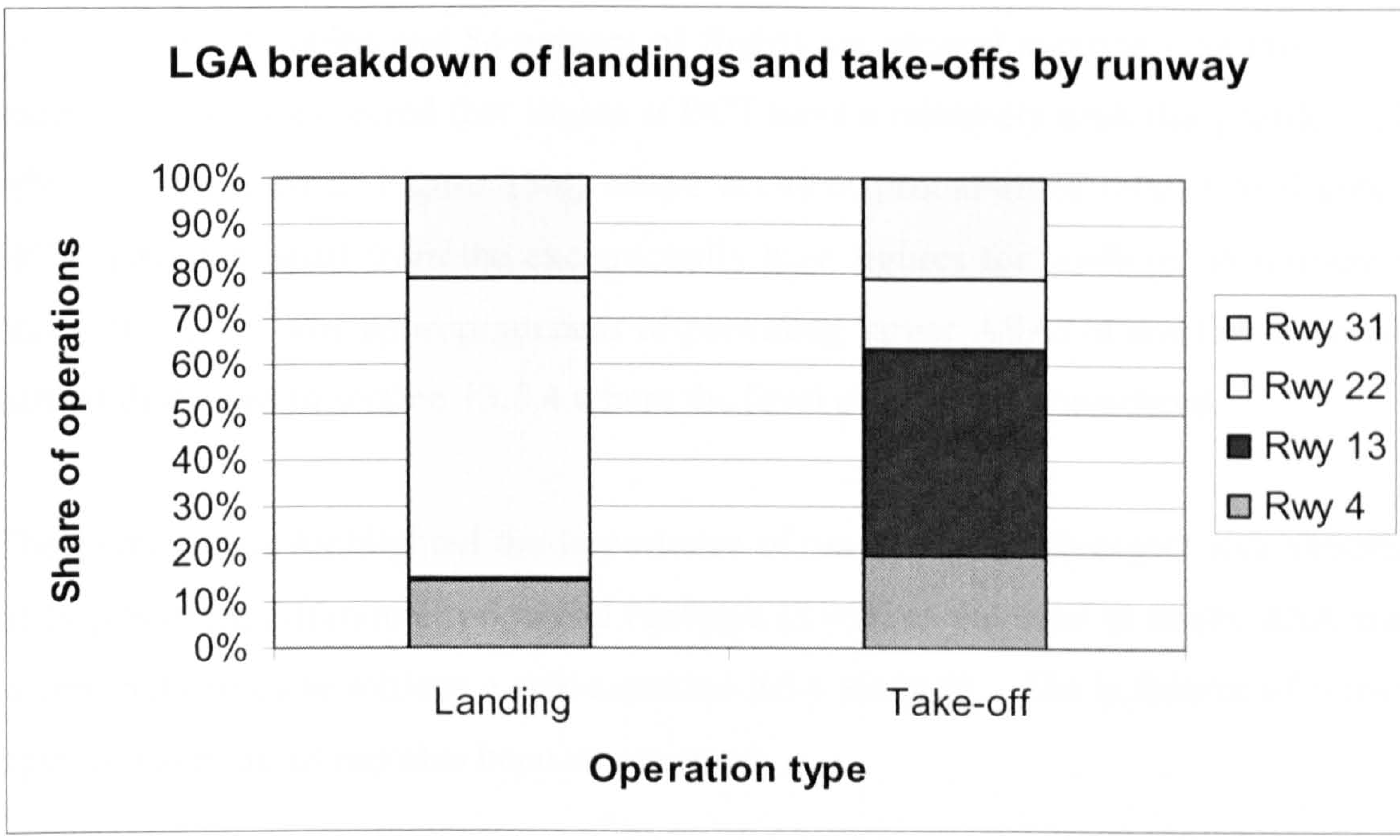


Figure 13.7 Breakdown of operations at LGA by runway



In contrast, the ends of runway 13 and 4 require ASA lengths of 130ft and 267ft respectively in order to achieve a TLS of 10^{-7}. Figure 13.3 showed that crash scenario 1 (overruns of landings on runway 4) contributes most to the composite risk at the end of runway 4. From Figure 13.6, it could be seen that the probability of overruns on runway 4 is the highest except accidents of landings on runway 13. The ASA requirement for the end of runway 4 still exceeds that of runway 13 or runway 31 (the runway ends affected by the high overrun and undershoot probabilities of landings on runway 13) because there are many more landings on runway 4 than 13. In fact, Figure 13.7 shows that there are almost 20 times as many landings on runway 4 than 13 (14.5 percent vs. 0.7 percent). As a result, the high accident probabilities of landings on runway 13 are relatively subdued[13].

The smaller airport BCT has greater ASA requirement on average than any of LGA's runway ends. This contradicts the FAA's as well as ICAO's general policy of requiring larger ASAs at airports that serve large aircraft. The phenomenon can be traced to the traffic profile of BCT. The accident frequency models identify small aircraft and general aviation flights as high risk operations. Since BCT is a non-

[13] Further investigation revealed that difference in adverse weather exposure is a key factor behind the particularly high accident probabilities of landings on runway 13. For example, all landings on runway 13 experienced fog. This again is likely to be related to LGA's runway use policy.

commercial service airport, 96 percent of its operations in the sample involve aircraft of 12,500 to 41,000lbs and 54 percent of flights are general aviation operations. As such, it would be expected that flights at BCT have a relatively high risk profile. The effect can be seen in Figure 13.6, where accident probabilities related to flights at BCT stand out, apart from the exceptionally high figures for landings on runway 13 and 4 at LGA. The appropriateness of providing larger ASAs at smaller airports is further discussed in section 13.5.4 where the level of traffic is considered.

The exercise has highlighted the importance of assessing the divergent risk exposure of flights using different airports and runways as well as the need to attune ASA sizes accordingly so as to achieve a risk-sensitive ASA strategy. The influence of runway operational patterns has also been emphasised.

13.5.3 ASA widths

Table 13.8 shows the results for ASA widths. The figures in the column on the left show the entire width of the ASA centred on the runway centreline. The middle column shows the associated residual risk on either side of the centreline. Since all runways at LGA and BCT are currently 150ft wide, the column furthest right indicates the additional ASA width required from the runway edge on either side of the runway to achieve the associated residual risk.

Table 13.8 ASA width requirements & residual risks

Total ASA width (ft)	**Residual risk (either side of the centreline)**	**Width either side from edge of 150ft wide runway (ft)**
LGA runway 4/22		
100	1.186×10^{-7}	N.A.
150	1.083×10^{-7}	0
200	1.987×10^{-7}	25
197	*1.000×10^{-7}*	*24*
6180	*1.000×10^{-8}*	*3015*
LGA runway 13/31		
100	9.306×10^{-8}	N.A.
150	8.701×10^{-8}	0
200	8.177×10^{-8}	25
52	*1.000×10^{-7}*	*N.A.*
5542	*1.000×10^{-8}*	*2696*

BCT runway 5/23		
100	2.632×10^{-7}	N.A.
150	2.413×10^{-7}	0
200	2.222×10^{-7}	25
849	1.000×10^{-7}	*350*
13045	1.000×10^{-8}	*6448*

As with the ASA length results, Table 13.8 shows the dissimilar risks associated with each of the three runways. With no ASA and just the runway width of 150ft, runway 4/22 at LGA is close to meeting the TLS of 10^{-7} and runway 13/31 exceeds it. On the other hand, a simple runway of 150ft at BCT falls short of the same TLS. The key difference in risk between runway 4/22 and 13/31 lies chiefly in the crash location distributions of their associated operations. Even though runway 4/22 is the principal landing runway and is thus at risk from landing overruns which have the highest probabilities amongst accident types, the larger y distances of crashes after take-off dominate risks at runway 13/31, the main take-off runway, to the extent of eclipsing the relatively low probabilities of take-off accidents. The greater ASA width needs at BCT is attributed to the generally higher accident probabilities at the facility.

Once more, the results highlight the inconsistent margin of safety currently provided. Eliminating this mismatch between risk and safety margin would result in BCT having vastly wider ASAs than LGA, which again is contradictory to ICAO and FAA aerodrome design principles. Section 13.5.5 examines an additional factor that is pertinent to the subject.

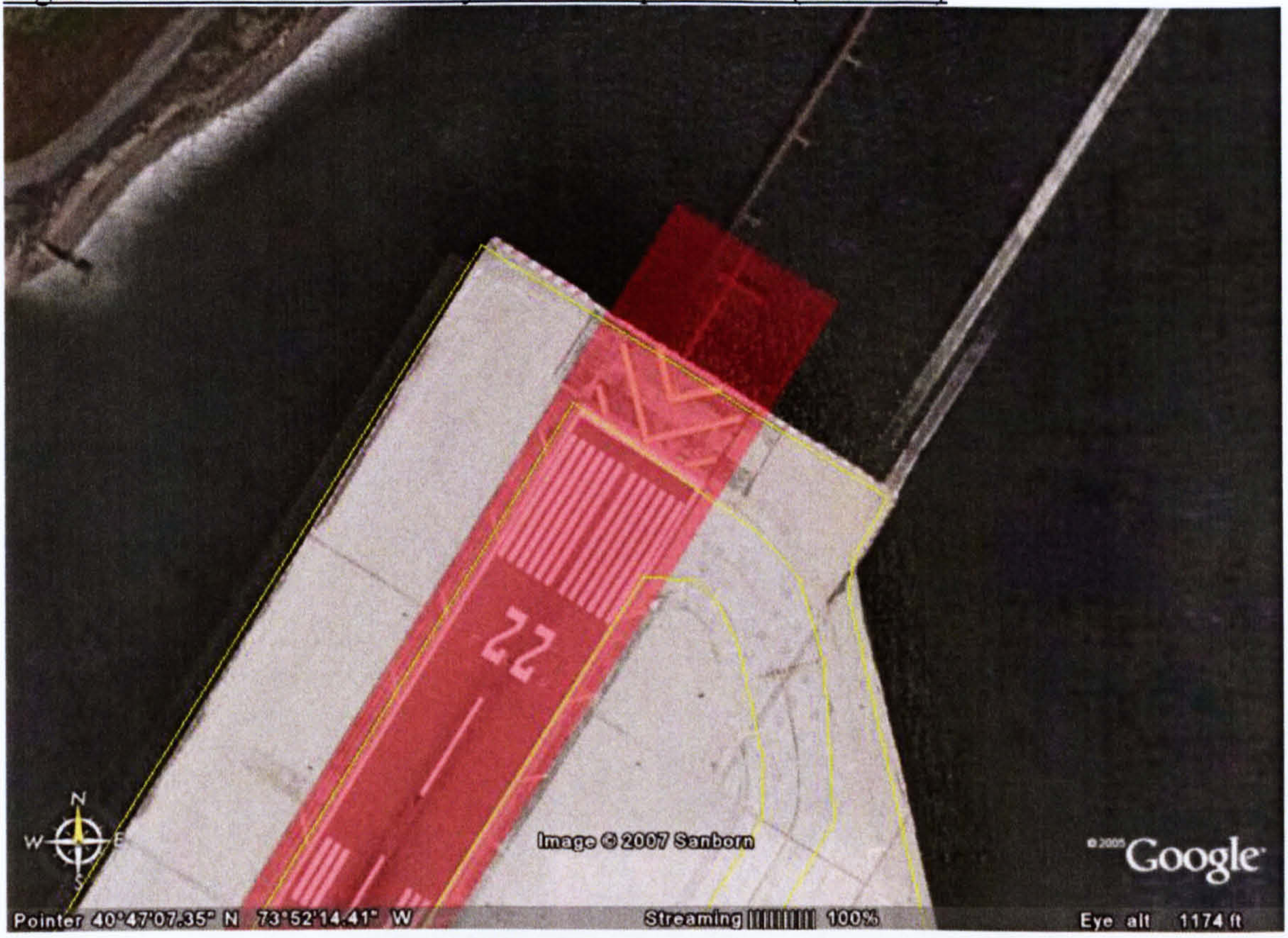
13.5.4 ASA diagrams

The computed ASA sizes were also visually compared with the existing ASAs. The dimensions of ASAs necessary to achieve a TLS of 10^{-7} were overlaid in red onto maps of LGA and BCT as available from Google Earth in February 2007. Figure 13.8 shows the ASA requirements for LGA. It can be seen that current ASAs mostly exceed the TLS of 10^{-7} except the end of runway 4 where extra ASA length is needed, as shown in Figure 13.9. This would involve additional reclamation of Eastchester Bay.

Figure 13.8 LGA ASA Requirements (TLS 10^{-7})

(Background map source: Google Earth)

Figure 13.9 LGA end of runway 4 ASA requirement (TLS 10^{-7})



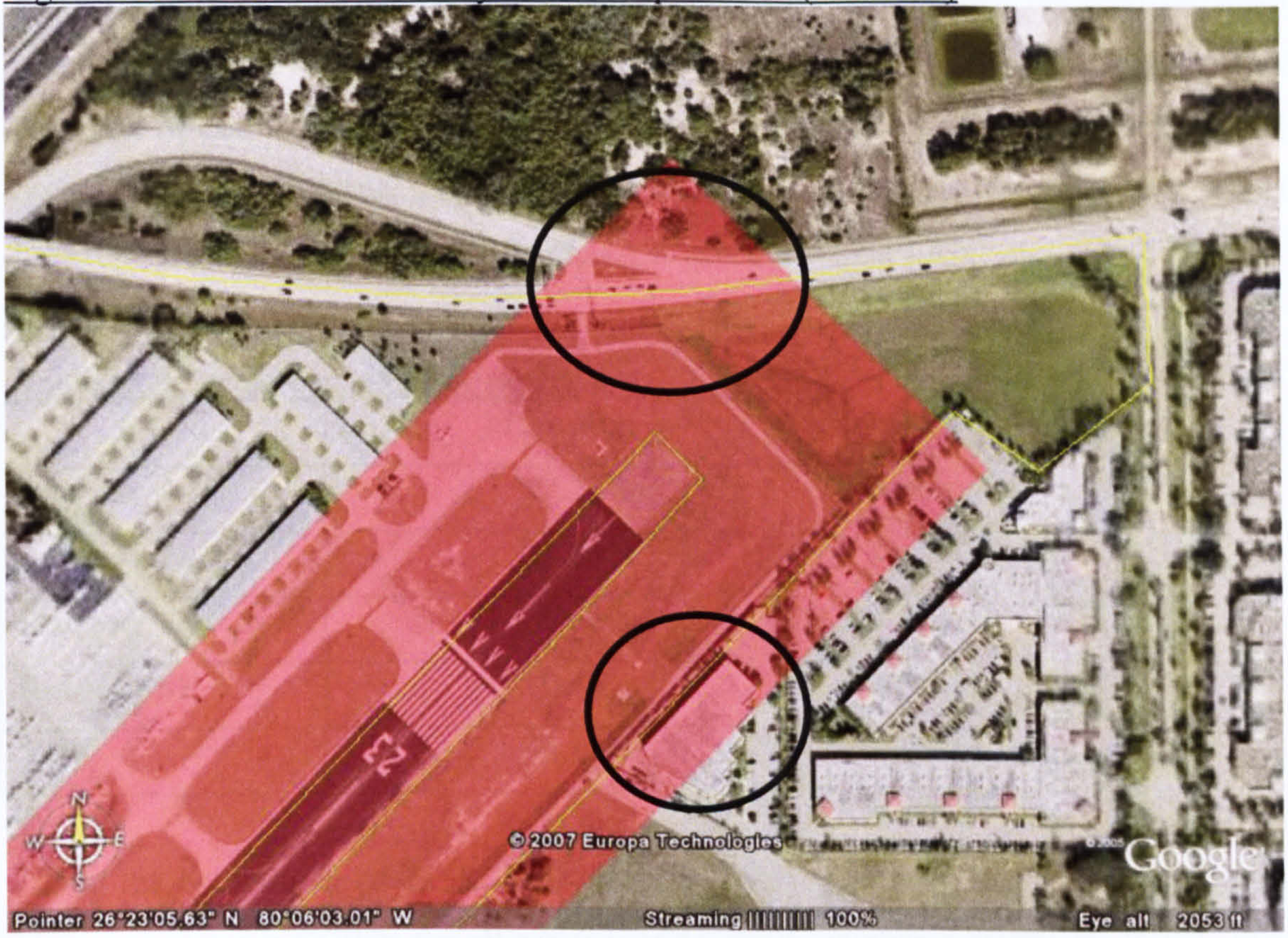
(Background map source: Google Earth)

Figure 13.10 shows and compares the calculated and existing ASAs at BCT. Unlike LGA, current ASAs at BCT fail to provide a TLS of 10^{-7}. The required ASA would cover the parallel taxiway, parts of the airport apron, a building near the end of runway 5 as well as parts of the NW Spanish river boulevard and airport road. Figure 13.11 offers a close-up view of the area around the end of runway 5 with noticeable ASA infringements circled in black.

Figure 13.10 BCT ASA Requirements (TLS 10^{-7})

(Background map source: Google Earth)

Figure 13.11 BCT end of runway 5 ASA requirement (TLS 10^{-7})



(Background map source: Google Earth)

13.5.5 Impact of traffic level (Step 9-12)

A TLS of 10^{-7} translates into an accident occurrence rate of one per ten million movements. Given the large difference in traffic volume between LGA and BCT, the expected number of years between accident occurrences varies greatly too. From the Terminal Area Forecast, the volume of relevant traffic in 2005 was calculated to be 398,681 movements and 11,631 movements for LGA and BCT respectively. If all ASAs were designed to meet the TLS of 10^{-7}, an accident involving locations beyond the ASAs would be expected to occur once every 25.1 years at LGA and every 859.8 years at BCT, assuming that the annual traffic level stays unchanged.

The current FAA and ICAO regulations do not take into account the level of traffic as a factor but certain land-use planning rules do, e.g. PSZ policy in the UK. The risk assessment methodology developed in this study can also be used to assess the impact of traffic level on accident frequency.

For airports with multiple runways such as LGA, the use pattern between runways would affect the overall frequency of accident occurrence at the airport since the risk exposure of each runway end differs. 'Airport movement CCFDs' could be obtained by multiplying the basic CCFDs by the breakdown of airport movements. The breakdown of airport movements for LGA is given in Table 13.9.

Table 13.9 Breakdown of LGA movements

	Landing	Take-off
Runway 4	7.23%	9.83%
Runway 22	31.64%	7.56%
Runway 13	0.36%	22.12%
Runway 31	10.60%	10.65%
Total	49.84%	50.16%

Using the breakdown of Table 13.9 and the basic CCFDs of each runway end, the airport movement CCFDs for all runway ends could be obtained and summed to give an overall CCFD for the airport. Figure 13.12 compares the overall CCFDs for LGA and BCT.

Figure 13.12 Overall airport movement CCFDs for LGA & BCT

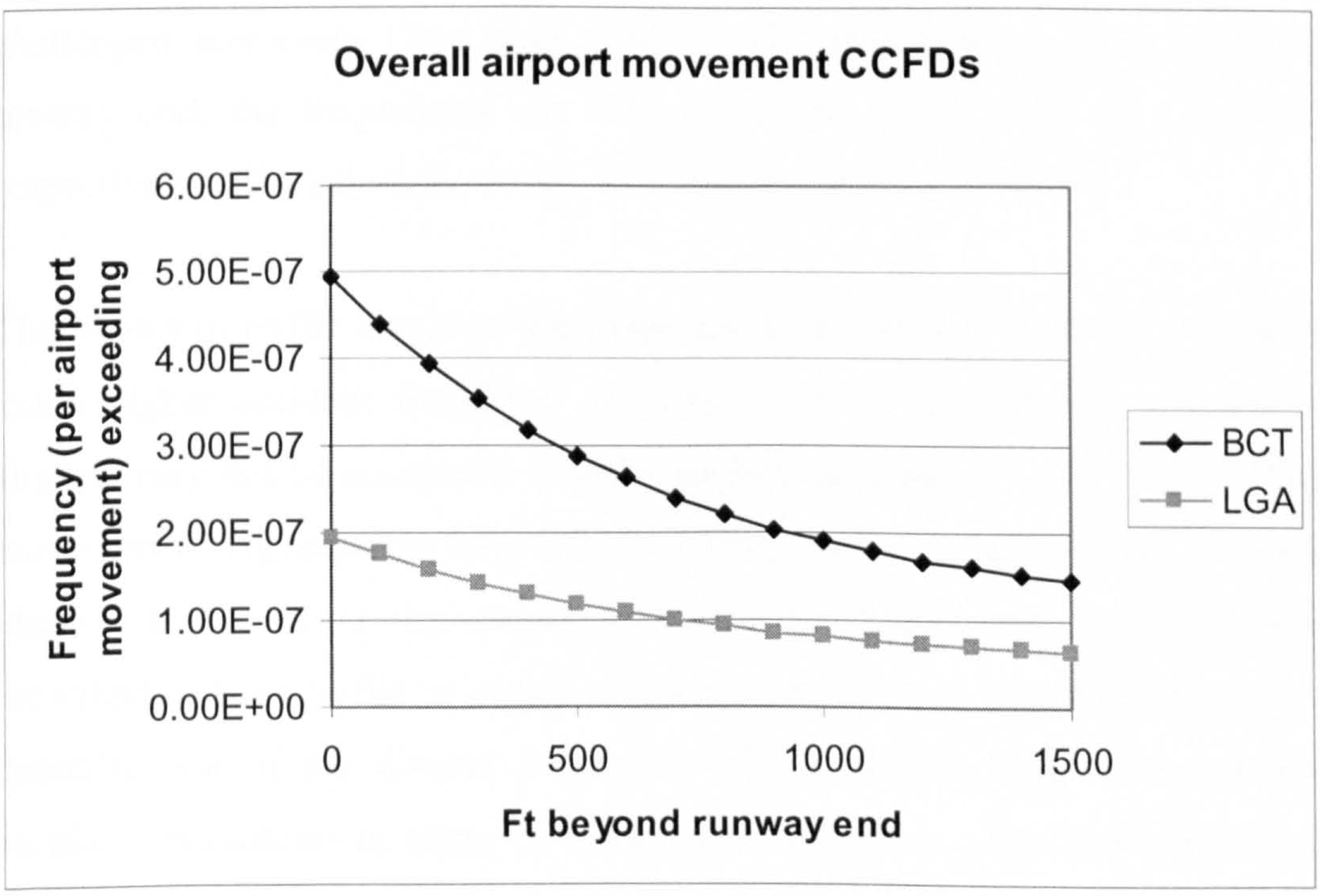
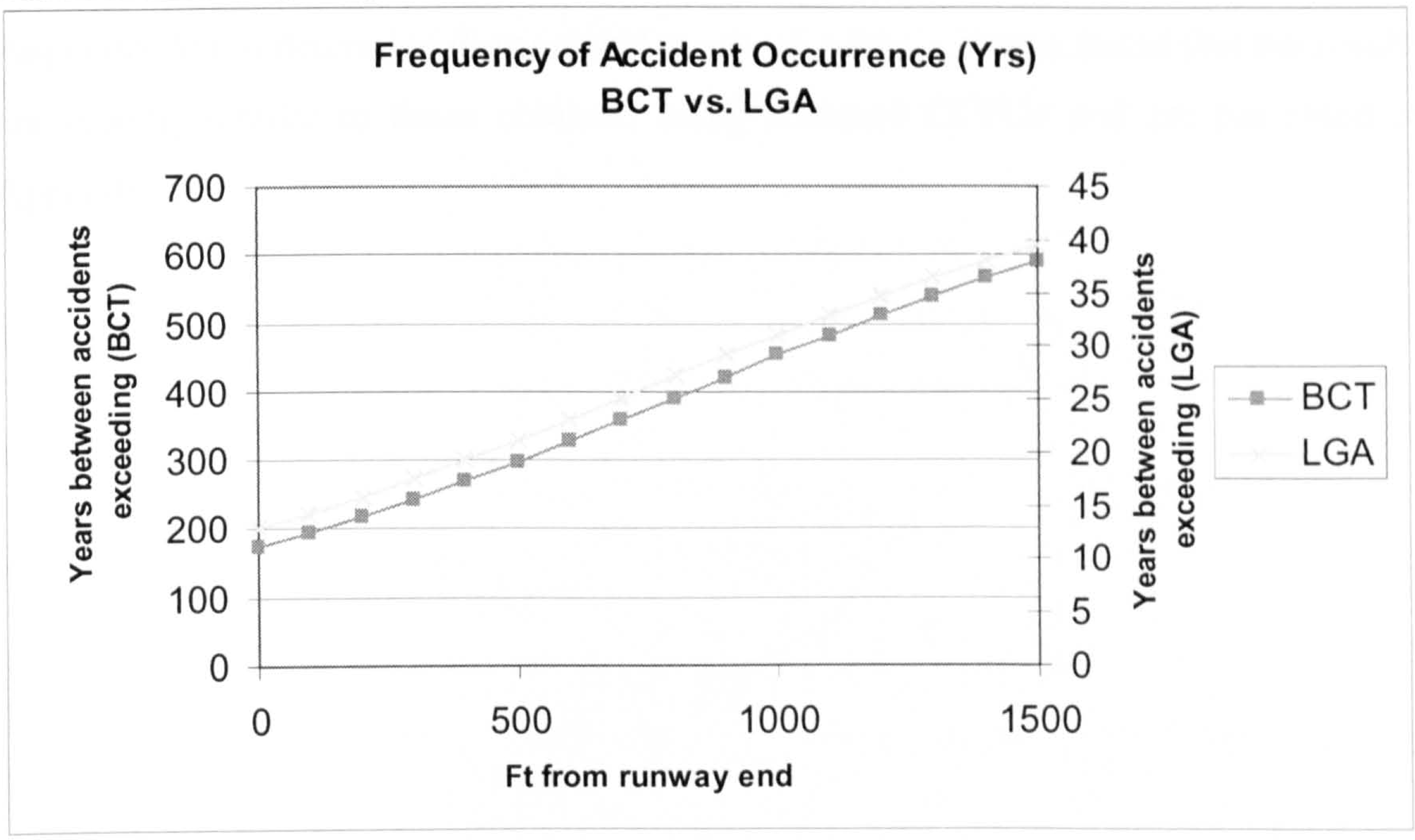


Figure 13.12 indicates the frequency of accidents that exceed a certain distance from the runway end. Given the traffic volumes of the airports, the frequency in terms of years between accident occurrences could be obtained, as shown in Figure 13.13.

Figure 13.13 Frequency of accident occurrence in years



An accident that challenges the ASA length of any runway end at LGA is estimated to occur once every 12.8 years. On the other hand, ASA length is only expected to be challenged once every 174.6 years at BCT. For an accident in excess of 500ft of the runway end, the frequencies are 21.2 years and 297.8 years for LGA and BCT respectively. The calculations assume constant 2005 traffic levels.

The impact of traffic levels on the frequency of accident occurrence is evident. The much higher accident frequency in terms of years between occurrences of busy airports may not be acceptable despite the low accident rates as measured by flight movements. By requiring larger ASAs for airports handling larger aircraft, which are likely to be the busier airports, the FAA and ICAO may have implicitly considered the effect of large traffic volumes. However, the current research allows an explicit quantification of the diverse influences of risk and facilitates the assessment of accident frequencies in terms of movements as well as years between occurrences.

ASA dimensional needs could therefore be adjusted with consideration for both criteria[14].

13.6 Setting the size of ASAs Using Normalised CCPDs

The research explored the use of CCPDs of normalised location distances (detailed in Appendix M) to determine dimensional needs of ASAs. It was found that the results are broadly similar to those obtained using standard CCPDs and are presented in Appendix N.

[14] Additional factors also play a role in determining the acceptable TLS and ASA dimensions, such as fatality and injury rates, which fall under the consequence modelling of airport risk assessment.

CHAPTER 14 CONCLUSIONS & IMPLICATIONS

The rules regarding the use, size and application of Airport Safety Areas do not meet the demands of safety management as stipulated by standards such as the ICAO's Safety Management System. The greatest flaw in current ASA policies lies in the mismatch between actual risks and the margin of safety provided. The current thesis set out to improve the effectiveness of Airport Safety Areas as a means of managing risks related to aircraft accidents near airports. This final chapter concludes the thesis by highlighting its key achievements, their significance and implications on the development of a more risk-based, flexible and effective strategy of risk mitigation by ASAs. The limitations of the work and avenues of further research are also discussed.

14.1 Research Outcome & Significance

The body of research is made up of several key elements. Their outcomes, significance and implications for future airport risk assessment and ASA policies are highlighted here.

14.1.1 Accident database

One of the principal outputs of the thesis is the comprehensive database of ASA-related accidents. The database is a significant achievement as its breadth and depth are unmatched by previous research efforts. Analysis of the database revealed important insights on the different types of accidents that implicate ASAs and demonstrated the importance of disaggregating the subsequent modelling by accident type.

The database not only contributes to the present thesis but could also be used in the future research of airport risk assessment, land-use planning as well as take-off, approach and landing operations. The unprecedented coverage and detail of the database would assist in areas as diverse as the development of improved flight procedures, airport approach procedures and pilot training.

14.1.2 Normal operations database

The collection of a vast database of normal flight parameters was crucial to quantifying and characterising accident risk factors as well as the development of accident frequency models. Not only does the normal operations database developed by this study cover a multitude of operational and meteorological parameters, it is also multi-dimensional, therefore allowing multivariate analysis to be performed. This has not been achieved in prior attempts to use normal operations data for risk assessment.

As with the accident database, the normal operations database's value is not restricted to the current thesis. It adds to the overall body of knowledge on flight risk exposure and opens significant opportunities for future research. It could be flexibly coupled with other landing and take-off datasets to assess the criticality of risk factors for events outside the scope of this work, e.g. incidents in addition to accidents. With ETMSC as the backbone of the database, it could easily be expanded to incorporate additional parameters as they become available.

14.1.3 Quantification of risk factor criticality

Using the accident and normal operations databases, the criticality of a series of risk factors was successfully quantified. The study quantitatively defined the magnitude and direction of the relationship between risk exposure and accident probability. The individual risk factors were characterised using different numerical procedures in order to provide an in-depth profile of each factor's effect on accident likelihood. A specific focus was placed on meteorological factors, which previous research has not been able to analyse. The use of a single coherent accident database for the analysis also allowed for sound comparisons to be made between risk factor characteristics.

The results and techniques developed to quantify accident risk factors are important steps forward in identifying factors that contribute most to accident risk and differentiating between them when considering ASA policies. Understanding the effect that different conditions have on accident risk plays a key role in reducing the current mismatch between actual risk and the margin of safety provided through ASAs. The odds ratios obtained from the bivariate and multivariate analyses of this thesis form a sound basis from which to review the relevance of factors considered in current ASA policies.

14.1.4 Accident frequency models

On the subject of risk assessment for third party risk near airports, Piers (1996) claimed that "[Accident] frequency modelling is relatively straightforward." Indeed, traditional models of accident occurrence only consider a handful of risk factors, principally aircraft size and engine type. The resultant risk models, therefore, have limited ability to discriminate between accident and incident-free flights, which contributes to the mismatch between risk exposure and safety margins. The current research made significant breakthroughs in terms of including more risk factors in accident frequency modelling. More than a dozen risk factors were used for predicting accident occurrence in addition to traditional ones. These include a range of meteorological as well as operational parameters. Moreover, the present study was able to conduct multivariate modelling, allowing multiple risk factors to be considered 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. This is of significant value to more accurate risk assessment and risk-sensitive ASA deployment.

The increased quantification of risks would allow better cost benefit analyses to be performed for a more rigorous justification of ASA-compliance costs and to evaluate alternative risk mitigation solutions. For example, where one runway end has insufficient ASA but the other has an excess of safety margin, the runway threshold could be shifted to provide equivalent safety margins at both ends, commensurate to their respective risk exposure. While the FAA has previously suggested similar alternatives to full Runway Safety Areas (FAA 1999a), such a robust tool for their justification and evaluation was not available.

The advocated models offer a data-driven process that minimises the role of expert judgement and subjectivity in risk assessment. They could be adopted gradually, starting by differentiating the risk exposure of individual airports and runways, followed by considering accident locations and adjusting the ASA requirements accordingly.

14.1.5 Risk assessment & ASA-sizing

The accident frequency models form part of the overall risk assessment methodology developed by the present research, which features a number of improvements compared to traditional approaches to airport risk assessment.

Firstly, the dynamic interactions between diverse sources of risk are explicitly accounted for throughout the risk assessment process. Not only are the risks of individual flights assessed according to their respective risk exposure levels, but the usage pattern of the runway concerned is also considered. This is necessary so that the final ASA dimensions reflect not only the risk exposure but also the operational characteristics of the airport. For example, high risk landings are of less concern for a runway used predominantly for take-offs. These operational considerations have not featured in previous risk assessments but are intrinsic elements of the technique developed.

Secondly, the proposed risk assessment methodology accounts for multiple dimensions of risk. Whereas the accident frequency models consider the frequency dimension of airport risk, accident locations are also incorporated through Complementary Cumulative Probability Distributions in the risk assessment process. ICAO and FAA ASA regulations may account for these separate aspects of risk implicitly but the current research does so explicitly and quantitatively.

Thirdly, the methodology developed offers a framework for assessing all risks that are implicated by ASAs in an integrated and systematic manner. Previous approaches to managing accident risk near airports compartmentalised the various risks and dealt with each using different methodologies and solutions. The approach used in the current research allows all relevant risks, including crash risks within the airport boundary as well as off-site third party risks, to be considered simultaneously. Integrated solutions that target an airport's entire profile of relevant risks could therefore be formulated.

The above advances together contribute to a more systematic and risk-sensitive approach to airport risk assessment, which is fundamental to reducing the mismatch between true risk levels and safety margin provision. This was demonstrated in two case studies. They showed that the methodology developed can be successfully applied to airports to quantify risk levels at individual runway ends, which form the basis for determining appropriate ASA dimensions. The case studies also illustrated the comprehensive approach of the proposed technique, in addition to its transparency and independence from qualitative judgements.

The proposed risk assessment methodology allows the length and width of ASAs to be tailored according to the residual risk at individual runways, such that the margin of safety provided meets the Target Level of Safety (TLS). This implies phasing out the current set of multiple ASAs under rigid and prescriptive regulations in favour of an integrated ASA around the runway that is sized in accordance with risk exposure. This would put an end to the compartmentalised and fragmented policies that govern the various ASAs and instil a coherent ASA that covers all risks related to aircraft landing and take-off accidents. In terms of ASA size, the case studies found that the TLS of 10^{-7} could be achieved and even exceeded relatively easily. However, the goal of attaining a TLS of 10^{-8} seems rather remote, especially if only on-airport ASAs were considered. The authorities may therefore consider a minimum level of safety of 10^{-7} for on-airport ASAs and one of 10^{-8} for off-site ASAs. This would also facilitate the transition towards an integrated ASA, given the present separation of responsibilities between aviation and land-use planning agencies.

The recommended ASA-sizing methodology also points to innovative solutions such as displacing runway thresholds and altering runway use patterns. For instance, the provision of adequate safety margins may be achieved by changing the operational characteristics of a runway. This could take the form of modifying its landing and take-off balance or limiting traffic of certain aircraft or operational types. The resulting change in risk exposure could be quantified with the proposed methodology to ensure that the residual risk does not exceed the risk budget afforded by the ASA available. This thesis hence offers a far more dynamic and flexible approach to risk control and management. Authorities should find that adopting the recommended methods would release the development potential of certain near-airport real-estate and unlock its revenue potential where it is condemned under current rules, and vice versa.

14.2 Recommendations on Safety Management

In formulating the TLS, it is suggested that consideration be given to the frequency of accidents in terms of the expected number of years between occurrences at a specific runway or airport. This is not a factor in current ASA policies but should play an increasing role in setting ASA dimensions, in tune with public tolerances of accident frequency.

For the full benefits of the improved accident frequency models and the proposed risk assessment methodology to be realised, a broader overhaul of the oversight and management of related risks is necessary. Responsibilities across relevant authorities should be re-examined and clearly delineated. The role of airports should also be more proactive, especially concerning third party risks. Aviation agencies ought to be given more power to influence decisions that affect flight and airport risk exposure, e.g. the land-use planning of airport surroundings.

It is also proposed that manuals such as ICAO Annex 14 be modified to reflect the pressures that airports face operationally, physically and financially. It should therefore provide guidance on appraising and prioritising alternative risk mitigation measures when the TLS could not be met through simple ASA provision. This would also stress the fact that ASAs are only one component of the risk management system and provide a more versatile approach to managing safety.

Finally, there is much room for improving the collection and recording of accident investigation data. A more complete, consistent, accurate and objective approach to data collection by the accident investigation bodies would greatly enhance the risk assessment process. A systematic recording of data irrespective of investigators' subjective judgement on relevance would yield a far greater pool of data than what is currently available. Not only does the increase in data points enlarge the scope for risk analysis, modelling and assessment, it also adds statistical significance and confidence to the entire exercise.

14.3 Research Limitations

While the advances of the present thesis clearly contribute to improving the assessment and management of risks at airports, the study naturally has its limitations too. The complex nature of aviation accidents means they are inherently difficult to predict. Although important breakthroughs have been made in improving the predictive power of accident frequency models, it is impossible to achieve perfect accuracy. The performance of the accident frequency models developed is especially constrained by the number of risk factors considered, which in turn is limited by the availability of normal operations data. The models presented in the thesis are therefore, at least theoretically, incapable of identifying accidents caused by factors completely independent from those used to calibrate the models. However, it is expected that cases that do not involve any of the operational and meteorological factors considered are relatively rare.

The second shortcoming of this research lies in the intrinsic uncertainties of accident data. The NTSB is the sole source of US accident data and the quality of this information is not always assured. Inconsistencies within accident reports and dockets cast doubt on the overall accuracy of the reporting system. It is also not possible to verify the data in the absence of an alternative data provider. This is another inherent difficulty in air accident research.

14.4 Further Research

Collecting normal operations data for parameters not covered in this study would help to expand the accident frequency models to cover factors such as runway and weight criticality. This is likely to improve the predictive performance of the models and enhance the accuracy of the risk assessment, leading to further reductions in the mismatch between real risks and safety margin provision. Airline flight data recorder information is especially relevant but the cooperation of airlines and industry bodies are prerequisites to realising its value to risk assessment. Corresponding accident data must also be available and compatible.

The accident location analysis should also be developed into a model that predicts accident sites based on pertinent factors. Understanding the dynamic relationship between longitudinal and lateral deviation, for example, may yield important results that would significantly affect the dimensions of ASAs. Vertical deviation should also be modelled such that the size and shape of three-dimensional safety zones around runways could be determined. Finally, accident consequences in terms of fatalities, injuries and financial damage, should also be modelled to distinguish relatively innocuous occurrences from grave accidents. Although detailed location and consequence modelling are beyond the scope of the current thesis, they are necessary for the complete assessment of ASAs.

Some of these concerns are currently undertaken by a research project sponsored by the FAA. The work covered in this thesis forms a core part of this project, which will potentially play a part in improving FAA regulations on Runway Safety Areas. The achievements and significance of this thesis are therefore recognised by the industry and will contribute to improvements in airport safety management.

REFERENCES

AAIB, 1990. Report on the accident to Boeing 737-400 - G-OBME near Kegworth, Leicestershire on 8 January 1989. Aircraft Accident Report No: 4/90 (EW/C1095). Air Accidents Investigation Branch, UK

Aberdeen News, 2005. Judge rules for developer in suit against city. Aberdeen News. 24/06/05

Aberdeen News, 2006. Brookings studying its airport options. Aberdeen News. 22/01/06

ACI-NA, 2005. Airports Council International – North America Spring Operational & Technical Affairs Committee Meeting, San Diego, May 15-18

Aho, E., 1995. Third party risk around Vantaa airport of Helsinki. IVO International Ltd. for Finnish Civil Aviation Authority

Airports World, 2005. Running out of runway? Airports of the World. November-December

Airports World, 2006. Safety Regulation Group Aerodrome Standards. Letters, Airports of the World, January-February

Ale, B., Smith, E., Pitblado, R., undated. Safety around airports – developments in the 1990s and future directions. Papers for IBC conference

Ale, B., Piers, M., 1999. Dealing with third party risk around a major airport. 9th Conference on Risk Analysis: Facing the new millennium, Rotterdam. p.59-63

Ale, B., Piers, M., 2000a. The assessment and management of third party risk around a major airport. Journal of Hazardous Materials. Vol. 71, p.1-16

Ale, B., Piers, M., 2000b. The use of risk information for the development of a safety policy around airports. Safety Engineering and Risk Analysis (SERA) technical sessions. November, Orlando. ASME, 2000, Vol. 10, p.51-58

Ale, B., Bellamy, L., Roelen, A., Cooke, R., Goossens, L., Smith, E., 2005. Development of a casual model for air transport safety. Proceedings of a causal model for air transport safety. Proceedings of 2005 ASME International Mechanical Engineering Congress and Exposition. 5-11 November, Orlando, p.107-116

Alexander, A., Clark, R., Miller, C., Rigdon, L., 1996. A probabilistic aircraft crash methodology. International System Safety Conference, Albuquerque

Andrews, J., Moss, T., 1993. Reliability and risk assessment. Longman Scientific and Technical, Harlow

Ash, A., Schwartz, M. 1999. R^2: a useful measure of model performance when predicting a dichotomous outcome. Statistics in Medicine, February 28; 18(4), p.375-384

Ash, J., 2005. Witham airport critics charge deceit. Palm Beach Post. 07/07/05

Ashford, N., Wright, P., 1992. Airport Engineering. 3rd edition. John Wiley & Sons Inc., New York

Ashford, R., 1998. A study of fatal approach and landing accidents worldwide, 1980-1996. Flight Safety Digest. Vol. February-March 1998, Flight Safety Foundation., VA, USA

Avweb, 2005. Planning versus fighting. www.avweb.com/news/columns/190294-1.html, accessed 08/08/05

BBC, 2006a. Many dead in Kentucky plane crash. British Broadcasting Company News. 28 August

BBC, 2006b. Boy dies as jet skids off runway. British Broadcasting Company News. 9 December

Benedetto, A., 2002. A decision support system for the safety of airport runways: the case of heavy rainstorms. Transportation Research Part A, Vol. 36, p.665-682

Bienz, A., 2004. Analysis of the risks of the population due to airplane crashes around Zurich airport. Probabilistic Safety Assessment and Management. PSAM7-ESREL 2004 Conference. June 14-18, Berlin. Springer, London

Boeing, 1992. Takeoff safety training aid July-September 1992. Boeing, Seattle

Boeing, 2005. Statistical summary of commercial jet airplane accidents. Worldwide operations 1959-2005. Boeing, Seattle

Borque, A., Sanz, G., Allepuz, C., Plaza, L., Gil, P., Rioja, L., 2001. The use of neural networks and logistic regression analysis for predicting pathological stage in men undergoing radical prostatectomy: a population based study. Journal of Urology. November, Vol. 166, No. 5, p.1672-1678

Brady, S., Hillestad, R., 1995. Modelling the external risks of airports for policy analysis. RAND, Santa Monica

Brooker, P., 2006. Air traffic management accident risk. Part 1: The limits of realistic modelling. Safety Science. Vol. 44, p.419-450

Button, K., Drexler, J., 2006. Are measures of air-misses a useful guide to air transport safety policy? Journal of Air Transport Management. Vol. 12, p.168-174

CAA, 1998. Risks from aeroplanes overrunning aerodrome runways. Edition one. Civil Aviation Authority, London

CAA, 2000. Extract of Aviation safety review 1990-1999. CAP701. Civil Aviation Authority, London

CAA, 2003. Flight data monitoring. CAP 739. Safety Regulation Group. Civil Aviation Authority, London

CAA, 2006. Guidance on the conduct of hazard identification. Safety Regulation Group. Civil Aviation Authority, London

Carey, B., 2004a. Rare plants prompt changes for runway. Berkshire Eagle. 20/10/04

Carey, B., 2004.b Accord reached to protect plants in runways' path. Berkshire Eagle. 05/11/04

Carroll, K., 2005. Crash sparks airport debate. NorthJersey.com 04/03/05

CAST, 1999. Approach and Landing Joint Safety Analysis Team Results and Analysis. Commercial Aviation Safety Team

Caves, R., 1996. Control of risk near airports. Built Environment. Vol.22, No.3, p.223-233

Como, J., 2005. Runway project advances. Indiana Gazette. 22/07/05

Couwenberg, M., 1994. Determination of the statistical accident location model from worldwide historical accident location data. NLR-TR-94601L, Dutch National Aerospace Laboratory, Amsterdam

Cowell, P., Gerrard, R., Paterson, D., 1997. A crash location model for use in the vicinity of airports. Report No. R&D 9705. National Air Traffic Services. London

Cowell, P., Foot, P., Gerrard, R., Kent, D., mason, S., Rivoire, A., 2000. A method for calculating individual risk due to aircraft accidents near airports. R&D Report 0007. National Air Traffic Services. London

Croft, J., 2004. EMAS for the masses. Airport Magazine. January/February 2004

David, R., 1990. Location of aircraft accidents/incidents relative to runways. DOT/FAA/AOV 90-1. Office of Safety Oversight, Federal Aviation Administration, Washington DC

Davies, P., Quinn, D., 2004a. Airport public safety zones: part 1 – risk model derivation. Probabilistic Safety Assessment and Management PSAM 7-ESREL 2004 Conference. June 14-18, Berlin, Germany. Springers, London

Davies, P., Quinn, D., 2004b. Airport public safety zones: part 2 – risk model application. Probabilistic Safety Assessment and Management PSAM 7-ESREL 2004 Conference. June 14-18, Berlin, Germany. Springers, London

Davies, P., Smith, E., Purdy, G., 1994. Risk assessment – second runway technical appendix. DNV Technica. PAD/glc/C3982-5.007. August, revision 1

DeGroh, B., 2006. Rink or Runway? Air Line Pilot. November/December, p.14-19. Air Line Pilot Association, Washington, DC

DfT, 1997. Third party risk near airports and Public Safety Zone policy. Department for Transport, London

DfT, 2002.Control of development in airport Public Safety Zones. Circular 1/2002 Department for Transport, London

Dietz, D., Bordy, K., 2003. The missing element in airport compatibility planning. Mead & Hunt Inc. www.meadhunt.com, accessed 28/03/06

DOE, 1996. DOE standard: Accident analysis for aircraft crash into hazardous facilities. DOE-STD-3014-96 . Department of Energy, Washington, DC

DOT, 1979. Development of a systems risk methodology for single and multi-modal transportation system. Department of Transport, Washington, DC

DOT, 2006. Observation on FAA's oversight of aviation safety. Statement of Todd. J. Zinser, Acting Inspector General, US Department of Transportation before the Committee on Transport and Infrastructure Subcommittee on Aviation, US House of Representatives. 20/09/06

Duh, M., Walker, A., Pagano, M., Kronlund, K., 1998. Prediction and cross-validation of neural networks versus logistic regression using hepatic disorder as an example. American Journal of Epidemiology, February 15:147(4), p.407-413

Eddowes, M. 1994a. Risk of ground fatalities from aircraft crash accidents at Manchester airport. Proof of evidence in Manchester Airport Second Runway Public Inquiry

Eddowes, M. 1994b. Supplement on third party risks from operations at Manchester airport. Supplementary Proof of Evidence in Manchester Airport Second Runway Public Inquiry

Eddowes, M., Hancox, J., MacInnes, A., 2001. Final report on the risk analysis in support of aerodrome design rules. Report for the Norwegian Civil Aviation Authority. AEA Technologies plc, Warrington, UK

Eftekhar, B., Mohammad, K., Ardebili, H., Ghodsi, M., Ketabaci, E., 2005. Comparison of artificial neural network and logistic regression modes for prediction of mortality in head trauma based on initial clinical data. BMC Medical Informatics and Decision making. February, 5:3

Enders, J., Dodd, R., Tarrel, R., Khatwa, R., Roelen, A., Karwal, A., 1996. Airport Safety: A study of accidents and available approach-and-landing aids. Flight Safety Digest, March. Flight Safety Foundation, VA, USA

Eisenhut, D., 1973. Reactor siting in the vicinity of airfields. Transaction of the American Nuclear Society. Vol. 16209

Esler, D., 2006. Why your community needs its airport. Business and Commercial Aviation. Vol. 99, Iss.2, p.46

ETSC, 1999a. Safety in and around airports. European Transport Safety Council, Brussels

ETSC, 1999b. Safety in and around airports: need for EU action. Press Release. European Transport Safety Council, Brussels

Eurocontrol, 2005. Third party risk. www.eurocontrol.int, accessed 21/07/05

Evans, A., Foot, P., Mason, S., Parker, I., Slater, K., 1997. Third party risk near airports and public safety zone policy. R&D Report 9636. National Air Traffic Services, London

FAA, 1989. Airport Design. Advisory circular 150/5300-13. Federal Aviation Administration, Washington, DC

FAA, 1996. Discussion paper on Runway Protection Zones for airports. Federal Aviation Administration. www2.faa.gov/arp/ace/rpz.htm, accessed 31/10/03

FAA, 1997. Aviation safety data accessibility study. Office of System Safety, Federal Aviation Administration, Washington, DC

FAA, 1999a. Runway Safety Area Program. Order 5200.8. Federal Aviation Administration, Washington DC

FAA, 1999b. Runway Protection Zone and airport object clearing policy. Policy and procedures memorandum. Great Lakes Region, Federal Aviation Administration, Des Plaines

FAA, 2001. Airport safety, Runway Safety Area fact sheets. Federal Aviation Administration, Washington DC

FAA, 2004a. Airport Design. Advisory circular 150/5300-13, including Change 8. 29/09/89 Federal Aviation Administration, Washington DC

FAA, 2004b. Financial feasibility and equivalency of RSA improvements and EMAS. Order 5200.9. Federal Aviation Administration, Washington DC

FAA, 2005. Safety oversight of an air carrier industry in transition. Memorandum report AV-2005-062. 03/06/05

FAA, 2006a. FAA Aviation Forecasts FY 2006-2017. Federal Aviation Administration, Washington DC

FAA, 2006b. Landing performance assessments at time of arrival (turbojets). Safety Alert For Operators. Flight Standards Service, 8/31/06, Federal Aviation Administration, Washington DC

FAA 2006c. Personal communication with Ken Wilkes of Aviation System Standards Instrument Approach Procedure Branch, Federal Aviation Administration, Washington DC in April

FAA, 2007. Introduction, 7th Instrument Approach Procedure. US Terminal procedure Publications. Federal Aviation Administration, Washington DC http://avn.faa.gov/content/naco/online/pdf_files/7th_iap_intro.pdf, accessed 27/02/07

Fiorino, F., 2005. Safety in numbers. Aviation Week & Space Technology. 22-29 August

Fitzgerald, P., 1998. The Sydney Airport Fiasco. Hale & Iremonger, Alexandria, NSW, Australia

Freeman, R., Eagle, K., Bates, E., Werns, S., Kline-Rogers, E., Karavite, D., Moscucci, M., 2002. Comparison of artificial neural networks with logistic regression in prediction of in-hospital death after percutaneous transluminal coronary angioplasty. American Heart Journal, Vol., 140, p.511-520

FSF, 1999. Killers in aviation: FSF task force presents facts about approach-and-landing and controlled-flight-into-terrain accidents. Flight Safety Digest. November-December 1998, January-February 1999. Flight Safety Foundation, VA, USA

FSF, 2000. Foundation task force tool enhances crew awareness of approach-and-landing risks. Flight Safety Foundation news, 8 February. Flight Safety Foundation , VA, USA

FSF, 2003. Safety challenges in the second century of flight are focus of joint meeting in Washington DC. Flight Safety Foundation news. Flight Safety Foundation, VA, USA

GAASR, 1997. Aerodrome Licensing requirements; processes in GAASR states and the potential for harmonisation activity. Working paper 013. Group of Aerodrome Safety Regulators

GAIN, 2004. Role of analytical tools in airline flight safety management systems. 2nd edition. Global Aviation Information Network Working Group B. September

GAO, 2005a. FAA's safety oversight system is effective but could benefit from better evaluation of its programs' performance. Report GAO-66-266T. U.S. Government Accountability Office, Washington, DC

GAO, 2005b. System safety approach needs further integration into FAA's oversight of airlines. Report GAP-05-726. U.S. Government Accountability Office, Washington, DC

Garbell, M., 1988. Airport accident potential and safety areas. M.G.G. Consultants, Inc. Society of Automotive Engineers, Inc.

Garson, G., 2007. Logistic Regression. Statistical notes from quantitative research in public administration, North Carolina State University. www2.chass.ncsu.edu/garson/pa765/logistic.htm, accessed 22/01/07

GASR, undated. Guidelines to a systematic management of safety on aerodromes. Working paper 093. Group of Aerodrome Safety Regulators http://www.airports.unina.it/WP%20093.pdf, accessed 26/02/07

GASR, 1998. Harmonisation strategy for regulation and licensing of aerodromes. Working Paper 034. Group of Aerodrome Safety Regulators

GASR, 1999. Requirements for a systematic management of safety by aerodrome licensees. Working paper 046. Group of Aerodrome Safety Regulators

GASR, 2003. The Aerodrome Reference Code – method for height zoning, proposal to change, selection and legal compliance. Working Paper 082. Group of Aerodrome Safety Regulators

Ghosh, A., Sagar, B., 2002. Assessment of aircraft crash frequency during take-off and landing at an airport. 6th Probabilistic Safety Assessment and Management International Conference. June, San Juan. Elsevier, Oxford

Giaquinto, T., 2006. Personal communication with Regional Director of EMAS manufacturer 02/10/06

Gilkeson, F., 2005. Airport receives $1 million federal grant. Thepilot.com. www.thepilot.com/news/030405airport.html, accessed 13/09/05

Glaskin, M., 2006. Airport Organisation. The Engineer Online. www.theengineer.co.uk, accessed 19/10/06

Goossens, L., Hale, A., 1997. Risk assessment and accident analysis. Safety Science. Vol. 26, No. 1/2, p.21-23

Gouweleeuw, J., 1995. An accident location model for regional airports. Report No. CR 95158. Dutch National Aerospace Laboratory NLR, Amsterdam

Hagy, H., Marthinsen, H., 1987. Compilations of accidents/incidents involving runway overruns/undershoots/veeroffs. ALPA Accident Investigation Department. Air Line Pilot Association, Washington DC

Hale, A., Mulder, J., van Passen. J., 1999. Modelling safety management and safety measures for risk assessment at airports. 9th Conference on Risk Analysis: Facing the new millennium, Rotterdam. Delft University Press, Delft

Hale, A. 2001. Regulating airport safety: the case of Schiphol. Safety Science. Vol.37, p.127-149

Hale, A., 2002. Risk contours and risk management criteria for safety at major airports, with particular reference to the case of Schiphol. Safety Science. Vol. 40, p.299-323

Hale, A., Ale, B., Goossens, L., Bellamy, L., Mud, M., Papazoglou, I., Bloemhoff, A., Baksteen, H., Post, H., Oh, J., 2006. Modeling accidents for prioritising prevention. Proceedings of the 8th International Conference on Probabilistic Safety Assessment and Management. 14-18 May, New Orleans

Hammer, D., 2005. Jury awards local widow $2.1 million. Chicago Sun-Times. 04/06/05

Harris, R., 2005. Stuart council asks county to remove part of Witham runway. Palm Beach post. 13/09/05

Hayes, P., 2003. The challenge of air safety. August. Airclaims, London

Heald, D., 2005. The EMAS option. Airports International. Vol. 38, No.7, p.50-51

Helmreich, R., Klinect, J., Wilhelm, J., 1999. Models of threat, error, and CRM in flight operations. Proceedings of the 10th International Symposium on Aviation Psychology, Columbus, p.677

Hillestad,R. et al., 1993. Airport growth and safety - a study of the external risks of Schipol airport and possible safety-enhancement measures. EAC-RAND. Report No. MR-228-EAC/VW Santa Monica, CA

Hing, J., Stamatiadis, N., Aultman-Hall, L., 2003. Evaluating the impact of passengers on the safety of older drivers. Journal of Safety Research. Vol. 34, p. 343-351

Hornyik, K., Grund, J.,1974. Evaluation of air traffic hazards at nuclear plants. Nuclear Technology. Vol. 23, p.23

Hosmer, D., Lemeshow, S., 2000. Applied logistic regression. John Wiley & Sons, Hoboken

Hutcheson, G., Sofroniou, N., 1999. The multivariate social scientist. Sage, London

IATA, undated. Airport & Obstacle Database. International Air Transport Association. www.aodb.iata.org, accessed 26/02/07

IATA, 2005. IATA Passenger and Freight Forecast 2005-2009. International Air Transport Association, Montreal

IATA, 2006. Annual Report 2006. International Air Transport Association, Montreal

ICAO, 1980. Manual on the use of the collision risk model (CRM) for ILS operations. 1st edition. Doc 9274-AN/904. International Civil Aviation Organisation, Montreal

ICAO, 1999. Aerodromes. International Standards and Recommended Practices. Annex 14 to the Convention on International Civil Aviation. Vol. 1 Aerodrome Design and Operations. Third edition. International Civil Aviation Organisation, Montreal

ICAO 2000. Supplement to Annex 14 to the Convention on International Civil Aviation. Vol. 1 Aerodrome Design and Operations. Third edition. International Civil Aviation Organisation, Montreal

ICAO, 2002a. Amendment No. 1 to the supplement to Annex 14 to the Convention on International Civil Aviation. Vol. 1 Aerodrome Design and Operations. Third edition. International Civil Aviation Organisation, Montreal

ICAO, 2002b. Safety Management System. Aerodrome Safety Workshop, Almaty, Kazakhstan, November. International Civil Aviation Organisation

ICAO, 2005. Runway Safety Areas Improvements. Second meeting of North American, Central American and Caribbean Directors of Civil Aviation. Tegucigalpa, Honduras. 11-14 October. International Civil Aviation Organisation North American, Central American and Caribbean Office, Mexico City

ICAO, 2006. Safety Management Manual. First edition. Doc. 9859. International Civil Aviation Organisation, Montreal

Irvine, A., 1992. Kuala Lumpur international airport risk analysis. Four Elements Limited. Report No. C2315

Jerris, E., Gerafola, J., Dagen, H., Brady, F., 1963. Analysis of safety aspects of aircraft landing operations. Final report 238-01-3-392. ARINC Research Corporation, Annapolis

Jowett, J., Cowell, C., 1991. A study into the distribution of near airfield accidents (for fixed wing aircraft of mass greater than 2.3Te). Report No. AEA RS 5168. AEA Reactor Services, Safety and Performance Division, Atomic Energy Authority, UK

Juneau Empire, 2005. Assembly tables wetlands transfer. Northwest Digest. Juneau Empire 14/06/05

KATV, 2005. LR airport says it will not appeal $2.1 million judgement. KATV News. 03/09/05

Kent, D., 1998. Third party risk in the vicinity of Southampton airport. R&D Report 9848. National Air Traffic Services, London

Kent, D. and Mason, S., 1999a. Revised third party risk calculations in the vicinity of Farnborough aerodrome. R&D Report 9935. National Air Traffic Services, London

Kent, D. and Mason, S., 1999b. Third party risk in the vicinity of Guernsey airport. R&D Report 9934. National Air Traffic Services, London

Kent, D. and Mason, S., 1999c. Third party risk in the vicinity of Jersey airport. R&D Report 9933. National Air Traffic Services, London

Kent, D., Mason, S., 2001. Individual risk contours as a method for determining PSZs at UK airports. R&D Report 0101. National Air Traffic Services, London

Khatwa, R., Roelen, A., Karwal, A., Enders, J., Dodd, R., Tarrel, R, 1996. An evaluation of approach landing factors influencing airport safety. NLR-TP-96221U. Dutch National Aerospace Laboratory NLR, Amsterdam

Khatwa, R., Roelen, 1997. Controlled flight into terrain (CFIT) accidents of air taxi, regional and major operators. NLR-TP-97270. Dutch National Aerospace Laboratory NLR, Amsterdam

Khatwa, R., Helmreich, R., 1998. Analysis of critical factors during approach and landing in accidents and normal flight. Final report version 2.0. Flight Safety Digest. Vol. November 1998-February 1999. Flight Safety Foundation, VA, USA

Kimura, C., Bennett, C., 1993. A method for determining risk to ground facilities from aircraft accidents. Paper prepared for the Probabilistic Safety Assessment Meeting PSAM-II, March 20-24 1994, San Diego

Kimura, C., Bennett, C., Sandquist, G., Smith, S., 1995. Aircraft accident data development for aircraft risk evaluation to ground facilities through the use of G.I.S. ASME Joint Pressure Vessels & Piping Conference, Honolulu Vol. 256, p.493-513

Kimura, C., 1997. Aircraft crash frequency analysis of the Lawrence Livermore National Laboratory (LLNL). Lawrence Livermore National Laboratory, Livermore

Kimura, C., Sanzo, D., Sharirli, M., 2004. An approach to estimate the localized effects of an aircraft crash on a facility. UCRL-Conf-203793. Lawrence Livermore National Laboratory, Livermore

Kirkland, I., 2001a. The risk assessment of aircraft runway overruns accidents and incidents. Doctoral thesis. Loughborough University, Loughborough, UK

Kirkland, I., 2001b. Runway overrun risk assessment and consequence analysis. Grant review report GR/M20983/01. UK Engineering and Physical Sciences Research Council.

Kirkland, I., Caves, R., Pitfield, D., 2003a. An improved methodology for assessing risk in aircraft operations at airports, applied to runway overruns. Safety Science. Vol. 42, p.891-905

Kirkland, I. Caves, R., Pitfield, D., 2003b. The normalisation of aircraft overrun accident data. Journal of Air Transport Management.Vol.9, p.333-341

Klinect, J., Wilhelm, J., Helmreich, R., 1999. Threat and error management: Data from line operations safety audits. Proceedings of the 10th International Symposium on Aviation Psychology, Columbus, p.683

Lautenberg, 2005. Lautenberg runway safety law will require improvements at over 2080 major airport runways. Press release 09/12/05 Lautenberg Senate Office, Washington DC

Lee, W., 2006. Risk assessment modeling in aviation safety management. Journal of Air Transport Management. Vol. 12, p.267-273

Leveson, N., 2004. A new model for engineering safety systems. Safety Science. Vol. 42, p.237-270

Li, G., Baker, S., Grabowski, J., Rebok, G., 2001. Factors associated with pilot error in aviation crashes. Aviation, Space, and Environmental Medicine. Vol. 72, p.52-58

Loog, M., 1995. Individual risk around Helsinki Vantaa airport - verification contours. Unpublished contours provided to Civil Aviation Authority of Finland. Dutch National Aerospace Laboratory NLR, Amsterdam

Lowrance, W., 1976. Of Acceptable Risk. William Kaufmann Inc., Los Altos, CA, USA

Marchi, R. 2006. Letter to the Federal Aviation Administration regarding the announcement of policy for landing performance assessments after departure for all turbojet operators. July. Airports Council International – North America, Washington, DC

Maurino, D., 1997. Safety Philosophy. ICAO Journal Vol. 52. International Civil Aviation Organisation, Montreal

McCartney, S., 2005. A common runway hazard: Overrun. The Wall Street Journal. 16/08/05

McGee, D., 2005. Compromise sought in issue over development land. Bristol Herald Courier. 28/01/05

McGillivary, B., 2005. South Airport is safe: Facility will shift runway to north. Traverse City Record-Eagle. 17/03/05

McShane, B., 2005. LI aviation has its ups and downs. Newsday.com 10/02/05

Menard, S., 2001. Applied logistic regression analysis. 2nd edition. Sage University Papers Series on Quantitative Applications in the Social Sciences, 07-103. Sage, Thousand Oaks

Miami Herald, 2006. Latest runway plan could save money. Miami Herald. 08/02/06

Monk, K., 1981. A review of aircraft accidents between 1971 and 1977 relating to public safety zones. Report No. DORA Communication 8130. Civil Aviation Authority, London

Morier, Y., 2005. The future of aviation safety regulation in a changing environment: overview to the thematic workshops. The Europe-US International Aviation Safety Conference, June, Cologne

Muir, H. & Thomas, L., 2004. Passenger safety and very large transportation aircraft. Aircraft Engineering and Aerospace Technology, Vol. 76, No. 5, p.479-786

Munford, J., 2005. Appraisals needed for TDK extension. The Citizen Online. 03/11/05 www.thecitizen.com/index.php?q=node/820, accessed 26/02/07

Myers, R., 1990. Classical and modern regression with applications. 2nd edition. Duxbury, Boston

Nagelkerke, N., Smits, J., Le Cessie, S., van Houwelingen, H., 2005. Testing the goodness-of-fit of the logistic regression model in case-control studies using sample reweighting. Statistics in Medicine. Vol. 24, p.121-130

NOAA, 2004. Personal communication with William Brown of the National Oceanic and Atmospheric Administration, Washington DC in July

NRC, 1981. Aircraft hazards. Section 3.5.1.6, standard review plan. Report No. NUREG-0800. Nuclear Regulatory Commission, Washington, DC

NTSB, 1988. Aircraft Accident Docket for occurrence at Wheeling, IL on 01/02/88. National Transportation Safety Board, Washington, DC

NTSB, 1990. Aircraft Accident Report. NTSB/AAR-90/06. National Transportation Safety Board, Washington, DC

NTSB, 1991. Aircraft Accident Report. NTSB/AAR-91-08. National Transportation Safety Board, Washington, DC

NTSB, 2001. Aircraft Accident Report. NTSB/AAR-01-02. National Transportation Safety Board, Washington, DC

NTSB, 2003. Safety recommendation A-03-11, -12. National Transportation Safety Board, Washington, DC

NTSB, 2005. Risk factors associated with weather-related general aviation accidents. Safety Study NTSB/SS/05/01. National Transportation Safety Board, Washington, DC

NTSB, 2006a. Annual review of aircraft accident data. US general aviation. Calendar year 2001. National Transportation Safety Board, Washington, DC

NTSB, 2006b. Annual review of aircraft accident data. US air carrier operations. Calendar year 2001. NTSB/ARC-06/01 PB 2006-106641. National Transportation Safety Board, Washington, DC

NZALPA, 2004. Runway End Safety Area. New Zealand Air Line Pilots' Association. www.nzalpa.org.nz/Technical%203.htm, accessed 22/10/04

NZCAA, 2000. Runway End Safety Area. Terms of reference for CAA Industry rules advisory group. Civil Aviation Authority of New Zealand, Petone

Ohno-Machado, L., Rowland, T., 1999. Neural network applications in physical medicine and rehabilitation. Vol. 78, p.392-398

Palm Beach Post, 2005a. Close runway extension. Palm Beach Post editorial 31/07/05

Palm Beach Post, 2005b. A way to move runway. Palm Beach Post editorial 22/09/05

Pampel, F., 2000. Logistic regression: a primer. Sage University Papers Series on Quantitative Applications in the Social Sciences, 07-132. Sage, Thousand Oaks

Parry, W., 2005. Teterboro neighbors: We told you so. Newsday, NJ, USA www.newsday.com, accessed 08/02/2005

Phillips, D., 1987. Criteria for the rapid assessment of the aircraft crash rate onto major hazards installations according to their location. Report No. SRD R435. Safety and Reliability Directorate, Atomic Energy Authority, UK

Piers, M., Loog, M., Giesberts, M., Moek, G., Couwenberg, M., Smeets, M., 1993. 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

Piers, M., 1994. The development and application of a method for the assessment of third party risk due to aircraft accidents in the vicinity of airports. 19th International Council of Aeronautical Sciences Congress, Anaheim September ICAS proceedings. ICAS, Vol. 19, p.507-518

Piers, M., 1996. 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, 22-23 May, Utrecht

Piers, M., 1998a. Methods and models for the assessment of third party risk due to aircraft accidents in the vicinity of airports and their implications for societal risk. Technology Risk and Society. Vol. 12, p.166-204

Piers, M., 1998b. Models for the assessment of third party risk due to aircraft accidents in the vicinity of airports. 4th International Conference on Probabilistic Safety Assessment and management. September, New York. Springer. Vol. 3, Pt. 4, p.1547-1553

Piers, M., Ale, B., 2000. Policy options for managing societal risk around Schiphol. CR-2000-84/RIVM 610066011 Dutch National Aerospace Laboratory NLR, Amsterdam

Pikaar, A., Piers, M., Ale, B., 2000. External risk around airports. A model update. NLR-TP-2000-400. Dutch National Aerospace Laboratory NLR, Amsterdam

Post, J., Kooi, E., Weijts, J., 2006. Societal risk around Amsterdam airport Schiphol. Proceedings of the 8th International Conference on Probabilistic Safety Assessment and Management. May 14-18, New Orleans

Prassinos, P., Kimura, C., 1998. Air crash assessment of US nuclear power plant sites using the NRC methodology. UCRL-JC-128664. Lawrence Livermore National Laboratory, Livermore

Purdy, G., 1994. Manchester airport plc, proposed second runway, rebuttal of evidence, third party risk. DNV Technica. Report No. MA 1045

Raghavan, S., Rhoades, D., 2005. Revisiting the relationship between profitability and air carrier safety in the US airline industry. Journal of Air Transport Management. Vol. 11, p.283-290

Reason, J., 1990. Human error. Cambridge University Press, Cambridge

Reason, J., 1997. Managing the risk of organizational accidents. Ashgate, Aldershot

Roberts, T., 1987. A method for the site-specific assessment of aircraft crash hazards. Report No. SRD 9345. Safety and Reliability Directorate, Atomic Energy Authority, UK

Roelen, A., Bellamy, L., Hale, A., Molemaker, R., van Passen, M., 2000. Feasibility of the development of a causal model for the assessment of third party risk around airports. Part 1: Main Report. NLR-CR-2000-189-PT-1. Dutch National Aerospace Laboratory NLR, Amsterdam

Roelen, A., Wever, R., Hale, A., Goossens, L., Cooke, R., Lopuhaa, R., Simons, M., Valk, P., 2002. Causal modelling of air safety. Demonstration model. NLR-CR-2002-662. Dutch National Aerospace Laboratory NLR, Amsterdam

Roelen, A., Wever, R., Hale, A., Goossens, L., Cooke, R., Lopuhaa, R., Simons, M., Valk, P., 2004. Causal modelling using Bayesian belief nets for integrated safety at airports. Risk Decision and Policy. Vol. 9, No. 3, p.207-222

Rose, A., 2004. "Free lessons" in aviation safety. Aircraft Engineering and Aerospace Technology. Vol. 76, No. 5, p.467-471

Rose, A., 2005. Aviation: measuring safety and controlling risk. Measurement and Control. Vol. 38, Pt. 8, p.239-242

Rosero, J., 2005. The hero of Teterboro. The Hudson Reporter, 13 February

Salinero, M., 2005. Airport to clear wetlands it built. The Tampa Tribune. 25/09/05

Samples, E., 2005. Ex-Martin commissioner apologizes for runway vote. Palm Beach Post. 09/09/05

SDCRAA, undated. Policy statement 8.30. San Diego County Regional Airport Authority, San Diego

SDCRAA, 2004. Airport land use compatibility plan. San Diego International Airport. San Diego County Regional Airport Authority, San Diego

Sherman, A., 2005. Commission can't agree on hotel plan. The Miami Herald. 06/12/06

Simmie, S., McGran, K., Porter, C., 2005. Pearson disaster was avoidable. The Toronto Star, 2 October

Simmons, J., Forrest, J., 2005. United States aviation safety data: uses and issues related to sanctions and confidentiality. Journal of Air Law and Commerce. Vol. 70, Pt. 1, p.83-114

Slater, K., 1993. Method for estimating risk posed to UK sites by civil aircraft accidents. Report No. CS Report 9345. Civil Aviation Authority-National Air Traffic Services, London

Smith, R., 1983. Methodology for calculation of the probability of crash of an aircraft into structures in weapon storage areas. Report No. SAND82-2409. Sandia National Laboratories, Albuquerque

Smith, E., Spouge, J., 1990. Risk analysis of aircraft impacts at Schiphol airport - final report. Technica. Report No. C1884/EJS/ib

Smith, E., 1991a. Extension to risk analysis of aircraft impacts at Schiphol airport - interim report. Technica. Report No. C1884/EJS/ib

Smith, E. 1991b. A technique for analysing the risks of aircraft crashes in the vicinity of an airport. Spring Conference of the Safety and Reliability Society on Air Transport Safety.

Smith, E. 1995. Risks to third parties in the vicinity of airports. DNV Technica. Royal Aeronautical Society Conference, September 1995

Smith, E., 2000. Risk assessment and airport development. Airport 2000. Trends for the new millennium. Sovereign Publications, London

Solomon, K., Kenneth, A., 1975. Estimate of the probability that an aircraft will impact the PVINGS. NUS Corporation. Report No. NUS-1416

Spriggs, J., 2002. Airport risk assessment: examples, models and mitigations. 10th Symposium on Safety Critical Systems, Southampton

Stamatiadis, N., Deacon, J., 1995. Trends in highway safety: effects of an aging population on accident propensity. Accident Analysis and Prevention. Vol. 27, No. 4, p.443-459

Stamatiadis, N., Deacon, J., 1997. Quasi-induced exposure: methodology and insight. Accident Analysis and Prevention. Vol. 29, No. 1, p.37-52

Statler, I., Morrison, R., Rosenthal, L., 2003. Beyond error reporting toward risk assessment. Proceedings of the 12th International Symposium on Aviation Psychology, Dayton, p.293-242

State of California, 2002. California airport land use planning handbook. Department of Transportation Division of Aeronautics, CA, USA

Study, C., 2005. Airport Future. KSFY News Headlines. 05/06/05 www.kfsy.com, accessed 06/06/05

Swartz, S., 2005. Potential for tragedy ramps up. Palm Beach Post. 14/12/05

Szczesniak, J., 2006. Runway Safety Areas. Presentation at Airports Council International – North America 15th Annual Congress & Exhibition, Reno, September 25-28

Tabachnick, B., Fidell, L., 1996. Using multivariate statistics. Harper Collins, New York

Tape, T., 2007. Intepreting diagnostic tests. University of Nebraska Medical Center. http://gim.unmc.edu/dxtests/roc3.htm, accessed 25/01/07

Technica, 1991. Extension to risk analysis of aircraft impact at Schiphol airport, fifth runway. Technica. Report No. C2475

Thurber, M., 2006. FAA begins rulemaking process to extend runway safety margins. Aviation International News, October

Tompkins, A., 2005. Airports need runway space or EMAS. Poynter Online. www.poynter.org, accessed 11/12/05

Tu, J., 1996. Advantages and disadvantages of using artificial neural networks versus logistic regression for predicting medical outcomes. Journal of Clinical Epidemiology, Vol. 49, No. 11, p.1225-1231

Turner, T., 2006. Overgross! Aviation Safety. Vol. 26, Pt. 1, p.8-11

University of Sydney, 1990. Third runway proposal - draft environmental impact statement - Sydney (Kingsford Smith) airport - hazard analysis and risk assessment - working paper. Australian Centre of Advanced Risk and Reliability Engineering Ltd (ACARRE), Dept. of Chemical Engineering, University of Sydney, Sydney

Van Es, G., Van der Geest, P., Nieuwpoort, T., 2001. Safety aspects of aircraft operations in crosswind. NLR-TP-2001-217. Dutch National Aerospace Laboratory NLR, Amsterdam

Veillette, P., 2006. Crosswinds and contaminated runways. Business and Commercial Aviation. Vol. 98, Pt. 1, p.28-31

Watson, D., 2005. Summary and analysis of, and CAA response to, comments and submissions on NPRM 04-03 received during public consultation. Civil Aviation Authority of New Zealand, Petone

Weidl, T., Klein, G., 2004. A new determination of air crash frequencies and its implications for operation permissions. Probabilistic Safety Assessment and Management. PSAM7-ESREL 2004 Conference. June 14-18, Berlin. Springer, London

Wig, J., 2005. FAA says condos no threat to airport runway. Bristol Herald Courier. 26/07/05

Winn, R., 2006. Probing the causes of aircraft accidents. Aerospace America. September. American Institute of Aeronautics and Astronautics, VA, USA

Wong, D, Appleyard, A, Caves, R., Pitfield, D., 2005a. An approach to airport risk assessment using normal operations data with bootstrapped logistic regression. Presentation at the 44th Annual Meeting of the Western Regional Science Association, February, San Diego

Wong, D., Pitfield, D., Caves R., Appleyard, A., 2005b. The size and shape of airport safety areas. Presentation at the Airports Council International – North America Operations & Technical Affairs Committee Spring Meeting, May, San Diego

Wong, D., Appleyard, A., Caves R., Pitfield, D., 2005c. The development of models of the frequency of aircraft accidents near airports. Presentation at the 2005 Air Transport Research Society World Conference, July, Rio de Janeiro

Wong, D., Pitfield, D., Caves, R., Appleyard, A., 2006a. Quantifying and characterising aviation accident risk factors. Journal of Air Transport Management. Vol. 12, p.352-357

Wong, D., Pitfield, D., Caves, R., Appleyard, A., 2006b. The development of aircraft accident frequency models. In: Guedes Soares & Zio. Safety and Reliability for Managing Risk. Proceedings of the European Safety and Reliability Conference 2006 (ESREL 2006), 18-22 September, Estoril. Taylor & Francis, London, Vol. 1, p.83-90

Wong, D., Pitfield, D., Caves, R., Appleyard, A., 2006c. Identifying and quantifying the criticality of aviation accident risk factors. Presentation at the Air Transport Research Society World Conference, Nagoya, May

Wong, D., Appleyard, A., Caves R., Pitfield, D., 2006d. The assessment of risks to occupants and communities due to aircraft accidents on and near airports – methodology and policy implications. Guest lecture to Masters course in Transportation Policy, Operations, and Logistics at the School of Public Policy, George Mason University, September, VA, USA

Wong, D., Pitfield, D., Caves, R., Appleyard, A., 2006e. The development of aircraft accident frequency models. Presentation at the European Safety and Reliability Conference 2006 (ESREL 2006), 18-22 September, Estoril

Wong, D., Pitfield, D., Caves, R., Appleyard, A., 2006f. Assessing the need for runway safety areas. Presentation at the 2006 Airports Council International – North America Annual Conference Technical & Operational Affairs Committee Meeting, September, Reno

Yan, X., Radwan, E., Abdel-Aty, M., 2005. Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model. Accident Analysis and Prevention. Vol. 37, p. 983-995

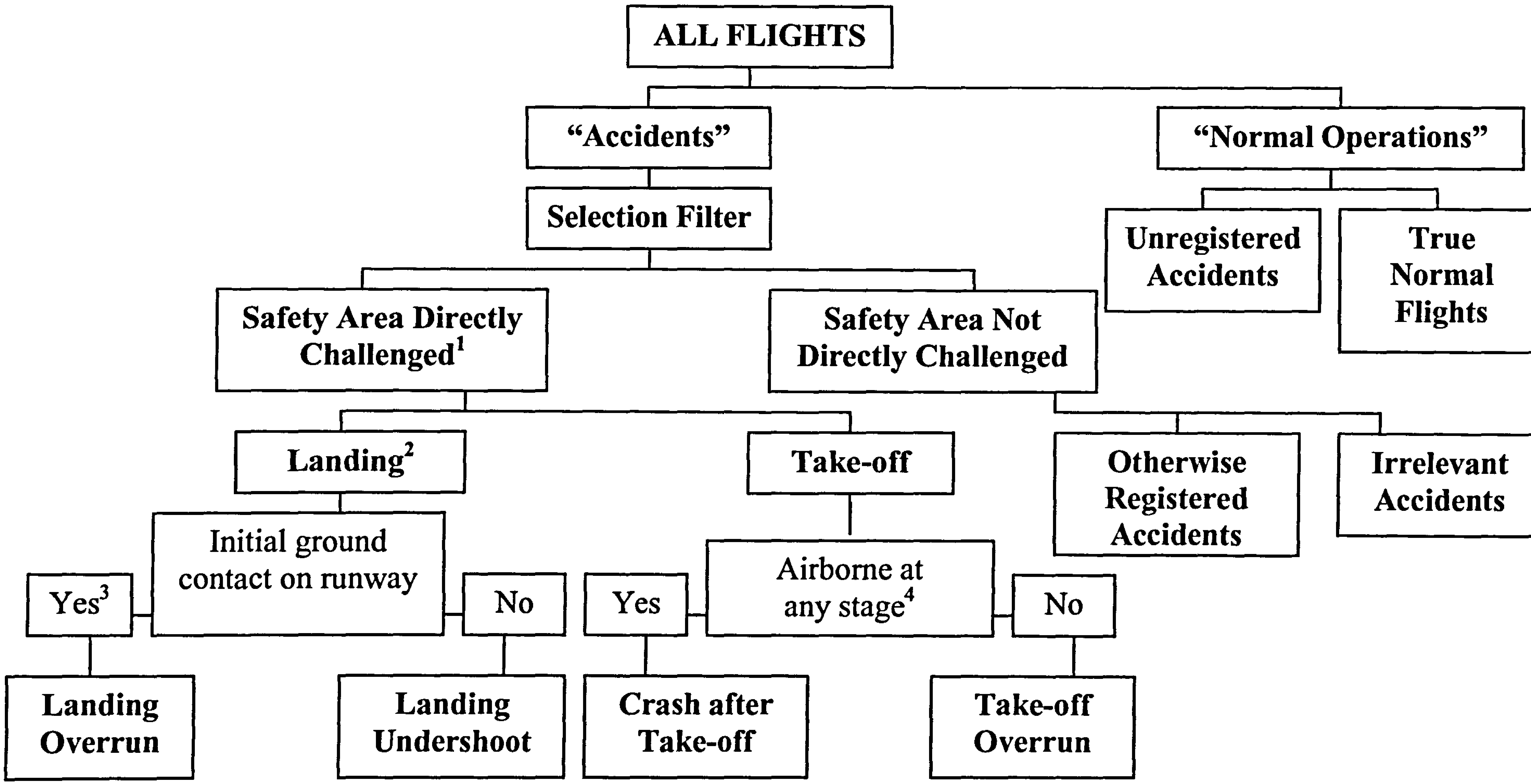
Young, M., Shorrock, S., Faulkner, J., Braithwaite, G., 2004. Who moved my (Swiss) cheese? The (r)evolution of human factors in transport safety investigation. Presentation at ISASI 2004. International Society Of Air Safety Investigators Annual Conference, Gold Coast

GLOSSARY

ALA	Approach and Landing Accident
ALUC	Airport Land Use Commission
ANN	Artificial Neural Network
APO	FAA Aviation Policy and Plans Office
ARC	Aerodrome/Airport Reference Code
ASA	Airport Safety Area
ASPM	Aviation System Performance Metrics
BCT	Boca Raton Airport
CAA	Civil Aviation Authority
CCFD	Complementary Cumulative Frequency Distribution
CCPD	Complementary Cumulative Probability Distribution
EMAS	Engineered Material Arresting System
ETMSC	Enhanced Traffic Management System Counts
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FOQA	Flight Operational Quality Assurance
FPR	False Positive Rate
FSF	Flight Safety Foundation
GA	General Aviation
GAATA	General Aviation and Air Taxi Activity
GAIN	Global Aviation Information Network
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFALPA	International Federation of Air Line Pilots' Associations
IMC	Instrument Meteorological Conditions
IR	Individual Risk
LDA	Landing Distance Available
LDOR	Landing Overrun
LDUS	Landing Undershoot
LGA	New York La Guardia Airport
LOSA	Line Operations Safety Audit
MTOW	Maximum Take-off Weight

NATS	National Air Traffic Services (UK)
NLR	National Aerospace Laboratory (The Netherlands)
NOD	Normal Operations Data
NTSB	National Transportation Safety Board (US)
PANS-OPS	Procedures for Air Navigation Services, Operations
PIREP	Pilot Report
POFI	Point of First Impact
PSZ	Public Safety Zone
RAIR	Relative Accident Involvement Ratio
RESA	Runway End Safety Area
ROC	Receiver Operating Characteristics
RPZ	Runway Safety Zone
RSA	Runway Safety Area
SAFO	Safety Alert for Operators
SMS	Safety Management System
SR	Societal Risk
STEADES	Safety Trend Evaluation Analysis & Data Exchange System
TAF	Terminal Area Forecast
TLS	Target Level of Safety
TODA	Take-off Distance Available
TOC	Crash after Take-off
TOOR	Take-off Overrun
TORA	Take-off Run Available
TPR	True Positive Rate
VIF	Variance Inflation Factor
VMC	Visual Meteorological Conditions

APPENDIX A ACCIDENT CLASSIFICATION SCHEME



1. This means that the aircraft has exited from the 'normal' areas of operation on the airfield, e.g. veering off the runway, hitting obstacles on landings or take-offs.
2. The aircraft must be in the landing sequence to be qualified as a landing accidents. Aircraft that have just taken off and declared its desire to return to land at the airport but has yet to engage in the landing sequence are classed as take-off accidents.
3. All landing overruns must strictly meet this criterion. All other landing accidents that directly challenge airport safety areas are classed as "Landing Undershoots".
4. The airborne criterion is in line with the fundamental difference between the 'Crash after Take-off' and 'Take-off Overrun' models – that the former deals with an airborne aircraft while the other is concerned with an entirely ground-based accident. This is especially relevant for the location models.

APPENDIX B ACCIDENT DATABASE FIELDS

1 – Basic Information

ID Number : 20001214X43522
Class of Accident : Takeoff and Crash
Class of Accident (Text) : Takeoff and Crash
Type : ACC
Date : 1983-06-09
City : SEATTLE
State : WA
Country : USA
Time : 707 Local
Accident Being Researched By : Derek
Basic Notes :
Delete from Database : No

2 – Aircraft

Aircraft Age : 3714 hours
Aircraft Make : LEARJET
Aircraft Model : 35
Aircraft Operator :
Aircraft Operator and Owner Same (Y / N) : No
Aircraft Owner : GLOBAL JET
Aircraft Registration : N1976L
Aircraft Serial Number : 053
Aircraft Series : 35
Aircraft Regulated By : FAA
Regulation Reference : 135
Aircraft Max Gross Weight : 18000 lbs
Maximum Certified Takeoff Weight : 0 lbs
Engine Type : High Bypass Turbofan
Engine Type Text : TF
Number of Engines : 2
Aircraft Notes :

3 – Airport

Airport Code :	BFI
Airport Reference Point Lat :	D M S
Airport Reference Point Long :	D M S
ARFF Inadequate :	No
Control Tower (Y / N) :	Unknown / NA
Groved Runway (Y / N) :	Unknown / NA
Runway Condition :	Normal
Runway Condition (txt) :	DRY
Runway Heading (degrees) :	Deg Mag
Runway Number :	13R
Runway Slope :	0 degrees
Runway Width :	200 ft
Temporary Runway / Works :	No
Takeoff Start of Roll Elevation :	13 ft above MSL
Takeoff Start of Roll Lat :	D M S
Takeoff Start of Roll Long :	D M S
Runway Takeoff Distance Available :	10000 ft
Runway Braking Condition :	Unknown / Not Applicable
Runway Braking Condition (txt) :	
Nearest Ground Feature (X) :	ft
Nearest Ground Feature (Y) :	ft
Obstacle Score (X) :	ft
Obstacle Score (Y) :	ft
Airport Notes :	

4 – Weather

Weather General : VMC
Weather General (txt) : VMC
Dew Point : 9 deg C
Temperature : 18 deg C
Gusts : 0 knots
Wind Direction (deg) : 160
Wind Shear : No
Wind Velocity : 8 knots
Actual Weather Different to Pilot Expectations : No
Localized Weather Variation : No
Runway Number : 13R
Ceiling Height : 2900 ft
Light Level : Day
Light Level (text) : DAYL
RVR : -1 ft
Snow (Y / N) : No
Visibility : 7 statute miles
Electric Storm (Y / N) : No
Fog (Y / N) : No
Frozen Precipitation (Y / N) : No
Icing Conditions (Y/N) : No
Intensity of Precipitation : None
Weather Notes :

5 – Flight Operation Conditions

Operation Scheduled : No
Operation Type : Cargo (All Freight)
Passenger Load Factor : -2
Departure Country : USA
Destination Country : USA
Foreign Origin / Destination (Y / N) : No
Flight was Delayed : No
Flight was Diverted (excludes go-around after T / O) : No
Runway Takeoff Distance Required : ft
Actual Weight at Time of Crash : 0 lbs
***Maximum Certified Weight for* Current Operation :** *0 lbs*
Was Actual Weight at Time of Crash Estimated : No
Weight Restrictions Violated : Unknown / NA
ELT Fitted and Operational : No
Fuel Load at Crash : 375 Gallons (US)
Flight Notes :

6 – Accident Details

Aircraft Collision Status : N/A
Did the accident involve a collision with another A/C : No
Aircraft Crash Controllability : Fully Controllable
Late Runway Change / Decision (Y / N) : No
Takeoff Abort Speed : 110 knots
Attempted Aborted Takeoff : Yes
Detailed Info Notes :

7 – Wreckage

Wreckage Location Lat : N47 32 D M S
Wreckage Location Long : W122 18 D M S
Wreckage Location X : 7292 ft
Wreckage Location Y : 339 ft
Wreckage Location Z : 3 ft
Wreckage Site Elevation : 16 ft above MSL
POFI X : 5104 ft
POFI Y : 156 ft
POFI Z : 999 ft
Angle of First Impact : 999
Speed of First Impact : 105 knots
Runway Exit Speed : 888 knots
Runway Exit X Distance : 888 ft
Wreckage Explosion : No
Wreckage Fire : No
Number of Obstacles Hit : 0
Wreckage Path Slope 1 : 0 degrees
Wreckage Path Surface Distance 1 : 2161 ft
Wreckage Path Surface Type 1 : Mud
Wreckage Path Slope 2 : 888 degrees
Wreckage Path Surface Distance 2 : 888 ft
Wreckage Path Surface Type 2 : Unknown
Wreckage Path Slope 3 : 888 degrees
Wreckage Path Surface Distance 3 : 888 ft
Wreckage Path Surface Type 3 : Unknown
Wreckage Path Slope 4 : 888 degrees
Wreckage Path Surface Distance 4 : 888 ft
Wreckage Path Surface Type 4 : Unknown
Pilot Actively Steered to Avioud Obstacle : No
Total Wreckage Path Length : 2161 ft
Wreckage Notes :

8 – Injuries

Events Highest Injury : NONE
Evacuation Injuries : 0
Passenger Fatal : -2
Passenger Fatality Rate % : -2
Passenger Minor : -2
Passenger None : -2
Passenger Serious : -2
Passenger Total Injuries : -2
Passenger Total On Board : 0
Flight Crew Fatal : 0
Flight Crew Fatality Rate % : 0
Flight Crew Minor : 0
Flight Crew None : 2
Flight Crew Serious : 0
Flight Crew Total Injuries : 0
Flight Crew Total On Board : 2
Cabin Crew Fatal : -2
Cabin Crew Fatality Rate % : -2
Cabin Crew Minor : -2
Cabin Crew None : -2
Cabin Crew Serious : -2
Cabin Crew Total Injuries : -2
Cabin Crew Total On Board : 0
Public Fatal : 0
Public Minor : 0
Public Serious : 0
Public Total Injuries : 0
Total Fatal Injuries : 0
Total Minor Injuries : 0
Total No Injuries : 2
Total Serious Injuries : 0
On Ground Fatal : 0
On Ground Minor : 0
On Ground Serious : 0
On Ground Total Injuries : 0
Ground Crew Fatal : 0
Ground Crew Minor : 0
Ground Crew Serious : 0
Ground Crew Total Injuries : 0
Injuries Notes :

9 - Consequences

Aircraft Damage : SUBS
Number of Seats : 2
Total Number of Passenger Seats : 0
Consequence Area : 395463 Square ft
Consequence Area Main Location : On Airport
Emergency Services had Difficulty Locating Wreckage : No
Change of Terrain in Consequence Area : No
Consequence Area Land Use 1 - % Total Area : 100
Consequence Area Land Use 1 - Type : On Airport
Consquence Area Land Use 2 - % Area : -2
Consquence Area Land Use 2 - Type : Not Applicable
Consquence Area Land Use 3 - % Area : -2
Consquence Area Land Use 3 - Type : Not Applicable
Consquence Area Land Use 4 - % Area : -2
Consquence Area Land Use 4 - Type : Not Applicable
Consequence Notes :

APPENDIX C ACCIDENT DATABASE RULES AND DEFINITIONS

In completing the database the following document types should be consulted in this order:
Full Narrative http://www.ntsb.gov/ntsb/query.asp
Factual Report from http://www.ntsb.gov/ntsb/query.asp
Probable Cause Report http://www.ntsb.gov/ntsb/query.asp
Publication Report (if available)
Docket Files
General Notes
Wreckage site should be checked first to see if the accident meets the 10km from the airport criterion.

Detailed Event Info

ALL FIELDS	-2 Not Applicable (e.g. abort speed when a/c not aborted)
Approach Category Required	Assume VMC when a visual approach was required. Otherwise IMC and determine the category required according to decision height and visibility. If conditions above ILS Cat I, II and III, assume non-precision instrument approach required
Approach Minimums Violated	Criteria based on Decision Height, Visibility (see an ILS categories table), aircraft fitment and pilot license Sometimes NTSB recorded Ceiling may be above minimums the accident report indicates another ceiling height, which is below minimums. In this case, if the accident report mentions that minimums have been violated, the violation is recorded in the database without changing the official NTSB ceiling height. Other minimum violations flagged and detailed in notes section.
Instrument Approach Type	For information only, data come directly from NTSB
Active/Passive Aircraft	In collision accidents, the active aircraft is that actively performing landing/take-off operations
Air Crash Controllability	Worse state during accident sequence This is considered from a mechanical perspective. So in cases of hydroplaning, the aircraft is still considered "fully controllable" because it's the environmental factor (runway braking = none) which causes the braking effectiveness. A stall, however, is a mechanical issue and should be reflected in this field.
Stabilised Approach Achieved	This applies to ILS as well as non-ILS flights. Judgement should be used to determine if the approach is vertically and horizontally stabilised. Assume stabilised unless specific stabilisation issues mentioned. Quantify deviance if possible in the notes section (e.g. height at threshold). Lack of aircraft controllability indicates unstabilised approach
Late Runway Change/Decision	ATC directed runway change OR crew made late decision to use particular runway
Go-around	Related to accident airport/site only, not at previous airport from which the aircraft diverted Prior to event only, i.e. excludes touch & go cases
Notes	Take note of other minimums violated

Aircraft

Aircraft Age	Airframe total time (from Factual report) (Not Total All Aircraft Hrs from Brief of accident) -1 = Unknown

Airport

Control Tower	Operating rather than physical existence
Runway Condition	Ice = contaminated
Runway Slope (+ / - %)	Only recorded when slope exceeds 0.3% 0 = under 0.3% For the relevant runway and direction of operation If not given in the airport diagram use difference between the 2 thresholds. Source: http://avn.faa.gov/ap_diagrams.asp

Temporary airfield works	Runway, taxiway works etc.
Runway threshold elevation (ft)	For the relevant end of the runway (i.e. take-off overrun and landing overrun = departure end) Source: http://avn.faa.gov/ap_diagrams.asp or www.airnav.com
Runway Distance Available	For the relevant runway and operation, taking into account stopways and clearways; i.e. official take-off distance available or landing distance available
Runway Braking Condition	5 standard semantic categories. Assume braking condition good unless otherwise mentioned Hydroplane: braking condition = none

Flight

Passenger load factor	Take into account passenger load factor only % -2 = Not Applicable (e.g. cargo flights) -1 = Unknown
Departure/Destination Country	Excludes fuelling/technical stops
Flight duration	Not recorded if fuel at time of crash known
Foreign O/D	Excludes fuelling/technical stops
Delay	No unless stated in the report
Diversion	Excludes aircraft that return to their origin airport after take-off
Maximum Certified Weight for Current	Maximum Allowable Weight
Operation	Calculated based on runway used (even if it is the wrong runway)
Was Actual Weight at Time of Crash Estimated	Estimated by ourselves (not NTSB)
Notes to make	Reasons for weight limitation (i.e. difference between max certified weight and max. allowable weight) e.g. short runway, hot & high Reason for diversion when applicable

Weather

The NTSB database figures are used for Ceiling Height, Wind Direction & Velocity, Gust (except when it is 0) and Visibility (except when it is 0) but **NOT** for RVR. However, in cases where meteorological conditions are cited as a factor in the accident report and the NTSB given observations are different from the most relevant observation as given in the accident report, the latter is used. Weather as reported in the pilot/operator report is considered generally more relevant than other NTSB or accident report sources.

Weather is often observed at the intended/ incident airport rather than where emergency was declared or failure occurred. It is acknowledged that even the NTSB data is taken from the nearest weather station and could be substantially different from the actual weather at the airport. This is taken into account by the local weather variations flag.

Always use actual data and not forecast data.

If runway aimed for was unknown, assume from wreckage site, wind direction and ATC instructions

All fields	If a range is given, take the maximum (or worse) condition e.g. gusts 4 – 6 knots, take 6 knots
Dew Point	999 = unknown
Temperature	999 = unknown
Gusts	If wind velocity is low, put Gust = 0 rather than Unknown or Not Applicable.
	999 = unknown
Wind Direction	777 = variable
	888 = not applicable
	999 = unknown
Wind Shear	Wind shear detected at time of accident or wind shear alert was effective
Wind Velocity	Calm set 0 knots
	999 = unknown
Actual Weather Different to Pilot Expectations	Notes cases where there is significant discrepancy between expected and actual weather
Localized Weather Variations	Notes cases where there is significant discrepancy between weather on approach/climb and at the incident airport.
Ceiling Height	-3 = no ceiling
	-4 = indefinite ceiling/obscured
	-1 = unknown
RVR	If only available for another runway at the same airport at the same time, it is considered a good enough approximate
	-1 = unknown
Visibility	-3 = unrestricted
Fog	Includes haze
Frozen precipitation	Excludes snow, icing conditions, which are separate flags
Icing conditions	As mentioned in accident report

Wreckage Info

All fields	For Landing accidents, measured from the landing threshold of intended runway
	For Take-off accidents, measured from the start of roll threshold
	X distance short of runway threshold –ve
	X distance beyond runway threshold (runway side) +ve
	Y distance always +ve
	888 = Not Applicable (e.g. undershoots that never reached the runway do not have runway exit location)
	999 = Unknown
	Unless otherwise stated, assume distance given in report is measured from the airport reference point, then use available

	information to deduce X and Y distances to the runway threshold Source: http://www.fcc.gov/mb/audio/bickel/distance.html to help find the distance between 2 sets of co-ordinates Source: http://www.airnav.com for runway threshold co-ordinates Source: http://www.landings.com/_landings/pages/search/search_ap-ident.html for airport maps
Wreckage X distance	In case of displaced thresholds, X distance measured from displaced threshold
Wreckage Y distance	0 if it is reasonable to expect little lateral deviance from report/docket 999 (unknown) if lateral significant deviation confirmed but extent unknown
Wreckage Z distance (ft MSL)	Elevation difference between rwy threshold and wreckage site Above threshold +ve; below threshold –ve Source: http://www.airnav.com for runway threshold elevation
Point of First Impact	Defined as the location where aircraft first hit anything it should not have hit, including trees, fences etc. Overruns: runway exit point. Take-off & crash: Could be runway if touched down on rwy after lift-off X distance measured from landing threshold (landings) or start of roll threshold (take-off) In case of displaced thresholds, X distance measured from displaced threshold Z: Elevation difference between rwy threshold and POFI (if POFI is an obstacle then measure from impact point)
Angle of First Impact	Not applicable to overruns (888)
Speed of First Impact	Overruns: same as runway exit speed
Number of Obstacles Hit	Accounted for in consecutive groups; e.g. tree, fence, tree = 3
Wreckage path slope	777=+ve slope/elevation; -777=-ve slope/elevation
Wreckage Path Surface Distance	Measured from POFI if obstacle hit/undershoot/take-off & crash Overruns: measured from runway exit point
Hit Terrain	
Hit Terrain	This page focuses on vertical terrain rather than the horizontal terrain type, which is recorded in the wreckage path section in the Wreckage Info page. Includes terrain on which struck obstacles are situated Overruns: only relevant when significant terrain is hit (in most cases none)
ALL Fields	999 = Unknown 888 = Not Applicable For Landing accidents, measured from the landing threshold of intended runway For Take-off accidents, measured from the start of roll threshold X distance short of runway threshold –ve X distance beyond runway threshold (runway side) +ve Y distance always +ve Z distanced: elevation difference with relevant runway threshold elevation

	Depth = Longest distance along rwy centreline Height= Largest elevation difference with rwy threshold Width = Longest distance perpendicular to rwy centreline 777=+ve slope/elevation; -777=-ve slope/elevation
Hit Obstacles	
Obstacles	Obstacles defined as anything substantial enough to change aircraft's course (e.g. road embankment) as well as free-standing objects (e.g. tree) In cases of an overrunning aircraft falling off/hitting an embankment, depending if the aircraft's course is affected significantly, the embankment could be either an obstacle or just part of the wreckage path (a degree of subjectivity accepted). This is consistent with the definition of obstacle above.
ALL Fields	999 = Unknown 888 = Not Applicable For Landing accidents, measured from the landing threshold of intended runway For Take-off accidents, measured from the start of roll threshold X distance short of runway threshold –ve X distance beyond runway threshold (runway side) +ve Y distance always +ve Z = Elevation difference between rwy threshold and obstacle impact point Depth = Longest distance along rwy centreline Height= Largest elevation difference with rwy threshold Width = Longest distance perpendicular to rwy centreline 777=+ve slope/elevation; -777=-ve slope/elevation
Consequences	
All fields	-1 = Unknown -2 = Not Applicable
Consequence Area (m^2)	Length measured from POFI/rwy exit point to final wreckage site / furthest debris scatter. Overruns: measured from runway exit point. Width measured between furthest debris scatter either side of wreckage path or the aircraft wingspan, whichever is greater Stretches to include where trees and other obstructions are hit, i.e. not only ground impact area In cases of undershoots then overrun, add consequence areas before runway and after runway exit.
Change of Terrain in Consequence Area	E.g. steep embankment (also recorded as obstacle) etc.
Injuries	
ALL Fields	-2 = Not Applicable (e.g. when there are no cabin crew)

Total Injuries	Includes fatal injuries
Ground Injuries	Ground crew & travelling public injuries
Public Injuries	Third parties (non-aviation related)

APPENDIX D NTSB DATABASE FILTERING CRITERIA & JUSTIFICATION

Filter Number	Description	Accidents	Incidents	Justification
1	Remove non US entries	49964	1496	• Scope of current work is to concentrate on accidents occurring in the US • To ensure consistency of data collection, classification and analysis • To have consistency in safety regulations and standards
2	Remove non fixed wing aircraft entries	44102	1434	• Study is concerned with fixed wing aircraft crashes only
3	Remove entries for airplanes with certified max gross weight <6,000 lbs	5373	1147	• Previous work used 6,000 lbs certified max gross weight as a cut off point
4	Remove entries with unwanted FAR Parts	4426	1136	• Removed events occurring to aircraft governed by the following FAR Parts: o Part 91F: Special Flt Ops. o Part 103: Ultralight o Part 105: Parachute Jumping o Part 133: Rotorcraft Ext. Load o Part 137: Agricultural o Part 141: Pilot Schools o Armed Forces • These FAR Parts have very different safety regulations • General Aviation is included to increase the data set available for analysis

5	Remove entries occurring in unwanted phases of flight	3723	807	• The study is concerned with flying operations therefore accidents occurring whilst either standing or taxiing were removed
6	Remove all single engine aircraft and all piston engine aircraft entries	1312	714	• Good quality data for accidents involving single engine or piston engine aircraft is scarce • Single engine accidents usually only involve the crew and maybe a very small number of passengers with very little effect on third parties • Piston engine aircraft are now used less frequently in civil aviation and therefore have been removed, to increase the validity of the modelling • Single and piston engine aircraft behave differently in accidents due to the lower energy levels involved
7	Remove all FAR Part 91 entries with a certified max gross weight < 12,500 lbs	944	700	• The quality of accident data is poor • Lack of matching normal operations data
8	Remove entries where aircraft damage and injury levels were minor or less	935	4	• Good quality data for accidents with innocuous consequences is scarce • Scope of work concentrates on cases with more serious consequences

APPENDIX E 2001 FAA HUB AIRPORTS

Locid	Airport Name	City	ST	Region	Hub Type	2001 Boardings
ABE	Lehigh Valley International	Allentown	PA	EA	S	478,367
ABQ	Albuquerque International Sunport	Albuquerque	NM	SW	M	3,095,899
ACY	Atlantic City International	Atlantic City	NJ	EA	S	386,746
ALB	Albany International	Albany	NY	EA	S	1,463,632
AMA	Amarillo International	Amarillo	TX	SW	S	424,318
ANC	Ted Stevens Anchorage International	Anchorage	AK	AL	M	2,419,261
ATL	The William B Hartsfield Atlanta International	Atlanta	GA	SO	L	37,181,068
AUS	Austin-Bergstrom International	Austin	TX	SW	M	3,428,202
BDL	Bradley International	Windsor Locks	CT	NE	M	3,416,243
BHM	Birmingham International	Birmingham	AL	SO	S	1,505,133
BIL	Billings Logan International	Billings	MT	NM	S	341,308
BNA	Nashville International	Nashville	TN	SO	M	4,209,465
BOI	Boise Air Terminal/Gowen Field	Boise	ID	NM	S	1,425,007
BOS	General Edward Lawrence Logan International	Boston	MA	NE	L	11,739,553
BTR	Baton Rouge Metropolitan, Ryan Field	Baton Rouge	LA	SW	S	363,419
BTV	Burlington International	Burlington	VT	NE	S	509,031
BUF	Buffalo Niagara International	Buffalo	NY	EA	M	2,204,087
BUR	Burbank-Glendale-Pasadena	Burbank	CA	WP	M	2,250,685
BWI	Baltimore-Washington International	Baltimore	MD	EA	L	10,098,665
CAE	Columbia Metropolitan	Columbia	SC	SO	S	537,727
CAK	Akron-Canton Regional	Akron	OH	GL	S	349,841
CHS	Charleston AFB/International	Charleston	SC	SO	S	786,326
CID	The Eastern Iowa	Cedar Rapids	IA	CE	S	440,797
CLE	Cleveland-Hopkins International	Cleveland	OH	GL	M	5,633,495
CLT	Charlotte/Douglas International	Charlotte	NC	SO	L	11,548,952
CMH	Port Columbus International	Columbus	OH	GL	M	3,296,013
COS	City of Colorado Springs Municipal	Colorado Springs	CO	NM	S	1,050,344

CRP	Corpus Christi International	Corpus Christi	TX	SW	S	404,151
CVG	Cincinnati/Northern Kentucky International	Covington/Cincinnati, Oh	KY	SO	L	8,586,907
DAL	Dallas Love Field	Dallas	TX	SW	M	3,352,083
DAY	James M Cox Dayton International	Dayton	OH	GL	S	1,070,456
DCA	Ronald Reagan Washington National	Arlington	VA	EA	M	6,267,395
DEN	Denver International	Denver	CO	NM	L	17,178,872
DFW	Dallas/Fort Worth International	Fort Worth	TX	SW	L	25,610,562
DSM	Des Moines International	Des Moines	IA	CE	S	789,715
DTW	Detroit Metropolitan Wayne County	Detroit	MI	GL	L	15,819,584
ELP	El Paso International	El Paso	TX	SW	S	1,544,734
EUG	Mahlon Sweet Field	Eugene	OR	NM	S	356,108
EWR	Newark International	Newark	NJ	EA	L	15,497,560
FAI	Fairbanks International	Fairbanks	AK	AL	S	384,828
FAT	Fresno Yosemite International	Fresno	CA	WP	S	457,570
FLL	Fort Lauderdale/Hollywood International	Fort Lauderdale	FL	SO	L	8,015,055
FSD	Joe Foss Field	Sioux Falls	SD	GL	S	336,252
GCN	Grand Canyon National Park	Grand Canyon	AZ	WP	S	422,061
GEG	Spokane International	Spokane	WA	NM	S	1,423,624
GPT	Gulfport-Biloxi International	Gulfport	MS	SO	S	420,769
GRB	Austin Straubel International	Green Bay	WI	GL	S	337,737
GRR	Gerald R. Ford International	Grand Rapids	MI	GL	S	906,768
GSN	Saipan International	Saipan Island	MP	WP	S	516,137
GSO	Piedmont Triad International	Greensboro	NC	SO	S	1,317,519
GSP	Greenville-Spartanburg International	Greer	SC	SO	S	701,606
GUM	Guam International	Agana	GU	WP	S	1,489,164
HNL	Honolulu International	Honolulu	HI	WP	L	9,810,860
HOU	William P Hobby	Houston	TX	SW	M	4,128,980
HPN	Westchester County	White Plains	NY	EA	S	456,296
HRL	Valley International	Harlingen	TX	SW	S	439,932
HSV	Huntsville International-Carl T Jones Field	Huntsville	AL	SO	S	473,148
IAD	Washington Dulles International	Chantilly	VA	EA	L	8,484,112
IAH	George Bush Intercontinental	Houston	TX	SW	L	16,173,551
ICT	Wichita Mid-Continent	Wichita	KS	CE	S	527,062

IND	Indianapolis International	Indianapolis	IN	GL	M	3,595,425
ISP	Long Island Mac Arthur	Islip	NY	EA	S	1,009,919
ITO	Hilo International	Hilo	HI	WP	S	714,537
JAN	Jackson International	Jackson	MS	SO	S	642,146
JAX	Jacksonville International	Jacksonville	FL	SO	M	2,523,809
JFK	John F Kennedy International	New York	NY	EA	L	14,553,815
JNU	Juneau International	Juneau	AK	AL	S	402,117
KOA	Kona International at Keahole	Kailua Kona	HI	WP	S	1,235,893
LAS	Mc Carran International	Las Vegas	NV	WP	L	16,633,435
LAX	Los Angeles International	Los Angeles	CA	WP	L	29,365,436
LBB	Lubbock International	Lubbock	TX	SW	S	536,174
LEX	Blue Grass	Lexington	KY	SO	S	440,797
LGA	La Guardia	New York	NY	EA	L	11,352,248
LIH	Lihue	Lihue	HI	WP	S	1,342,287
LIT	Adams Field	Little Rock	AR	SW	S	1,211,753
MAF	Midland International	Midland	TX	SW	S	437,045
MCI	Kansas City International	Kansas City	MO	CE	M	5,614,347
MCO	Orlando International	Orlando	FL	SO	L	13,622,397
MDT	Harrisburg International	Harrisburg	PA	EA	S	556,672
MDW	Chicago Midway International	Chicago	IL	GL	L	7,112,784
MEM	Memphis International	Memphis	TN	SO	M	5,560,524
MHT	Manchester	Manchester	NH	NE	S	1,599,062
MIA	Miami International	Miami	FL	SO	L	14,941,663
MKE	General Mitchell International	Milwaukee	WI	GL	M	2,825,473
MLI	Quad City International	Moline	IL	GL	S	367,688
MOB	Mobile Regional	Mobile	AL	SO	S	356,083
MSN	Dane County Regional-Truax Field	Madison	WI	GL	S	675,034
MSP	Minneapolis-St Paul International/Wold-Chamberlain/	Minneapolis	MN	GL	L	15,852,433
MSY	New Orleans International/Moisant Field/	New Orleans	LA	SW	M	4,767,533
MYR	Myrtle Beach International	Myrtle Beach	SC	SO	S	695,502
OAK	Metropolitan Oakland International	Oakland	CA	WP	M	5,566,100
OGG	Kahului	Kahului	HI	WP	M	2,777,692
OKC	Will Rogers World	Oklahoma City	OK	SW	M	1,675,889
OMA	Eppley Airfield	Omaha	NE	CE	M	1,773,894
ONT	Ontario International	Ontario	CA	WP	M	3,168,975
ORD	Chicago O'Hare International	Chicago	IL	GL	L	31,529,561

ORF	Norfolk International	Norfolk	VA	EA	S	1,478,687
PBI	Palm Beach International	West Palm Beach	FL	SO	M	2,954,015
PDX	Portland International	Portland	OR	NM	M	6,168,103
PHL	Philadelphia International	Philadelphia	PA	EA	L	11,736,129
PHX	Phoenix Sky Harbor International	Phoenix	AZ	WP	L	17,478,622
PIT	Pittsburgh International	Pittsburgh	PA	EA	L	9,939,223
PNS	Pensacola Regional	Pensacola	FL	SO	S	520,953
PSP	Palm Springs International	Palm Springs	CA	WP	S	586,028
PVD	Theodore Francis Green State	Providence	RI	NE	M	2,751,762
PWM	Portland International Jetport	Portland	ME	NE	S	625,591
RDU	Raleigh-Durham International	Raleigh/Durham	NC	SO	M	4,890,606
RIC	Richmond International	Richmond	VA	EA	S	1,187,681
RNO	Reno/Tahoe International	Reno	NV	WP	M	2,388,923
ROC	Greater Rochester International	Rochester	NY	EA	S	1,132,597
RSW	Southwest Florida International	Fort Myers	FL	SO	M	2,596,005
SAN	San Diego International-Lindbergh Field	San Diego	CA	WP	L	7,506,320
SAT	San Antonio International	San Antonio	TX	SW	M	3,313,545
SAV	Savannah International	Savannah	GA	SO	S	836,791
SBA	Santa Barbara Municipal	Santa Barbara	CA	WP	S	363,581
SBN	South Bend Regional	South Bend	IN	GL	S	375,817
SDF	Louisville International-Standiford Field	Louisville	KY	SO	M	1,876,499
SEA	Seattle-Tacoma International	Seattle	WA	NM	L	13,184,630
SFB	Orlando Sanford	Orlando	FL	SO	S	645,944
SFO	San Francisco International	San Francisco	CA	WP	L	16,475,611
SJC	San Jose International	San Jose	CA	WP	M	5,981,440
SJU	Luis Munoz Marin International	San Juan	PR	SO	M	4,706,307
SLC	Salt Lake City International	Salt Lake City	UT	NM	L	8,951,776
SMF	Sacramento International	Sacramento	CA	WP	M	4,021,102
SNA	John Wayne Airport-Orange County	Santa Ana	CA	WP	M	3,688,304
SRQ	Sarasota/Bradenton International	Sarasota/Bradenton	FL	SO	S	590,391
STL	Lambert-St Louis International	St. Louis	MO	CE	L	13,264,751

STT	Cyril E King	Charlotte Amalie	VI	SO	S	516,389
SYR	Syracuse Hancock International	Syracuse	NY	EA	S	936,450
TLH	Tallahassee Regional	Tallahassee	FL	SO	S	424,132
TPA	Tampa International	Tampa	FL	SO	L	7,901,725
TUL	Tulsa International	Tulsa	OK	SW	S	1,627,293
TUS	Tucson International	Tucson	AZ	WP	M	1,749,560
TYS	Mc Ghee Tyson	Knoxville	TN	SO	S	705,607
VPS	Eglin AFB	Valparaiso	FL	SO	S	375,196
XNA	Northwest Arkansas Regional	Fayetteville/Springdale/	AR	SW	S	360,639

APPENDIX F AIRPORTS IN SIGNIFICANT TERRAIN

State	City	Airport
AK	ATKA	ATKA AIRPORT
AK	KAKE	KAKE
AK	HOMER	HOMER
AK	SITKA	SITKA ROCKY GUTIERREZ
AK	WALES	WALES
AK	AMBLER	AMBLER
AK	JUNEAU	JUNEAU INTL
AK	KODIAK	KODIAK
AK	NULATO	NULATO
AK	PALMER	PALMER MUNI
AK	VALDEZ	VALDEZ PIONEER FIELD
AK	CORDOVA	MERLE K (MUDHOLE) SMITH
AK	ILIAMNA	ILIAMNA
AK	KLAWOCK	KLAWOCK
AK	WASILLA	WASILLA
AK	YAKUTAT	YAKUTAT
AK	BIG LAKE	BIG LAKE
AK	COLD BAY	COLD BAY
AK	COLDFOOT	COLDFOOT
AK	GUSTAVUS	GUSTAVUS
AK	SAVOONGA	SAVOONGA
AK	SHUNGNAK	SHUNGNAK
AK	UNALASKA	UNALASKA
AK	WRANGELL	WRANGELL
AK	ALLAKAKET	ALLAKAKET
AK	ANCHORAGE	MERRILL FIELD
AK	FAIRBANKS	FAIRBANKS INTL
AK	KETCHIKAN	KETCHIKAN INTL
AK	KING COVE	KING COVE AIRPORT
AK	NONDALTON	NONDALTON
AK	TALKEETNA	TALKEETNA
AK	PERRYVILLE	PERRYVILLE AIRPORT
AK	PETERSBURG	PETERSBURG JAMES A. JOHNSON
AK	SAND POINT	SAND POINT
AK	ADAK ISLAND	ADAK
AK	PORT HEIDEN	PORT HEIDEN
AK	ANAKTUVUK PASS	ANAKTUVUK PASS
AK	ARCTIC VILLAGE	ARCTIC VILLAGE
AS	PAGO PAGO	PAGO PAGO INTL
AZ	GLOBE	SAN CARLOS APACHE
AZ	SEDONA	SEDONA
AZ	TUCSON	RYAN FIELD
AZ	TUCSON	TUCSON INTL
AZ	TUCSON	MARANA REGIONAL
AZ	KINGMAN	KINGMAN
AZ	NOGALES	NOGALES INTL
AZ	SAFFORD	SAFFORD REGIONAL
AZ	WILLCOX	COCHISE COUNTY
AZ	PRESCOTT	ERNEST A. LOVE FIELD

AZ	FLAGSTAFF	FLAGSTAFF PULLIAM
AZ	SCOTTSDALE	SCOTTSDALE
AZ	BULLHEAD CITY	LAUGHLIN/BULLHEAD INTL
AZ	LAKE HAVASU CITY	LAKE HAVASU CITY
AZ	FORT HUACHUCA-SIERRA VISTA	SIERRA VISTA MUNI-LIBBY AAF
CA	CHICO	CHICO MUNI
CA	CHINO	CHINO
CA	UKIAH	UKIAH MUNI
CA	BISHOP	EASTERN SIERRA REGIONAL
CA	CORONA	CORONA MUNI
CA	LOMPOC	LOMPOC
CA	MARINA	MARINA MUNI
CA	OXNARD	OXNARD
CA	RAMONA	RAMONA
CA	RIALTO	RIALTO MUNI-MIRO FIELD
CA	UPLAND	CABLE
CA	ALTURAS	ALTURAS MUNI
CA	BURBANK	BOB HOPE
CA	FORTUNA	ROHNERVILLE
CA	NEEDLES	NEEDLES
CA	ONTARIO	ONTARIO INTL
CA	REDDING	REDDING MUNI
CA	SALINAS	SALINAS MUNI
CA	TRUCKEE	TRUCKEE-TAHOE
CA	CARLSBAD	MCCLELLAN-PALOMAR
CA	EL MONTE	EL MONTE
CA	INYOKERN	INYOKERN
CA	LA VERNE	BRACKETT FIELD
CA	LAKEPORT	LAMPSON FIELD
CA	MARIPOSA	MARIPOSA-YOSEMITE
CA	MONTAGUE	SISKIYOU COUNTY
CA	MONTEREY	MONTEREY PENINSULA
CA	PALMDALE	PALMDALE REGIONAL/USAF PLANT
CA	PETALUMA	PETALUMA MUNI
CA	REDLANDS	REDLANDS MUNICIPAL
CA	SAN JOSE	BRYANT FIELD
CA	SAN JOSE	NORMAN Y MINETA SAN JOSE INTL
CA	SAN JOSE	REID-HILLVIEW OF SANTA CLARA CO
CA	CAMARILLO	CAMARILLO
CA	FALLBROOK	FALLBROOK COMMUNITY AIRPARK
CA	FULLERTON	FULLERTON MUNI
CA	GROVELAND	PINE MOUNTAIN LAKE
CA	LANCASTER	GENERAL WM. J. FOX AIRFIELD
CA	OCEANSIDE	OCEANSIDE MUNI
CA	RIVERSIDE	RIVERSIDE MUNI
CA	SANTA ANA	JOHN WAYNE AIRPORT-ORANGE COUNTY
CA	BECKWOURTH	NERVINO
CA	CLOVERDALE	CLOVERDALE
CA	HEMET-RYAN	HEMET-RYAN
CA	SAN MARTIN	SOUTH COUNTY AIRPORT OF SANTA CLARA COUNTY
CA	SANTA ROSA	CHARLES M. SCHULZ-SONOMA COUNTY

CA	SANTA YNEZ	SANTA YNEZ
CA	BAKERSFIELD	MEADOWS FIELD
CA	BAKERSFIELD	BAKERSFIELD MUNI
CA	LOS ANGELES	WHITEMAN
CA	PORTERVILLE	PORTERVILLE MUNI
CA	SAN ANDREAS	CALAVERAS COUNTY-MAURY RASMUSSEN FIELD
CA	SANTA MARIA	SANTA MARIA PUBLIC/CAPTAIN G. ALLAN HANCOCK FIELD
CA	PALM SPRINGS	BERMUDA DUNES
CA	PALM SPRINGS	PALM SPRINGS INTL
CA	PALM SPRINGS	JACQUELINE COCHRAN REGIONAL
CA	SANTA MONICA	SANTA MONICA MUNI
CA	ARCATA-EUREKA	ARCATA
CA	BIG BEAR CITY	BIG BEAR CITY
CA	CRESCENT CITY	JACK MCNAMARA FIELD
CA	MAMMOTH LAKES	MAMMOTH YOSEMITE
CA	MOUNTAIN VIEW	MOFFETT FEDERAL AFLD
CA	SANTA BARBARA	SANTA BARBARA MUNI
CA	SAN BERNARDINO	SAN BERNARDINO INTL
CA	BORREGO SPRINGS	BORREGO VALLEY
CA	CALIFORNIA CITY	CALIFORNIA CITY MUNI
CA	SAN LUIS OBISPO	SAN LUIS COUNTY REGIONAL
CA	SOUTH LAKE TAHOE	LAKE TAHOE
CA	TWENTYNINE PALMS	TWENTYNINE PALMS
CA	MURRIETA/TEMECULA	FRENCH VALLEY
CA	SAN DIEGO(EL CAJON)	GILLESPIE FIELD
CO	ERIE	ERIE MUNI
CO	ASPEN	ASPEN PITKIN COUNTY-SARDY FIELD
CO	EAGLE	EAGLE COUNTY REGIONAL
CO	RIFLE	GARFIELD COUNTY REGIONAL
CO	CORTEZ	CORTEZ MUNI
CO	DENVER	JEFFCO
CO	HAYDEN	YAMPA VALLEY
CO	MEEKER	MEEKER
CO	GUNNISON	GUNNISON-CRESTED BUTTE REGIONAL
CO	LONGMONT	VANCE BRAND
CO	MONTROSE	MONTROSE REGIONAL
CO	KREMMLING	MC ELROY AIRFIELD
CO	LEADVILLE	LAKE COUNTY
CO	TELLURIDE	TELLURIDE REGIONAL
CO	CANON CITY	FREMONT COUNTY
CO	BUENA VISTA	CENTRAL COLORADO REGIONAL
CO	MONTE VISTA	MONTE VISTA MUNI
CO	GRAND JUNCTION	WALKER FIELD
CO	COLORADO SPRINGS	CITY OF COLORADO SPRINGS MUNI
CO	STEAMBOAT SPRINGS	STEAMBOAT SPRINGS/BOB ADAMS FIELD
FM	KOSRAE ISLAND	KOSRAE
FM	POHNPEI ISLAND	POHNPEI INTL
HI	HANA	HANA
HI	HILO	HILO INTL
HI	LIHUE	LIHUE
HI	KAHULUI	KAHULUI

HI	KAMUELA	WAIMEA-KOHALA
HI	LANAI CITY	LANAI
HI	KAILUA-KONA	KONA INTL AT KEAHOLE
ID	ARCO	ARCO-BUTTE COUNTY
ID	BOISE	BOISE AIR TERMINAL(GOWEN FIELD)
ID	NAMPA	NAMPA MUNI
ID	BURLEY	BURLEY MUNI
ID	DRIGGS	DRIGGS-REED MEMORIAL
ID	HAILEY	FRIEDMAN MEMORIAL
ID	MCCALL	MCCALL MUNI
ID	SALMON	LEMHI COUNTY
ID	POCATELLO	POCATELLO REGIONAL
ID	SANDPOINT	SANDPOINT
ID	GRANGEVILLE	IDAHO COUNTY
ID	COEUR D'ALENE	COEUR D'ALENE AIR TERMINAL
ID	MOUNTAIN HOME	MOUNTAIN HOME MUNI
MT	BUTTE	BERT MOONEY
MT	LIBBY	LIBBY
MT	DILLON	DILLON
MT	HELENA	HELENA REGIONAL
MT	POLSON	POLSON
MT	BOZEMAN	GALLATIN FIELD
MT	HAMILTON	RAVALLI CO
MT	MISSOULA	MISSOULA INTL
MT	KALISPELL	GLACIER PARK INTL
MT	LIVINGSTON	MISSION FIELD
MT	STEVENSVILLE	STEVENSVILLE
NC	ANDREWS	ANDREWS-MURPHY
NC	ASHEVILLE	ASHEVILLE REGIONAL
NH	WHITEFIELD	MOUNT WASHINGTON REGIONAL
NM	TAOS	TAOS REGIONAL
NM	BELEN	ALEXANDER MUNI
NM	GRANTS	GRANTS-MILAN MUNI
NM	SOCORRO	SOCORRO MUNI
NM	SANTA FE	SANTA FE MUNI
NM	ALAMOGORDO	ALAMOGORDO-WHITE SANDS REGIONAL
NM	ANGEL FIRE	ANGEL FIRE
NM	LAS CRUCES	LAS CRUCES INTL
NM	LOS ALAMOS	LOS ALAMOS
NM	ALBUQUERQUE	DOUBLE EAGLE II
NM	ALBUQUERQUE	ALBUQUERQUE INTL SUNPORT
NM	SILVER CITY	GRANT COUNTY
NV	ELY	ELY AIRPORT-YELLAND FIELD
NV	ELKO	ELKO REGIONAL
NV	RENO	RENO/STEAD
NV	RENO	RENO/TAHOE INTL
NV	MINDEN	MINDEN-TAHOE
NV	LAS VEGAS	MCCARRAN INTL
NV	LAS VEGAS	NORTH LAS VEGAS
NV	LAS VEGAS	HENDERSON EXECUTIVE
NV	WINNEMUCCA	WINNEMUCCA MUNI

NV	BATTLE MOUNTAIN	BATTLE MOUNTAIN
NY	LAKE PLACID	LAKE PLACID
OR	EUGENE	MAHLON SWEET FIELD
OR	MEDFORD	ROGUE VALLEY INTL-MEDFORD
OR	JOHN DAY	GRANT CO REGIONAL/OGILVIE FIELD
OR	LAKEVIEW	LAKE COUNTY
OR	PORTLAND	PORTLAND INTL
OR	PORTLAND	PORTLAND-TROUTDALE
OR	SUNRIVER	SUNRIVER
OR	LA GRANDE	LA GRANDE/UNION COUNTY
OR	BAKER CITY	BAKER CITY MUNI
OR	THE DALLES	COLUMBIA GORGE REGIONAL/THE DALLES MUNI
OR	GRANTS PASS	GRANTS PASS
OR	KLAMATH FALLS	KLAMATH FALLS
PR	PONCE	MERCEDITA
UT	DELTA	DELTA MUNI
UT	LOGAN	LOGAN-CACHE
UT	OGDEN	OGDEN-HINCKLEY
UT	PRICE	CARBON COUNTY
UT	PROVO	PROVO MUNI
UT	TOOELE	BOLINDER FIELD-TOOELE VALLEY
UT	MILFORD	MILFORD MUNI/BEN AND JUDY BRISCOE FIELD
UT	WENDOVER	WENDOVER
UT	RICHFIELD	RICHFIELD MUNI
UT	CEDAR CITY	CEDAR CITY REGIONAL
UT	HEBER CITY	HEBER CITY MUNI-RUSS MCDONALD FIELD
UT	HUNTINGTON	HUNTINGTON MUNI
UT	ST. GEORGE	SAINT GEORGE MUNI
UT	BRIGHAM CITY	BRIGHAM CITY
UT	SALT LAKE CITY	SALT LAKE CITY INTL
UT	SALT LAKE CITY	SALT LAKE CITY MUNI
VT	BENNINGTON	WILLIAM H MORSE STATE
WA	OMAK	OMAK
WA	YAKIMA	YAKIMA AIR TERMINAL/MCALLISTER FIELD
WA	SPOKANE	FELTS FIELD
WA	PUYALLUP	PIERCE COUNTY-THUN FIELD
WA	ARLINGTON	ARLINGTON MUNI
WA	BREMERTON	BREMERTON NATIONAL
WA	WENATCHEE	PANGBORN MEMORIAL
WA	ELLENSBURG	BOWERS FIELD
WA	WALLA WALLA	WALLA WALLA REGIONAL
WA	PORT ANGELES	PORT ANGELES CGAS
WA	PORT ANGELES	WILLIAM R. FAIRCHILD INTL
WA	BURLINGTON/MOUNT VERNON	SKAGIT REGIONAL
WV	PETERSBURG	GRANT COUNTY
WY	CODY	YELLOWSTONE REGIONAL
WY	AFTON	AFTON MUNI
WY	CASPER	NATRONA COUNTY INTL
WY	BUFFALO	JOHNSON COUNTY
WY	JACKSON	JACKSON HOLE
WY	GREYBULL	SOUTH BIG HORN COUNTY

WY	PINEDALE	RALPH WENZ FIELD
WY	SARATOGA	SHIVELY FIELD
WY	SHERIDAN	SHERIDAN COUNTY
WY	COWLEY-LOVELL-BYRON	NORTH BIG HORN COUNTY

Source: FAA Aviation System Standard

APPENDIX G STRATIFIED SAMPLING STRATA & WEIGHTS

Stratum	TAF Relevant Traffic (2000-2005 incl.)	Stratum share of total TAF relevant traffic	Sampled flights	Stratum share of total sampled flights	Weight
HAALF	1,250,158	0.65%	0	0.00%	N.A.
HAALT	929,768	0.48%	1243	0.51%	0.94
HACEF	4,932,783	2.57%	5322	2.20%	1.17
HAEAF	21,567,290	11.24%	26028	10.74%	1.05
HAGLF	20,049,157	10.45%	50604	20.87%	0.50
HANEF	4,731,238	2.47%	0	0.00%	N.A.
HANMF	6,089,146	3.17%	11403	4.70%	0.67
HANMT	4,279,446	2.23%	20483	8.45%	0.26
HASOF	29,120,284	15.17%	43886	18.10%	0.84
HASWF	14,202,438	7.40%	3899	1.61%	4.60
HASWT	753,505	0.39%	0	0.00%	N.A.
HAWPF	14,584,951	7.60%	47943	19.78%	0.38
HAWPT	8,857,981	4.62%	16271	6.71%	0.69
NAALF	4,118,123	2.15%	427	0.18%	12.18
NAALT	1,093,992	0.57%	0	0.00%	N.A.
NACEF	2,423,410	1.26%	965	0.40%	3.17
NAEAF	7,420,230	3.87%	4513	1.86%	2.08
NAEAT	24,256	0.01%	0	0.00%	N.A.
NAGLF	15,294,362	7.97%	1098	0.45%	17.60
NANEF	3,306,238	1.72%	1034	0.43%	4.04
NANET	1,722	0.00%	0	0.00%	N.A.
NANMF	4,398,816	2.29%	1637	0.68%	3.39
NANMT	2,545,756	1.33%	1589	0.66%	2.02
NASOF	8,657,697	4.51%	573	0.24%	19.09
NASOT	133,284	0.07%	750	0.31%	0.22
NASWF	5,104,589	2.66%	1134	0.47%	5.69
NASWT	232,655	0.12%	0	0.00%	N.A.
NAWPF	2,890,900	1.51%	248	0.10%	14.73
NAWPT	2,908,415	1.52%	1370	0.57%	2.68
TOTAL	191,902,590	100.00%	242420	100.00%	

Stratum Key:

First letter:
H = Hub
N = Non-hub

2nd, 3rd, 4th letters:
AAL = Alaska Region
ACE = Central Region
AEA = Eastern Region
AGL = Great Lakes Region
ANE = New England Region
ANM = Northwest Mountain Region
ASO = Southern Region
ASW = Southwest Region
AWP = Western Pacific Region

Final letter:
T = Significant Terrain
F = Non-significant Terrain

APPENDIX H SAMPLED AIRPORTS

Airport Code	Sampling Stratum	Runway Layout	Runway Operative Configuration
ADS	NASWF	Single	
ADW	NAEAF	2 Parallel	
ASE	NANMT	Single	
ASG	NASWF	Single	
ASH	NANEF	Single	
ATL	HASOF		Parallel
AUS	HASWF	2 Parallel	
AVL	NASOT	Single	
BCT	NASOF	Single	
BET	NAALF	Single	
BFI	NANMF	2 Parallel	
BFL	NAWPT	2 Parallel	
BGR	NANEF	Single	
BKL	NAGLF	2 Parallel	
BLI	NANMF	Single	
BOI	HANMT	2 Parallel	
CGF	NAGLF	Single	
CHD	NAWPF	2 Parallel	
CKB	NAEAF	Single	
CLE	HAGLF		Parallel
CMH	HAGLF	2 Parallel	
CWF	NASWF	Single	
DTW	HAGLF		Parallel
EGE	NANMT	Single	
EMT	NAWPT	Single	
ENA	NAALF	Single	
EUG	HANMT	2 Parallel	
EWR	HAEAF		Parallel
FAI	HAALT	2 Parallel	
FAT	HAWPF	2 Parallel	
FLG	NAWPT	Single	
FYV	NASWF	Single	
GCN	HAWPF	Single	
GLH	NASOF	2 Parallel	
GSP	HASOF	Single	
GYR	NAWPF	Single	
HEF	NAEAF	2 Parallel	
IND	HAGLF		Parallel
ISO	NASOF	Single	
JNU	HAALT	Single	
LAW	NASWF	Single	
LAX	HAWPF		Parallel
LGA	HAEAF		Parallel
LVK	NAWPF	2 Parallel	
LWB	NAEAF	Single	
MCI	HACEF		Parallel
MCO	HASOF		Parallel
MDT	HAEAF	Single	
MSP	HAGLF		Parallel
MYR	HASOF	Single	

NQA	NASOF	Single	
OJC	NACEF	Single	
ONT	HAWPT	2 Parallel	
OXC	NANEF	Single	
OXR	NAWPT	Single	
PDX	HANMT		Parallel
PHX	HAWPF		Parallel
PSP	HAWPT	2 Parallel	
RNT	NANMF	Single	
SAW	NAGLF	Single	
SCK	NAWPF	2 Parallel	
SEA	HANMF		Parallel
SFF	NANMT	2 Parallel	
SFO	HAWPF		Parallel
SJC	HAWPT		Parallel
SLC	HANMT		Parallel
SMO	NAWPT	Single	
SNA	HAWPT		Parallel
SQL	NAWPF	Single	
SUN	NANMT	Single	
SUS	NACEF	2 Parallel	
TEB	NAEAF		Single
TIW	NANMF	Single	
TTD	NANMT	Single	
TUP	NASOF	Single	
TUS	HAWPT		Parallel
TYS	HASOF	2 Parallel	
TZR	NAGLF	Single	

APPENDIX I CALCULATION OF RELEVANT TERMINAL AREA FORECAST TRAFFIC

Identifying the relevant traffic from Terminal Area Forecasts (TAFs) is important for deriving the weights to be applied to each stratum after stratified sampling because TAF's coverage goes beyond that of the population of flights of interest as defined by the accident database filtering criteria. TAF breaks down traffic into Air Carrier, Air Taxi & Commuter, General Aviation (GA) and Military flights. Whereas itinerant Air Carrier and Air Taxi & Commuter traffic is clearly relevant and Military operations not, only a portion of GA traffic is pertinent to the current study. The accident database only includes GA flights that involve aircraft of over 12,500lbs.

The 2002 FAA General Aviation and Air Taxi Activity (GAATA) survey was used to identify the portion of itinerant GA flights that is within the scope of the present research. The GAATA survey breaks down GA traffic by aircraft type. The relevant aircraft types were first identified. These are 2 Engine Turboprops, "Other" Turboprops, 2 engine Turbojets and "Other" Turbojets. Other aircraft types, such as single engine turboprops and turbojets and rotorcraft, were considered irrelevant.

For each aircraft type, the GAATA survey gives a breakdown of the fleet according to primary use (but not by FAA region). Four uses were considered relevant to the study. These are Business, Corporate, Air Tours and Sightseeing. Other uses such as Aerial Observation and External Load were deemed irrelevant. Air Taxi operations were not considered relevant because they are already explicitly identified and included in TAF. The following table shows the statistics for the relevant aircraft types and their primary use breakdown.

Aircraft Type	Fleet Size	Business	Corporate	Air Tours	Sight See	Proportion of fleet in relevant use
TBP 2 Engine	5,703	1,241	2,386	0	0	
% of fleet		21.76%	41.84%	0.00%	0.00%	63.60%
Turboprop Other	30	0	0	0	0	
% of fleet		0.00%	0.00%	0.00%	0.00%	0.00%
Turbojet 2 Engine	7,655	948	5,368	0	0	
% of fleet		12.38%	70.12%	0.00%	0.00%	82.51%
Turbojet: Other	701	170	323	0	0	
% of fleet		24.25%	46.08%	0.00%	0.00%	70.33%

The share of each fleet in relevant use was then applied correspondingly to the number of landings performed by each aircraft type per FAA region[15]. This yielded an approximate number of relevant GA landings in each FAA region, as shown below.

Alaskan	1.75%
Central	8.73%
Eastern	9.29%
Great Lakes	17.82%
New England	5.64%
Northwest	4.38%
Southern	6.92%
South Western	5.20%
Western-Pacific	3.93%
Overall	7.92%

Because the regional landings data is only broken down by aircraft type and region but not by primary use, the calculation assumes that the proportion of fleet in relevant use computed for each aircraft type (identified by their primary use) approximates the proportion of relevant landings of the respective aircraft types. Additionally, it was assumed that figures on the proportion of fleet in relevant use vary little from region to region.

The regional rates above were then applied to the TAF itinerant GA traffic statistics accordingly to deduce the number of relevant GA operations in each region and thus the total normal GA traffic that is relevant to the current study.

[15] The GAATA landing statistics includes air taxi aircraft but excludes commuter aircraft.

APPENDIX J BIVARIATE LOGISTIC REGRESSION RESULTS

Landing Overruns

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		274.187	p<.0001			
Eqpt_class AB	0.526	2.054	0.152	1.691	0.824	3.471
Eqpt_class D	-0.497	1.835	0.176	0.609	0.297	1.249
Eqpt_class E	1.709	54.755	p<.0001	5.523	3.512	8.685
Eqpt_class F	3.355	178.445	p<.0001	28.632	17.503	46.839
User_class (Ref:C/T)		103.581	p<.0001			
User_class F	1.735	63.407	p<.0001	5.669	3.699	8.689
User_class G	1.305	71.555	p<.0001	3.686	2.724	4.987
Eqpt_type T	1.329	86.841	p<.0001	3.778	2.857	4.997
Ceiling 100Ft	-0.095	200.843	p<.0001	0.91	0.898	0.922
Visband (Ref:8+)		343.673	p<.0001			
Visband <2	3.014	334.226	p<.0001	20.375	14.749	28.148
Visband 2-4	1.264	22.738	p<.0001	3.54	2.105	2.952
Visband 4-6	0.307	0.693	0.405	1.36	0.659	2.805
Visband 6-8	0.828	11.616	0.001	2.288	1.422	3.683
Fog	2.502	271.191	p<.0001	12.208	9.064	16.442
Dawn/Dusk	0.65	9.53	0.002	1.916	1.268	2.895
Xwind	0.074	20.747	p<.0001	1.077	1.043	1.112
Rain	1.312	72.481	p<.0001	3.712	2.744	5.02
Elec_storm	1.808	27.818	p<.0001	6.099	3.115	11.941
Temp10	-0.518	56.785	p<.0001	0.596	0.521	0.682
Icing	3.821	165.905	p<.0001	45.666	25.531	81.683
FrozPrep	3.287	60.216	p<.0001	26.75	11.663	61.352
Snow	3.043	210.279	p<.0001	20.967	13.897	31.634
Terrain	-0.069	0.098	0.754	0.933	0.604	1.441
Hub NH	1.553	101.802	p<.0001	4.724	3.494	6.387
For OD	-1.618	5.18	0.023	0.198	0.049	0.799

Landing Undershoots

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		284.458	p<.0001			
Eqpt_class AB	0.165	0.081	0.776	1.179	0.38	3.656
Eqpt_class D	-0.858	2.207	0.137	0.424	0.137	1.315
Eqpt_class E	1.666	26.961	p<.0001	5.293	2.822	9.929
Eqpt_class F	3.986	153.794	p<.0001	53.823	28.668	101.05
User_class (Ref:C/T)		54.085	p<.0001			
User_class F	1.786	49.269	p<.0001	5.964	3.622	9.82
User_class G	0.848	16.023	p<.0001	2.335	1.541	3.536
Eqpt_type T	1.919	107.826	p<.0001	6.817	4.745	9.793
Ceiling 100Ft	-0.106	153.154	p<.0001	0.899	0.884	0.915
Visband (Ref:8+)		239.331	p<.0001			
Visband <2	3.19	228.448	p<.0001	24.287	16.059	36.73
Visband 2-4	1.736	34.514	p<.0001	5.673	3.179	10.123
Visband 4-6	0.771	3.634	0.057	2.161	0.979	4.773
Visband 6-8	0.577	2.531	0.112	1.781	0.875	3.627
Fog	2.545	175.132	p<.0001	12.739	8.739	18.569
Dawn/Disk	0.13	0.154	0.695	1.138	0.596	2.175
Xwind	0.007	0.079	0.778	1.007	0.957	1.061

Rain	1.217	36.903	p<.0001	3.378	2.281	5.003
Elec_storm	1.896	20.376	p<.0001	6.659	2.923	15.169
Temp10	-0.6	48.487	p<.0001	0.549	0.464	0.65
Icing	4.356	206.635	p<.0001	77.926	43.029	141.126
FrozPrep	3.077	27.107	p<.0001	21.692	6.812	69.079
Snow	3.324	188.217	p<.0001	27.771	17.273	44.651
Terrain	0.506	4.77	0.029	1.658	1.053	2.611
Hub NH	1.454	56.784	p<.0001	4.281	2.933	6.248
For OD	-0.708	1.467	0.226	0.493	0.157	1.549

Take-off Overrun

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		71.617	p<.0001			
Eqpt_class AB	1.254	3.931	0.047	3.505	1.014	12.108
Eqpt_class D	-0.38	0.27	0.603	0.684	0.163	2.863
Eqpt_class E	1.68	11.672	0.001	5.364	2.046	14.059
Eqpt_class F	3.426	43.978	p<.0001	30.765	11.175	84.695
User_class (Ref:C/T)		16.011	p<.0001			
User_class F	1.569	14.037	p<.0001	4.801	2.113	10.909
User_class G	0.728	5.111	0.024	2.071	1.102	3.894
Eqpt_type T	1.046	13.884	p<.0001	2.847	1.642	4.936
Ceiling 100Ft	-0.048	8.988	0.003	0.953	0.924	0.983
Visband (Ref:8+)		21.019	p<.0001			
Visband <2	1.739	19.65	p<.0001	5.69	2.638	12.274
Visband 2-4	-0.74	0.532	0.466	0.477	0.065	3.484
Visband 4-6	0.4	0.574	0.449	1.492	0.53	4.198
Visband 6-8	0.059	0.012	0.911	1.061	0.377	2.985
Fog	1.543	17.686	p<.0001	4.677	2.279	9.599
Dawn/Disk	0.445	0.894	0.344	1.56	0.62	3.924
Xwind	0.082	7.153	0.007	1.086	1.022	1.154
Rain	0.855	6.745	0.009	2.352	1.233	4.484
Elec_storm	-13.442	0	0.991	0	0	NA
Temp10	-0.415	10.168	0.001	0.661	0.512	0.852
Icing	2.676	6.98	0.008	14.522	1.995	105.698
FrozPrep	3.179	9.816	0.002	24.024	3.288	175.529
Snow	3.135	59.11	p<.0001	22.994	10.34	51.137
Terrain	-0.114	0.069	0.792	0.892	0.381	2.089
Hub NH	1.274	18.558	p<.0001	3.574	2.002	6.381
For OD	0.898	4.273	0.039	2.545	1.048	5.747

Crashes after Take-off

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		96.717	p<.0001			
Eqpt_class AB	0.849	2.591	0.107	2.336	0.831	6.565
Eqpt_class D	-0.457	0.67	0.413	0.633	0.212	1.89
Eqpt_class E	1.21	9.874	0.002	3.352	1.576	7.129
Eqpt_class F	3.126	60.556	p<.0001	22.789	10.37	50.084
User_class (Ref:C/T)		79.486	p<.0001			
User_class F	2.634	79.437	p<.0001	13.93	7.805	24.861
User_class G	1.1	13.886	p<.0001	3.005	1.685	5.36
Eqpt_type T	1.267	26.802	p<.0001	3.549	2.194	5.734
Ceiling 100Ft	-0.075	37.069	p<.0001	0.928	0.906	0.95

Visband (Ref:8+)		65.249	p<.0001			
Visband <2	2.376	62.882	p<.0001	10.765	5.983	19.368
Visband 2-4	0.814	2.917	0.088	2.257	0.887	5.745
Visband 4-6	-0.349	0.231	0.631	0.706	0.17	2.928
Visband 6-8	0.563	1.865	0.172	1.756	0.783	3.94
Fog	1.947	46.078	p<.0001	7.011	3.995	12.301
Dawn/Disk	0.822	5.263	0.022	2.276	1.127	4.595
Xwind	0.048	2.237	0.135	1.049	0.985	1.116
Rain	0.98	12.178	p<.0001	2.665	1.537	4.622
Elec_storm	0.567	0.316	0.574	1.762	0.244	12.71
Temp10	-0.461	16.348	p<.0001	0.631	0.504	0.789
Icing	4.288	97.256	p<.0001	72.848	31.065	170.827
FrozPrep	4.593	93.312	p<.0001	98.81	38.91	250.924
Snow	2.998	62.776	p<.0001	20.043	9.548	42.077
Terrain	-0.834	2.618	0.106	0.434	0.158	1.193
Hub NH	0.641	6.87	0.009	1.899	1.176	3.067
For OD	-0.126	0.045	0.831	0.882	0.277	2.808

APPENDIX K MULTIVARIATE LOGISTIC REGRESSION RESULTS

Landing Overruns

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		96.658	p<.0001			
Eqpt_class AB	0.486	1.614	0.204	1.626	0.768	3.442
Eqpt_class D	-1.631	14.651	p<.0001	0.196	0.085	0.451
Eqpt_class E	0.893	7.047	0.008	2.443	1.263	4.724
Eqpt_class F	1.951	25.734	p<.0001	7.036	3.311	14.951
Eqpt_type T	1.050	20.578	p<.0001	2.859	1.816	4.501
User_class (Ref:C/T)		23.441	p<.0001			
User_class F	0.934	14.651	p<.0001	2.544	1.577	4.104
User_class G	0.835	13.743	p<.0001	2.305	1.482	3.584
For OD	-1.565	4.360	0.037	0.209	0.048	0.909
Ceiling 100Ft	-0.014	1.596	0.206	0.986	0.965	1.008
Visband (Ref:8+)		63.022	p<.0001			
Visband <2	1.443	20.639	p<.0001	4.232	2.271	7.885
Visband 2-4	-0.239	0.476	0.490	0.787	0.399	1.552
Visband 4-6	-1.429	7.842	0.005	0.239	0.088	0.651
Visband 6-8	0.276	1.136	0.287	1.318	0.793	2.191
Fog	2.437	96.815	p<.0001	11.444	7.042	18.596
Dawn/Dusk	0.486	4.535	0.033	1.626	1.040	2.545
Xwind	0.089	31.157	p<.0001	1.094	1.060	1.128
Icing conditions	2.164	30.307	p<.0001	8.705	4.029	18.809
Snow	1.860	47.762	p<.0001	6.426	3.791	10.891
Hub NH	0.588	6.937	0.008	1.801	1.162	2.791
Terrain	0.417	2.928	0.087	1.517	0.941	2.446
Constant	-8.431	447.335	p<.0001	0.000		

Landing Undershoots

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		89.131	p<.0001			
Eqpt_class AB	0.139	0.056	0.814	1.149	0.362	3.651
Eqpt_class D	-2.017	9.936	0.002	0.133	0.038	0.466
Eqpt_class E	1.457	12.084	0.001	4.293	1.888	9.760
Eqpt_class F	2.932	38.560	p<.0001	18.766	7.438	47.347
Eqpt_type T	1.086	11.750	0.001	2.963	1.592	5.513
User_class (Ref:C/T)		11.363	0.003			
User_class F	0.894	9.210	0.002	2.445	1.373	4.356
User_class G	0.610	4.011	0.045	1.841	1.013	3.346
Ceiling 100Ft	-0.017	1.787	0.181	0.983	0.958	1.008
Visband (Ref:8+)		37.140	p<.0001			
Visband <2	1.881	24.735	p<.0001	6.560	3.126	13.767
Visband 2-4	0.446	1.297	0.255	1.562	0.725	3.367
Visband 4-6	-0.234	0.213	0.644	0.791	0.293	2.139
Visband 6-8	0.321	0.739	0.390	1.379	0.663	2.870
Fog	1.738	35.348	p<.0001	5.687	3.206	10.086
Xwind	0.043	2.382	0.123	1.044	0.988	1.103
Icing conditions	3.775	54.710	p<.0001	43.609	16.037	118.588
Frozen precipitation	-2.562	7.346	0.007	0.077	0.012	0.492
Snow	2.011	33.332	p<.0001	7.469	3.774	14.782
Terrain	0.819	9.151	0.002	2.268	1.334	3.855

Constant	-8.911	296.667	p<.0001	0.000

Take-off Overrun

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		83.924	p<.0001			
Eqpt_class AB	1.157	3.226	0.072	3.182	0.900	11.250
Eqpt_class D	-0.485	0.437	0.509	0.616	0.146	2.592
Eqpt_class E	2.082	17.124	p<.0001	8.018	2.991	21.489
Eqpt_class F	3.860	53.108	p<.0001	47.455	16.805	134.003
Foreign O/D	0.968	4.427	0.035	2.633	1.069	6.487
Ceiling 100Ft	-0.008	0.099	0.753	0.992	0.944	1.020
Visband (Ref:8+)		6.351	0.174			
Visband <2	0.320	0.187	0.666	1.377	0.323	5.869
Visband 2-4	-2.077	3.470	0.062	0.125	0.014	1.114
Visband 4-6	-0.470	0.560	0.454	0.625	0.183	2.141
Visband 6-8	-0.544	0.957	0.328	0.581	0.195	1.726
Fog	1.847	11.073	0.001	6.342	2.136	18.823
Xwind	0.093	9.453	0.002	1.098	1.034	1.165
Temperature	-0.254	2.961	0.085	0.776	0.581	1.036
Snow	2.932	31.268	p<.0001	18.760	6.714	52.423
Constant	-9.281	113.325	p<.0001	0.000		

Crashes after Take-off

Variable	B	Wald	Sig.	Exp(B)	Lower 95CI for Exp(B)	Upper 95CI for Exp(B)
Eqpt_class (Ref:C)		42.533	p<.0001			
Eqpt_class AB	0.760	1.784	0.182	2.138	0.701	6.519
Eqpt_class D	-0.776	1.408	0.235	0.460	0.128	1.658
Eqpt_class E	1.251	4.431	0.035	3.496	1.090	11.210
Eqpt_class F	2.842	19.569	p<.0001	17.149	4.868	60.404
Eqpt_type T	0.934	4.660	0.031	2.545	1.090	5.943
User_class (Ref:C/T)		37.327	p<.0001			
User_class F	2.049	35.528	p<.0001	7.764	3.957	15.232
User_class G	1.316	7.820	0.005	3.730	1.483	9.386
Ceiling 100Ft	-0.003	0.019	0.890	0.997	0.960	1.036
Visband (Ref:8+)		17.213	0.002			
Visband <2	1.307	5.304	0.021	3.694	1.215	11.231
Visband 2-4	-0.790	1.464	0.226	0.454	0.126	1.632
Visband 4-6	-1.104	2.000	0.157	0.331	0.072	1.532
Visband 6-8	0.178	0.168	0.682	1.195	0.509	2.810
Fog	1.753	14.926	p<.0001	5.771	2.372	14.044
Dawn/Dusk	0.683	3.336	0.068	1.980	0.951	4.120
Xwind	0.074	5.967	0.015	1.076	1.015	1.142
Icing conditions	2.246	9.040	0.003	9.449	2.185	40.851
Frozen precipitation	2.188	6.332	0.012	8.915	1.622	48.991
Snow	2.561	28.741	p<.0001	12.945	5.076	33.013
Hub NH	-0.734	5.190	0.023	0.480	0.255	0.903
Terrain	-1.213	4.718	0.030	0.297	0.100	0.888
Constant	-9.540	186.050	p<.0001	0.000		

APPENDIX L MODEL FUNCTIONAL FORM JUSTIFICATION

The functional form of the accident model seems to suggest that the probability of accident occurrence varies exponentially with the independent variables. While such a relationship between the dependent and independent variables appears to be an implied assumption, it is in fact related to the nature of a dichotomous regression problem and how logistic regression deals with that (Pampel 2000).

Models of a dichotomous response (e.g. accident and non-accident) have a 'boundary problem', which must be taken into account when regression analysis is performed. The 'boundary problem' stems from the fact that probabilities have maximum and minimum values of one and zero whereas a normal linear regression line can extend towards both positive and negative infinity giving predicted values of the dependent variable above one and below zero. The one and zero limit creates a floor and a ceiling to the dependent variable. As such, it is likely that the effect of a unit change in the independent variable on the predicted probability would be smaller near the floor or ceiling than near the middle. The general principle is that the same additional input has less impact on the outcome near the ceiling or floor and that increasingly large inputs are needed to have the same impact on the outcome near the ceiling or floor. A linear relationship would understate the actual relationship in the middle and overstate the relationship at the extremes.

The dependent variable's ceiling and floor also pose issues of additivity. Regression usually assumes additivity – that the effect of changes in one variable on the dependent variable stays the same regardless of the levels of the other independent variables[16]. Models can include selected product terms to account for non-additivity but a dichotomous dependent variable is likely to violate the additivity assumption for all combinations of the independent variables. If the value of one independent variable reaches a sufficiently high level to push the probability of the dependent variable to near the ceiling or the floor, then the effects of other variables cannot have much influence. The ceiling and floor make the influence of all independent variables inherently non-additive and interactive.

[16] This is not to be confused with the impact of slightly collinear X variables in a multiple regression.

The assumptions of normality and homoscedasticity are also violated as a result of only having two observed values for the dependent variable. Logistic regression overcomes these difficulties by transforming probabilities into logits. This transformation could be viewed as linearising the inherent non-linear relationship between X and the probability of Y. The floor and ceiling are eliminated as the logit expands or stretches the probabilities of Y at extreme values relative to the values near the midpoint, such that the same change in X comes to have similar effects throughout the range of the logit transformation of the probability of Y. In other words, the logit can relate linearly to changes in X. The logit transformation has straightened out the non-linear relationship between X and the original probabilities. The exponentiation of the model function results from transforming the model to express probability, rather than the logit, as a function of X.

In short, the dichotomous nature of the model creates a 'boundary problem' of having a ceiling and a floor to the dependent variable. Logistic regression overcomes the 'boundary problem', along with the violations of regression assumptions that it brings, by estimating the linear determinants of the logged odds or logit rather than the non-linear determinants of probabilities. As a result of this logit transformation, the probability model takes up an exponential form. Therefore, the exponential nature of the model reflects the inherent non-linear behaviour of probabilities in a regression model rather than that specifically related to accident occurrence.

APPENDIX M NORMALISED ACCIDENT LOCATION CCPDS

The current study explored the normalisation of the accident location x distances by the respective available runway lengths. As a result, x distances are expressed as percentages of LDA or TODA. This may provide a better comparison between the accident cases and accounts for the lengths of the runways involved, especially for overruns and crashes after take-off.

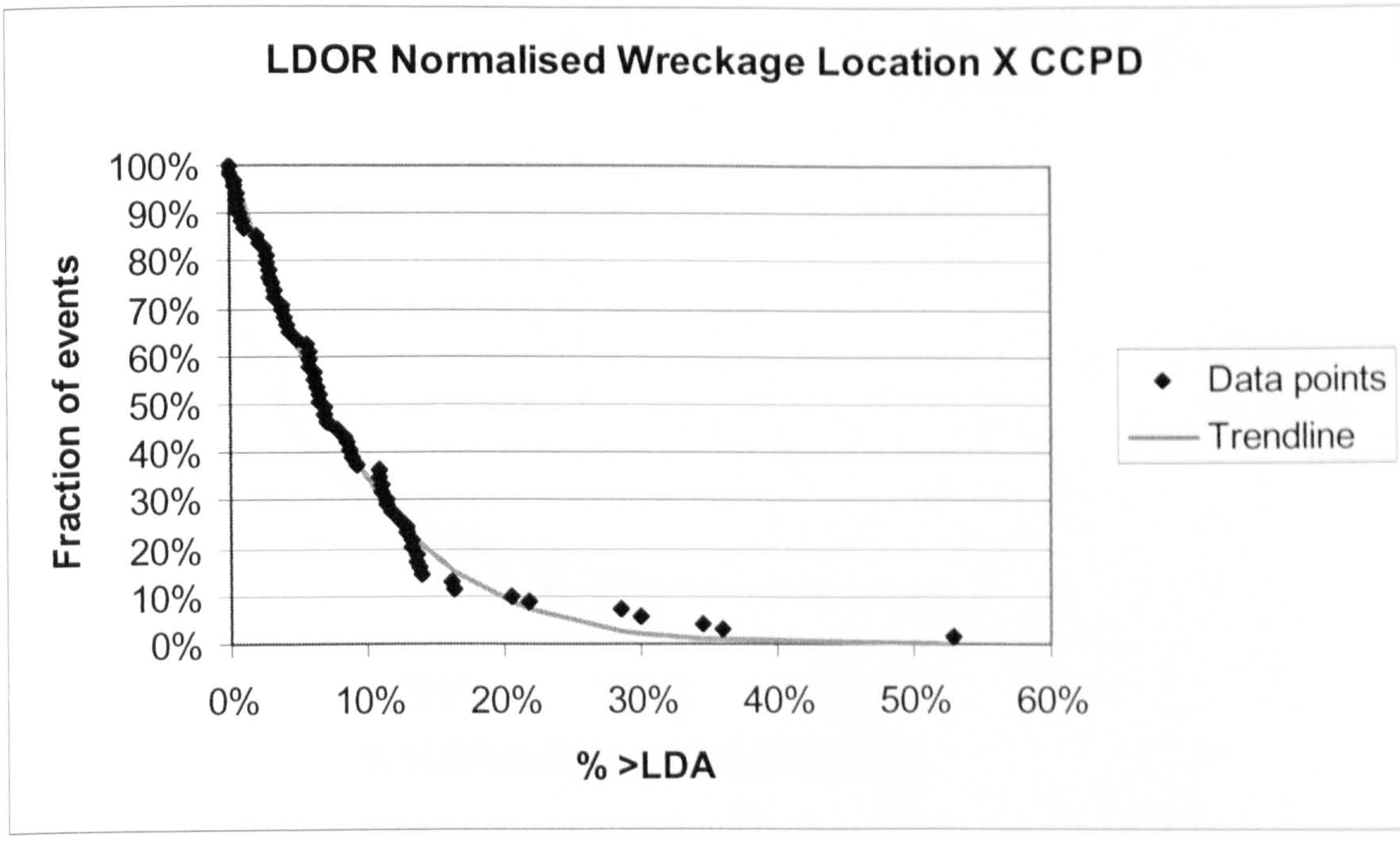
Due to the relatively uniform width of runways, the effect of varying runway widths was not expected to be great and so normalisation by runway width available was not carried out.

The effect of using normalised CCPDs for risk assessment is detailed in Appendix N.

<u>CCPD scenario 1 x distance</u>

For scenario 1, the cases that challenge longitudinal ASAs are those with final wreckage sites beyond the runway end. Out of 133 landing overruns with known wreckage locations, 71 cases involved x locations beyond the runway end. The x distances from the runway end to the final wreckage sites were measured and normalised as a percentage of LDA. Two cases with x distances of over 100 percent LDA were considered outliers and were removed. The remaining 69 cases were used to plot the CCPD, as shown in Figure M.1.

Figure M.1 Scenario 1 x distance CCPD

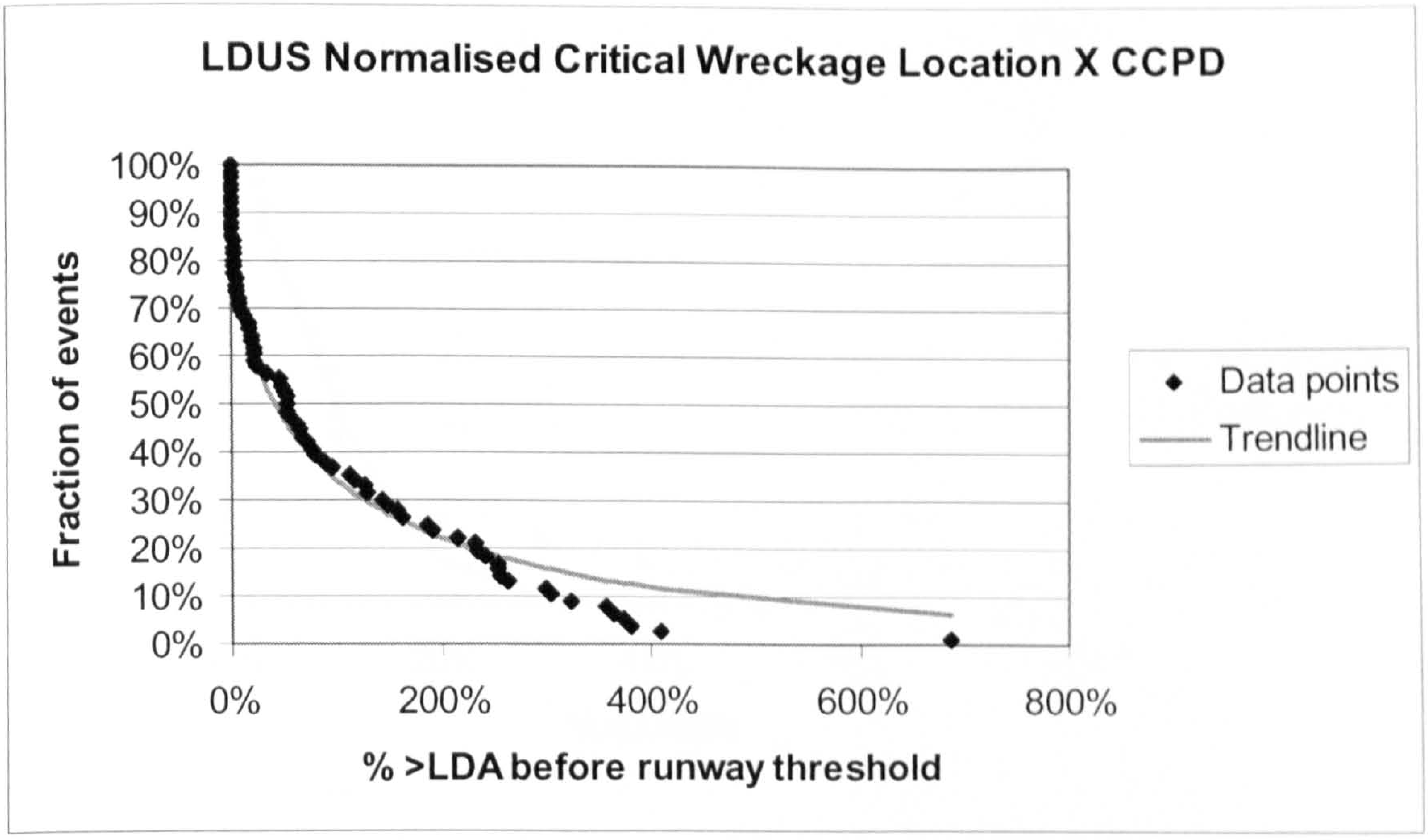


The CCPD shows that 80 percent of cases involve overrun distances more than 2.6 percent of LDA beyond the runway end. For a runway of 5000ft, this translates into an overrun distance of 130ft beyond the runway end. The plot also shows that 36.2 percent of cases involve overrun distances of 10 percent of LDA or more beyond the runway end. For the same 5000ft runway, this entails overrun distances of 500ft or more.

CCPD scenario 2 x distance

For scenario 2, the cases that challenge longitudinal ASAs are those with POFIs and/or final wreckage sites before the runway threshold. Out of 105 landing undershoots with known wreckage information, 78 cases involved x locations beyond the runway end. The critical x distances from the POFI/final wreckage site to the runway threshold were measured and normalised as a percentage of LDA. The LDAs for two cases were not known and were therefore removed. The remaining 76 cases were used to plot the CCPD, as shown in Figure M.2.

Figure M.2 Scenario 2 x distance CCPD

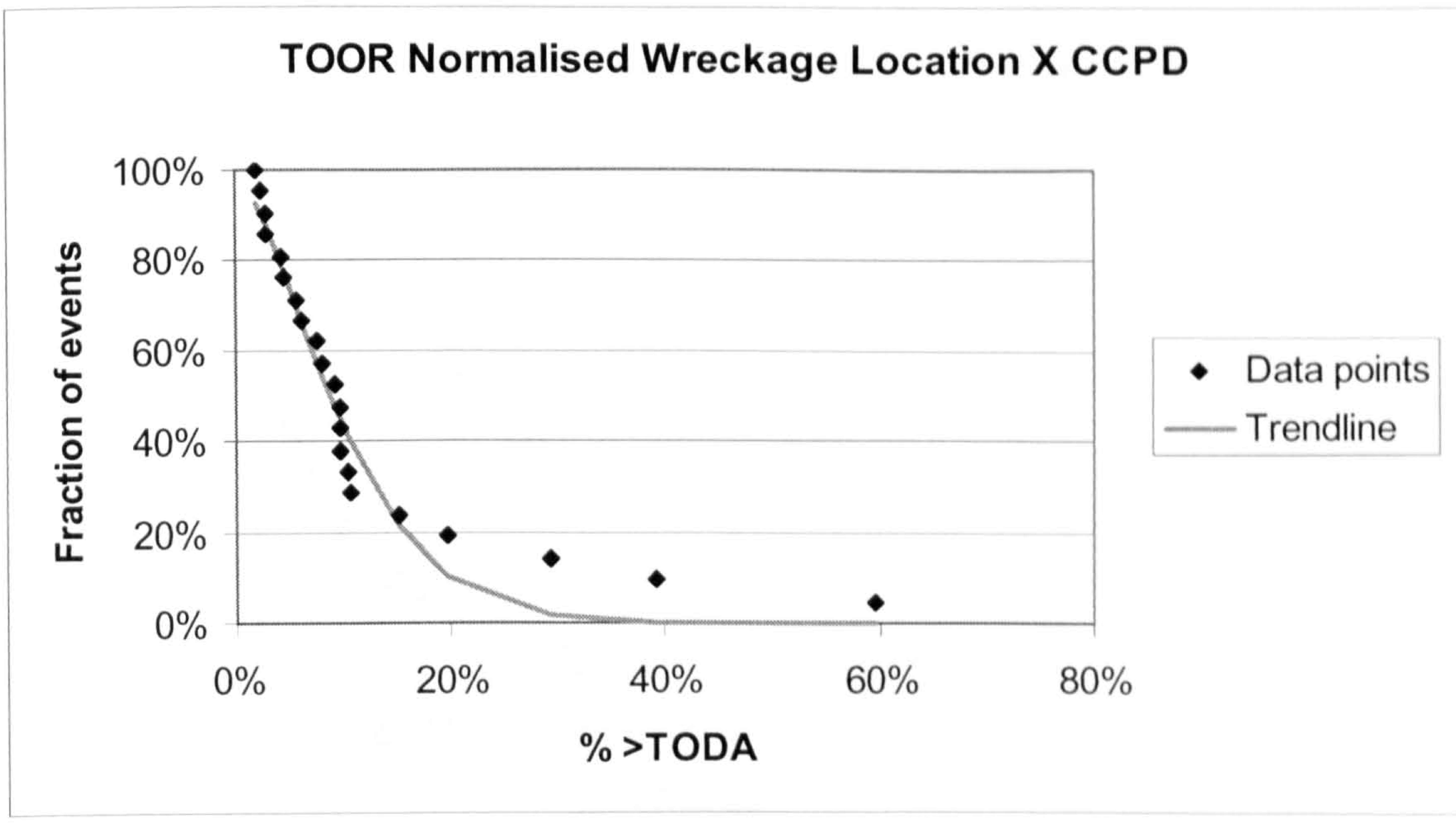


The CCPD shows that 80 percent of cases involve undershoot distances of more than 2.3 percent of LDA from the runway threshold. For a runway of 5000ft, this translates into an overrun distance of 115ft beyond the runway end. The plot also shows that a significant proportion of occurrences involve very large x distances. Roughly 22.5 percent of cases involve undershoot distances of 200 percent of LDA or more from the runway threshold. For the same 5000ft runway, this entails undershoots distances of 10,000ft or more. The greater x distances compared to landing overruns were expected due to the airborne nature of undershoots.

CCPD scenario 3 x distance

For scenario 3, the cases that challenge longitudinal ASAs are those with final wreckage sites beyond the runway end. Out of 37 take-off overruns with known wreckage locations, 21 cases involved x locations beyond the runway end. The x distances from the runway end to the final wreckage sites were measured and normalised as a percentage of TODA. Figure M.3 shows the corresponding CCPD.

Figure M.3 Scenario 3 x distance CCPD

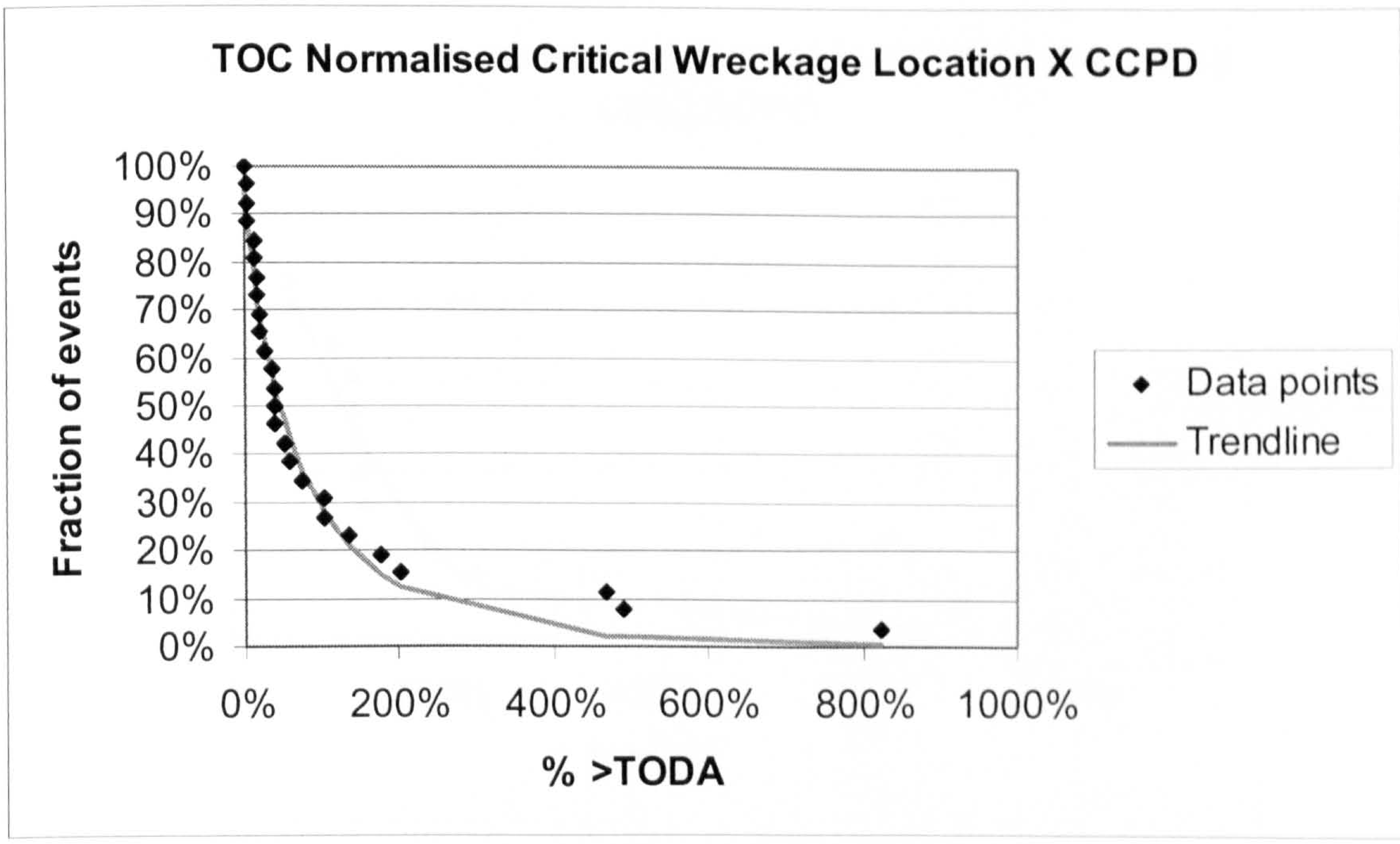


The CCPD shows that 80 percent of cases involve overrun distances of more than 4.2 percent of LDA beyond the runway end. For a runway of 5000ft, this translates into an overrun distance of 210ft beyond the runway end. The greater overruns distances compared to landing overruns are probably due to the high energy nature of many take-off overruns. The plot also shows that 33 percent of cases involve overrun distances of 10 percent of TODA or more beyond the runway end. For the same 5000ft runway, this entails overrun distances of 500ft or more.

CCPD scenario 4 x distance

For scenario 4, the cases that challenge longitudinal ASAs are those with POFIs and/or final wreckage sites beyond the runway end. Out of 57 crashes after take-off with known wreckage information, 26 cases involved x locations beyond the runway end. The critical x distances from the runway end to the POFI/final wreckage site were measured and normalised as a percentage of TODA. The LDAs for two cases were not known and were therefore removed. Figure M.4 shows the corresponding CCPD.

Figure M.4 Scenario 4 x distance CCPD

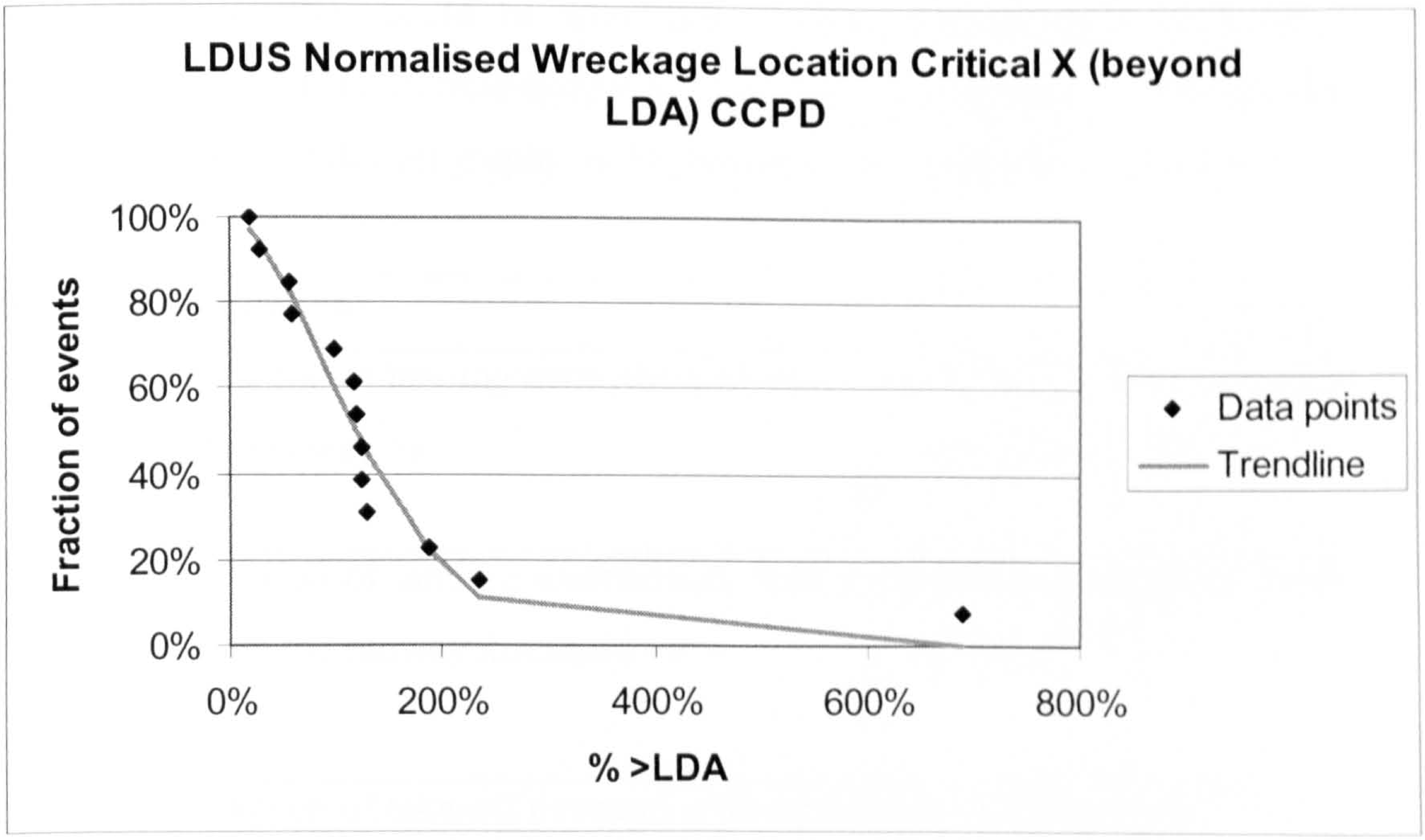


The CCPD shows that 80 percent of cases involve x distances of more than 11.3 percent of TODA from the runway threshold. For a runway of 5000ft, this translates into an x distance of 565ft beyond the runway end. Similar to landing undershoots, the plot also shows a significant proportion of cases involve very large x distances. Roughly 15.4 percent of cases involve undershoot distances of 200 percent of LDA or more from the runway threshold. For the same 5000ft runway, this entails undershoots distances of 10,000ft or more. The greater x distances compared to take-off overruns were expected due to the airborne nature of crashes after take-off.

CCPD scenario 5 x distance

For scenario 5, the cases of concern are landing undershoots with positive x distances beyond the LDA. Out of 105 landing undershoots with known wreckage information, thirteen cases fall into this category. The critical x distances from the POFI/final wreckage site to the runway end were measured and normalised as a percentage of LDA. Figure M.5 shows the corresponding CCPD.

Figure M.5 Scenario 5 x distance CCPD



The CCPD shows that approximately 80 percent of cases involve x distances beyond the runway end exceeding 61.4 percent of LDA from the runway threshold. For a runway of 5000ft, this translates into an overrun distance of 3072ft beyond the runway end. The large x distances suggest that the majority of the cases involved accidents far from the airports' immediate surroundings, where both POFIs and final wreckage sites are a distance away from the runway ends. The accident database indicates the same.

CCPD scenario 6 x distance

For scenario 6, the cases of concern are crashes after take-off with negative x distances, i.e. POFIs and/or final wreckage sites before the start-of-roll runway threshold. Out of 57 crashes after take-off with known wreckage information, only two cases fall into this category. Only one case had the corresponding TODA information. Its critical x distance is 135.77 percent The large distance suggests that the event was altogether removed from the immediate surroundings of the airport. The y distance confirms this. The lack of data prevents the CCPD and its trend equation to be computed.

CCPD Equations

The various CCPDs could be fitted into exponential functions as listed in the following table. Their corresponding R^2 values are also indicated. The functions are also plotted in the relevant graphs in this appendix and labelled as 'Trendline'.

Scenario	Equation	R^2
1	Fraction of landing overruns with an overrun distance beyond the runway >x = $e^{-15.261x^{1.156}}$	0.993
2	Fraction of landing undershoots with an undershoot distance from the runway threshold >x = $e^{-1.07x^{0.497}}$	0.984
3	Fraction of take-off overruns with an overrun distance beyond the runway >x = $e^{-24.00x^{1.465}}$	0.964
4	Fraction of crashes after take-off with an x distance from the runway end >x = $e^{-1.251x^{0.734}}$	0.982
5	Fraction of landing undershoots with an x distance beyond the runway end >x = $e^{-0.512x^{1.704}}$	0.946

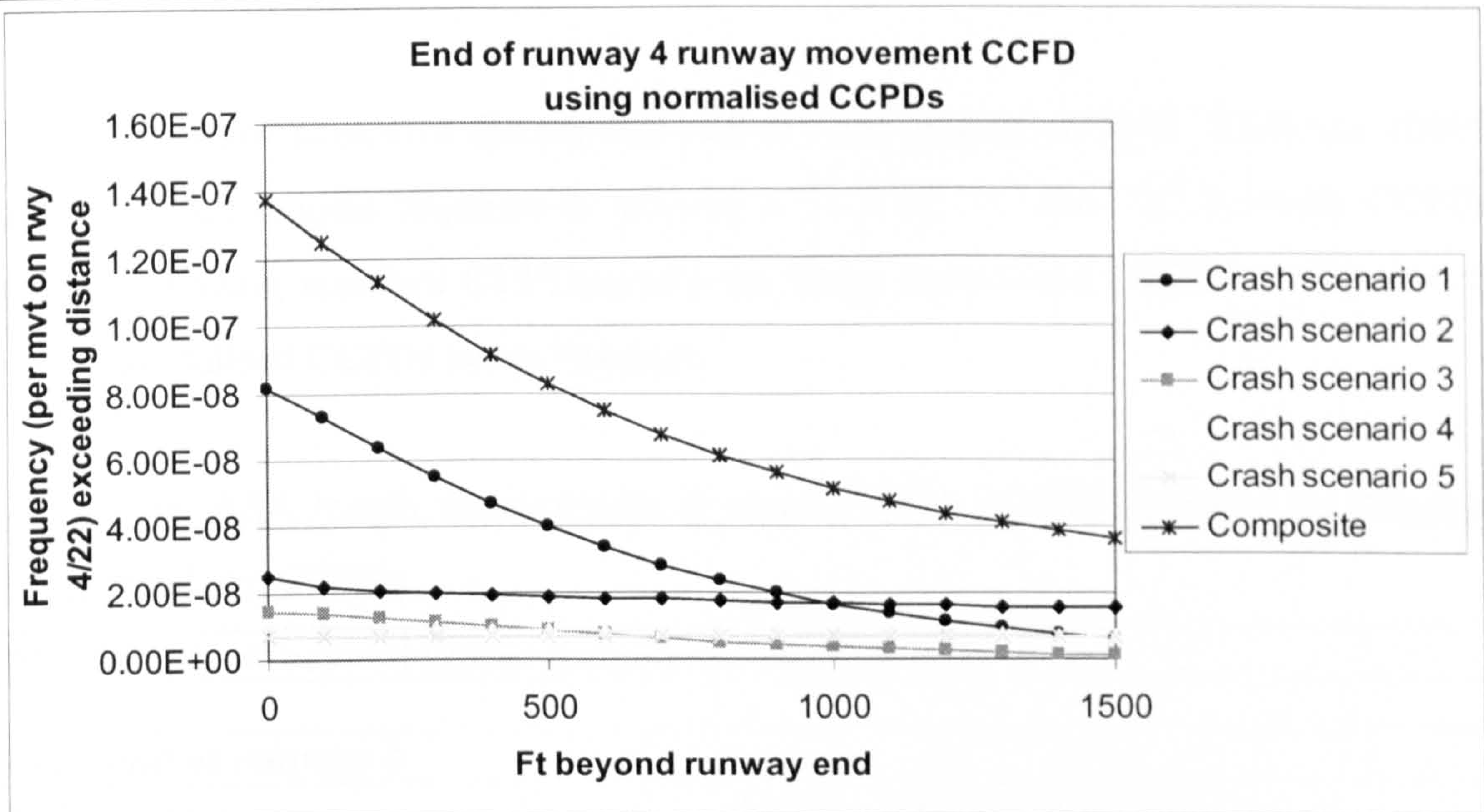
Although the overall fit of the functions are good, all of them, except for scenario 2, underestimate the proportion of cases involving large deviations. It would therefore be more prudent to only use the fitted functions for small and moderate deviation estimates.

APPENDIX N USING NORMALISED CCPDS FOR ASA ASSESSMENT

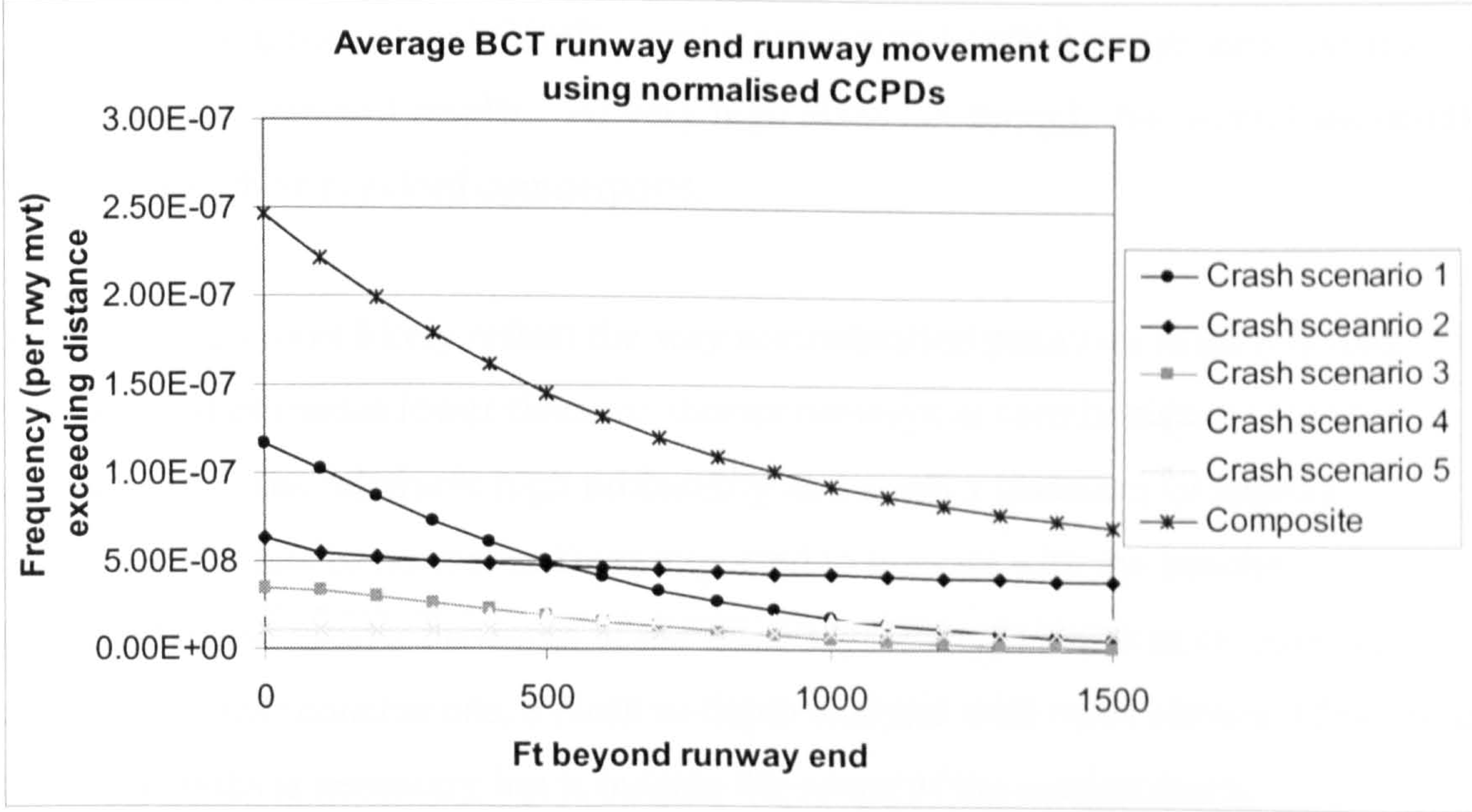
The research explored the impact of using normalised CCPDs of landing overruns, take-off overruns and crashes after take-off for risk assessment. Normalised CCPDs were not used for landing undershoots (crash scenario 2 and 5) because it is not expected that the runway length has much influence on landing undershoot locations.

The following graphs display the runway movement CCFDs calculated using normalised CCPDs for the end of runway 4 at LGA and the average runway end at BCT.

<u>Normalised runway movement CCFDs for end of runway 4 at LGA</u>



Normalised runway movement CCFDs for the average runway end at BCT



The table below compares the residual risk at ASA lengths of 300ft, 600ft and 1000ft and the ASA lengths required to achieve a TLS of 10^{-7} and 10^{-8} between CCFDs calculated using standard CCPDs and ones using normalised CCPDs. The results using normalised CCPDs are in brackets.

Comparing ASA length requirements & residual risks of CCFDs based on standard and normalised CCPDs

ASA length (ft beyond runway end)	**Residual risk**
LGA end of runway 4	
300	9.605×10^{-8} (1.020×10^{-7})
600	6.807×10^{-8} (7.447×10^{-8})
1000	4.676×10^{-8} (5.111×10^{-8})
267 (319)	*1.000×10^{-7}*
11690 (12254)	*1.000×10^{-8}*
BCT average runway end	
300	1.772×10^{-7} (1.793×10^{-7})
600	1.311×10^{-7} (1.312×10^{-7})
1000	9.500×10^{-8} (9.289×10^{-8})
927 (903)	*1.000×10^{-7}*
25302 (26073)	*1.000×10^{-8}*

The results using the two methods are broadly similar. For the end of runway 4 at LGA, residual risks and ASA requirements are all higher if calculated with normalised CCPDs than standard ones. For BCT, residual risk figures are higher if calculated using normalised CCPDs until approximately 600ft, when they become lower than the standard results. At very high distances though, the normalised results again exceed their standard counterparts.

These findings most likely reflect the way normalisation penalises relatively long runways and estimates lower risks for shorter runways at certain distances from the runway end. The relatively high probability and small x distances of landing overruns (absolute or normalised) are expected to interact with the smaller probabilities but greater distances of the other accident types such as crashes take-offs. For firmer conclusions, a more in-depth analysis with more airports of different runway lengths is necessary but is outside the scope of the current thesis.