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HEALTH & SAFETY LABORATORY

Module 14. Operational Efficiency: Ground Risk Analysis

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EXECUTIVE SUMMARY

The Health and Safety Laboratory (HSL) were asked by the Airports Commission to assess the likelihood of an aircraft crash in the vicinity of Heathrow and Gatwick airports. The Airports Commission were interested in the change in the likelihood of an aircraft crash in the year 2050 for expansion at either Heathrow or Gatwick compared to there being no expansion at either airport. Two proposed expansion plans at Heathrow and one proposed plan at Gatwick are under consideration for possible future expansion. Three different growth scenarios for the future of each airport have also been considered as part of this analysis.

An aircraft crash is defined as an uncontrolled landing or mid-air break-up leading to serious damage to the aircraft and/or at least one fatality. Due to the way the accidents are recorded, the fatality relates to people on board the aircraft, not to those on the ground. The likelihood of an aircraft crash, therefore, does not indicate the risk of death to a person on the ground should a crash occur. This is likely to be several orders of magnitude lower than the aircraft crash rates. This is due to a number of factors including the size of the crash location, the population within the location, the possible shielding effects from buildings, and other mitigating factors that will reduce the likelihood of a fatality occurring to a person on the ground from any aircraft crash calculated in this analysis.

A methodology to calculate the aircraft crash likelihood was developed following a review of the literature and an analysis of the available data. This involved calculating a background crash rate for five different categories of aircraft (light aircraft, helicopters, small transport aircraft, large transport aircraft and military aircraft) and calculating an airfield specific crash rate for these aircraft types at Heathrow and Gatwick airports.

The calculations were carried out to assess the crash likelihood for the two airports in the year 2013 and for a number of different scenarios in the year 2050. A trend analysis was performed on the data to determine if the number of crashes had increased or decreased over time. A 95% confidence interval was calculated in all cases.

The results indicate that the changes to the background crash rate are minimal, regardless of whether or not expansion takes place at the airports. It was also found that there had been a downward trend in the number of crashes from the data for the light aircraft, helicopters and military aircraft categories. No trend could be seen in the small transport aircraft category. The data for the large transport aircraft category was too sparse to perform a trend analysis.

The maximum airfield related crash rate in 2050 for Heathrow after airport expansion is lower than the rate that was presented to the Terminal 5 Inquiry. In 2000, the crash rate was predicted to be 1 every 14 years both with and without Terminal 5. This is equivalent to a rate of 7×10^{-2} per year and is over 10% higher than the highest forecast of 6×10^{-2} per year in this report. The maximum crash rates for Gatwick airport are lower than for Heathrow.

The airfield related crash rates have been split by take-offs and landings and by direction from the airport i.e. west or east. A narrative description has been given of the areas surrounding the airports to discuss where the crash rate is highest in the vicinity of the airports. The background crash rate applies to areas that are greater than 10 km (~5 nautical miles) from the airports. A proportion of the take-off and landing crash rates, or the west and east crash rates, apply within a radius of 10 km from the airports.

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1 INTRODUCTION

The Airports Commission asked the Health and Safety Laboratory (HSL) to assess the relative likelihoods of an aircraft crash in the year 2050 from potential expansion at either Heathrow or Gatwick airports when compared to there being no expansion at either airport. For this analysis, an aircraft crash is defined as an uncontrolled landing or mid-air break-up leading to serious damage to the aircraft and/or at least one fatality.

HSL provide scientific research and advice on health, safety and risk across a broad range of sectors for the Health and Safety Executive (HSE), other government departments and industry. HSL has previously calculated the aircraft crash risk for specific sites in the vicinity of airports, for which the aircraft crash likelihoods requested in this work formed part of the calculation.

There are two expansion plans under consideration for Heathrow airport and one expansion plan under consideration for Gatwick airport. The Airports Commission asked HSL to assess the aircraft crash likelihoods for locations in the vicinity of the two airports using historical data and projections of aircraft movements for the year 2050.

The plans investigated for the two airports to consider the potential expansion options are:

- Do Minimum: no expansion;
- ENR: extended northern runway at Heathrow;
- NWR: additional northwest runway at Heathrow;
- 2R: 2 runways at Gatwick.

The Airports Commission also provided HSL with three different growth scenarios for each airport for the year 2050 to account for different potential future traffic at the two airports. The growth scenarios used in the analysis are:

- AoN CT: Assessment of Need – Carbon Traded;
- AoN CC Assessment of Need – Carbon Capped;
- GGCT: Global Growth – Carbon Traded (Heathrow only);
- LCIK CT: Low Cost is King – Carbon Traded (Gatwick only).

The definitions of the growth scenarios are:

- AoN: Assessment of Need
  Future demand is primarily determined by central projections published by sources such as the Office for Budget Responsibility, Organisation for Economic Co-operation and Development (OECD) and the International Monetary Fund (IMF);
- GG: Global Growth
  Higher global growth in demand for air travel in the future, coupled with lower airline operating costs;

- LCIK: Low Cost is King
  Low-cost carriers strengthening their position in the short-haul market and capturing a substantial share of the long-haul market. It also sees higher passenger demand from all world regions and lower operating costs.

The Airports Commission has prepared two sets of forecasts based on different approaches to handling carbon emissions from aviation. These are defined as:

- CC: Carbon Capped
  This models the levels of aviation demand expected in a world where carbon dioxide emissions from flights departing UK airports are limited to 37.5 MtCO2e (million tonnes of carbon dioxide equivalent), the level recommended by the Committee on Climate Change (CCC), as a planning assumption to achieve reductions across the whole UK economy of 80% over 1990 levels by 2050;

- CT: Carbon Traded
  This models the levels of aviation demand in a future where carbon emissions from flights departing UK airports are traded at the European level until 2030 and then traded as part of a liberal global carbon market. In contrast to the carbon capped forecast, these do not constrain emissions to a pre-determined level, rather they reflect the demand response to the Department of Energy and Climate Change's (DECC) carbon values for appraisal.

The Airports Commission requested that the likelihood of an aircraft crash was considered, not the consequences to people on the ground should a crash occur. The risk to an individual in the vicinity of the airports will be significantly lower than the aircraft crash likelihood, by several orders of magnitude. This is due to a number of factors including the size of the crash location, the population within the location, the possible shielding effects from buildings, and other mitigating factors that will reduce the likelihood of a fatality occurring to a person on the ground from any aircraft crash.

A methodology has been developed to allow the aircraft crash likelihoods to be calculated. The data required for the analysis was identified and was provided to HSL through consultation with the Airports Commission.

The remaining sections of the report are as follows:

- Section 2 provides a brief description of the methodology used in the calculations;

- Section 3 presents the results;

- Section 4 concludes the report.

The results of a literature search and the data used in the calculations are contained in the Appendices.

2 METHODOLOGY

A review of literature was undertaken to identify a methodology to calculate the likelihood of an aircraft crash in the vicinity of either Heathrow or Gatwick airport. The literature review was also used to identify potentially useful sources of data. The literature reviewed is detailed in Appendix A. A discussion on the methodologies identified in the literature and the data identified is also given in Appendix A.

A methodology was identified from the literature that could be used to investigate the aircraft crash likelihood for a number of scenarios in 2050. The methodology is described in more detail in Appendix B.

The methodology involves calculating two elements: a background crash rate to account for aircraft cruising in UK airspace; and an airfield crash rate relating to aircraft taking off and landing at a specific airfield.

The key elements of the methodology include:

1. Calculating a background crash rate for 2013 for five aircraft categories:
    - Light civil aircraft;
    - Helicopters;
    - Small transport aircraft;
    - Large transport aircraft;
    - Military combat and jet trainers.
2. Investigating any time trends for the five aircraft categories.
3. Calculating a background crash rate for 2050 for the large transport aircraft category based on forecast data for Heathrow and Gatwick airports.
4. Calculating a total background crash rate for 2050 using the 2050 rates for the large transport aircraft category and the 2013 rates for the other categories.
5. Calculating an airfield specific crash rate for Heathrow and Gatwick airports for 2013. This rate should be split by the direction from the airport (i.e. west or east).
6. Investigating any time trends in the data.
7. Calculating an airfield specific crash rate for Heathrow and Gatwick airports for 2050 using forecast movement data. This rate should be split by the direction from the airport (i.e. west or east).

In all cases, a 95% confidence interval is calculated.

Data was obtained from the literature reviewed, the Air Accidents Investigation Branch (AAIB) bulletins (AAIB website) and the Ministry of Defence (MOD) Service Inquiries and Board of Inquiries (Government website). Additional data was obtained directly from the Civil Aviation Authority (CAA), the Airports Commission and the Royal Air Force (RAF).

The results of using this methodology are given in Section 3. The impacts of the results on the areas surrounding both airports are discussed in Section 3.4.

3 RESULTS

3.1 PRESENTATION OF RESULTS

The methodology developed and described in detail in Appendix B was used to determine the background crash rate and airfield crash rates appropriate to determine the likelihood of a crash in the vicinity of Heathrow and Gatwick.

The crash rates have been calculated with associated confidence intervals. In the tables presented in this section, the calculated crash rate is given with the calculated lower and upper confidence interval limits displayed in brackets below the crash rate. The calculated crash rate is based upon the data available and the lower and upper confidence limits give the 95% confidence interval range. In simple terms, the calculated value of the crash rate is the one based directly on the data and can be thought of as the "mean" value (this value is referred to as the mean subsequently in this report), whilst the confidence interval provides an upper and lower bound on the true value of the crash rate, i.e. it is a measure of the uncertainty in the process and can be thought of as limits on the true value of the crash rate.

3.2 BACKGROUND CRASH RATES

3.2.1 Background crash rates for the year 2013

The current background crash rate has been calculated using the methodology detailed in Appendix B for each of the five aircraft categories:

- Light aircraft;
- Helicopters;
- Small transport aircraft;
- Large transport aircraft;
- Military aircraft.

The calculated crash rates are shown in Table 1. The data listed in Appendix C has been used in the calculations and lower and upper confidence levels have also been calculated. The confidence levels are shown in brackets in Table 1.

Table 1 Calculated background crash rates (× 10^{-6} km^{-2} yr^{-1}) for the period 1990 to 2013. The 95% confidence interval crash rates are given in the brackets.

Location	*Light aircraft*	*Helicopters*	*Small transport aircraft*	*Large transport aircraft*	*Military aircraft*	*Total*
England	23.3 (18.3, 29.3)	14.1 (10.2, 18.9)	3.5 (1.8, 6.3)	0.3 (0.0,1.8)	7.7 (4.9, 11.4)	48.9 (35.2, 67.7)
Scotland	8.5 (4.8, 13.7)	4.2 (1.8, 8.3)	0.0 (0.0, 2.0)	1.6 (0.3, 4.6)	5.3 (2.5, 9.7)	19.6 (9.5, 38.4)
Wales	26.0 (13.9, 44.5)	10.0 (0.3, 23.4)	2.0 (0.1, 11.2)	0.0 (0.0, 7.4)	6.0 (1.2, 17.6)	44.1 (18.4, 104.0)
Total across GB	18.5 (15.1, 22.4)	10.3 (7.8, 13.4)	2.2 (1.1, 3.8)	0.7 (0.2, 1.9)	6.7 (4.7, 9.2)	38.4 (28.9, 50.7)

To understand the data in Table 1, the value of 23.3 × 10^{-6} km^{-2} yr^{-1} is the mean value calculated for the light aircraft crash rate for England i.e. the value calculated using the maximum likelihood method and based directly on the data. The value of 18.3 × 10^{-6} km^{-2} yr^{-1} is the lower confidence level and 29.3 × 10^{-6} km^{-2} yr^{-1} is the upper confidence level. These two values form the 95% confidence interval, as described in Section 3.1.

The crash rates in Table 1 indicate that, across Great Britain as a whole, the total likelihood of a crash occurring is 38.4 × 10^{-6} km^{-2} yr^{-1}, using the mean estimate. The mean crash rate in England alone is 48.9 × 10^{-6} km^{-2} yr^{-1}.

For the areas around Heathrow and Gatwick airports, the crash rates for England are most appropriate and these are the rates used in the analysis.

3.2.2 Time trends in the background crash rates

The data on light aircraft, helicopters, small transport aircraft and military aircraft was investigated to see if any time trends in the crash rate have been observed in the period 1990 to 2013. The model used to perform the analysis, for the Poisson distributed annual crash frequency distributed with mean λ, was:

$$ln(\lambda) = a + b(Year_i - 1990) \quad (1)$$

Equation 1 can be rearranged as:

$$\lambda = e^a e^{b(Year_i - 1990)} \quad (2)$$

where:

$\lambda = E(N_i)$, the expected value, where N_i is the number of crashes occurring in year i;
$Year_i$ is the calendar year;
e^a represents the "best estimate" of the crash rate in 1990; and
e^b represents the multiplicative change in crash rate per year after 1990.

The estimate of b can indicate if there is any evidence of a time trend in the data. If the estimate is close to 0, then no time trend can be inferred. A negative estimate of b may indicate that the crash rate is declining.

The model was fitted using the statistical software environment R (R Core Team, 2013) for crashes involving light aircraft, helicopters, small transport aircraft and military aircraft. The model was not fitted for large transport aircraft due to the sparse data for this aircraft category. For light aircraft and military aircraft, there was a downward trend in the number of crashes indicating that the number of crashes has decreased over the 24 year period from 1990 to 2013. For helicopters, a downward trend in the number of crashes was also observed, but it was less significant than for light aircraft and military aircraft. The percentage decrease per year is shown in Table 2, together with the lower and upper confidence levels from the 95% confidence interval. No trend was seen in the small transport aircraft category.

Table 2 Percentage decrease in aircraft crashes per year for each aircraft category

Aircraft category	***Percentage decrease (%) per year***		
	Mean	***Lower confidence level***	***Upper confidence level***
Light aircraft	3.0	0.3	5.8
Helicopters	3.7	-0.1	7.3
Military aircraft	8.3	3.6	13.1

The decreasing trend seen in the data for light aircraft, helicopters and military aircraft occurred during a time period when overall flight movements increased significantly. The number of movements for these three categories, however, may have been relatively unchanged or possibly even declined over the time period. If the number of movements declined in this time period, then the number of crashes could have declined in line with the decrease in movements. This would explain the downward trend seen in the number of crashes. As none of these categories of aircraft are relevant to Heathrow and Gatwick airports, however, the reasons for the trends have not been investigated further for this analysis.

Although no statistical trend was seen for the small aircraft category, this does not imply that there was no change in the crash rates over the period 1990 to 2013. It means that the data did not show any evidence of a trend.

It is not possible to perform the same analysis on the large transport aircraft category, although the number of movements that fall into this category has increased significantly (by approximately 80% between 1990 and 2013); however, no background crashes in this category have been observed since 1994. The information on the number of movements is listed in Appendix D.

3.2.3 Background crash rates for the year 2050

The background crash rate is applicable to aircraft in the cruise stage of flight and is not associated with any airfield.

The trend analysis has indicated that there is no evidence to support an assumption that an increase in the number of movements at Heathrow and Gatwick airports would increase the background crash rates. The number of movements in the large aircraft category has increased significantly between 1990 and 2013 but the frequency of crashes has remained low, meaning that it is not possible to determine if there has been any trend.

However, to fully explore the potential for this “worst-case” situation, the background crash rate for the large transport category has been adjusted by a factor to account for the increase in aircraft movements at the airports. This factor has been calculated by dividing the projected number of movements in 2050 by the movements observed in 2013. The forecast numbers of movements are listed in Appendix E. This analysis has not been performed in the literature reviewed as it has been assumed that the background rate is unchanging unless a trend analysis has proved otherwise.

The background rates for the other four aircraft categories have not been adjusted. In 2013, there were 21 movements from Heathrow airport that fell into the small transport aircraft category and 6 from Gatwick airport for this aircraft category. These numbers do not represent a significant proportion of the overall number of flights (less than 0.01%) and there are no small transport aircraft movements forecast for the year 2050. The small transport aircraft category therefore has not been considered further in these calculations.

The background crash rate factor calculation has been performed for three possible growth scenarios for each airport, for no expansion at either airport and for the three proposed future runway options. This information and the forecasts have been provided by the Airports Commission. The calculated factors are given in Table 3.

The different growth scenarios are:

- AoN CT: Assessment of Need – Carbon Traded;
- AoN CC: Assessment of Need – Carbon Capped;
- GGCT: Global Growth – Carbon Traded (Heathrow only);
- LCIK CT: Low Cost is King – Carbon Traded (Gatwick only).

The expansion scenario options are:

- Do Minimum: no expansion;
- ENR: extended northern runway at Heathrow;
- NWR: additional northwest runway at Heathrow;
- 2R: 2 runways at Gatwick.

Table 3 Factors showing the increase in movements at Heathrow and Gatwick airports for large transport aircraft

Growth scenario	*Expansion scenario*	*Heathrow*	*Gatwick*
AoN CT	Do Minimum	1.00	1.16
	ENR	1.50	-
	NWR	1.59	-
	2R	-	2.28
AoN CC	Do Minimum	1.00	1.17
	ENR	1.51	-
	NWR	1.60	-
	2R	-	1.95
GGCT LCIK CT	Do Minimum	0.97	1.12
	ENR	1.51	-
	NWR	1.57	-
	2R	-	2.28

The revised large transport aircraft background crash rate, related to the specific airport and for each of the growth and expansion scenarios, has been recalculated using the factors in Table 3.

The base background crash rates (from the 1990 to 2013 data) used in the calculations are those for England only as this is the most appropriate area to use for Heathrow and Gatwick airports. Only the large transport aircraft category has been multiplied by the factors as this is the only type of aircraft applicable to Heathrow and Gatwick airports.

The revised rates, together with those for 2013, taken from Table 1 (on Page 5), are given in Table 4 with the 95% confidence interval rates given in brackets. The table also lists the revised total background crash rate, assuming that the background rates for the other aircraft categories remain unchanged.

Table 4 Large transport aircraft background crash rate ($\times 10^{-6}$ km^{-2} yr^{-1}) and total background crash rate for Heathrow and Gatwick airports assuming different growth and expansion scenarios. The 95% confidence interval crash rates are in brackets.

Growth scenario	***Expansion scenario***	***Large transport aircraft crash rate***		***Total crash rate***	
		Heathrow	***Gatwick***	***Heathrow***	***Gatwick***
2013: base case		0.3 (0.0,1.8)	0.3 (0.0,1.8)	48.9 (35.2, 67.7)	48.9 (35.2, 67.7)
AoN CT	Do Minimum	0.3 (0.0, 1.8)	0.4 (0.0, 2.1)	48.9 (35.2, 67.7)	48.9 (35.2, 68.0)
	ENR	0.5 (0.0, 2.7)	-	49.0 (35.2, 68.6)	-
	NWR	0.5 (0.0, 2.8)	-	49.1 (35.2, 68.7)	-
	2R	-	0.7 (0.0, 4.1)	-	49.3 (35.2, 70.0)
AoN CC	Do Minimum	0.3 (0.0, 1.8)	0.4 (0.0, 2.1)	48.9 (35.2, 67.7)	48.9 (35.2, 68.0)
	ENR	0.5 (0.0, 2.7)	-	49.1 (35.2, 68.6)	-
	NWR	0.5 (0.0, 2.9)	-	49.1 (35.2, 68.8)	-
	2R	-	0.6 (0.0, 3.5)	-	49.2 (35.2, 69.4)
GGCT, LCIK CT	Do Minimum	0.3 (0.0, 1.7)	0.4 (0.0, 2.0)	48.9 (35.2, 67.6)	48.9 (35.2, 67.9)
	ENR	0.5 (0.0, 2.7)	-	49.1 (35.2, 68.6)	-
	NWR	0.5 (0.0, 2.8)	-	49.1 (35.2, 68.7)	-
	2R	-	0.7 (0.0, 4.1)	-	49.3 (35.2, 70.0)

There are only slight increases calculated in the total background crash rates for the different scenarios when compared to the total background crash rate for 2013. The maximum difference in the calculated mean crash rate is an increase of 0.4×10^{-6} km^{-2} yr^{-1}, which is seen at Gatwick airport for both the "Assessment of Need – Carbon Traded" (AoN CT) and "Low Cost is King – Carbon Traded" (LCIK CT) growth scenarios, in both cases when considering the "2 runways"

(2R) expansion scenario. The largest difference around Heathrow airport is an increase in the calculated mean crash rate of 0.2×10^{-6} km^{-2} yr^{-1}.

The change in crash rate for Gatwick should be compared to the "Do Minimum" scenarios rather than the 2013 base rate, as the forecasts indicate that the movements at Gatwick will increase, regardless of any airport expansion. However, this does not change the differences observed to the level of accuracy calculated for these values for Gatwick in this analysis. Heathrow is already at maximum capacity and hence there is no scope for an increase in movements for the "Do Minimum" scenario.

The background rate applies to areas that are beyond approximately 10 km (~ 5 nautical miles) from the airport, especially in the west-east directions as the airports run west to east. The background rate may apply closer to the airport than this distance for locations north and south of the airports; this will depend on the exact arrival and departure routes, which may bend to the north or south of the airport. As the arrival and departure routes are not being explicitly considered in this analysis, a cautious estimate is that the background rate applies beyond 10 km in all directions from the airport. The airfield related crash rate, or a proportion of it, applies within this radius.

3.3 AIRFIELD RELATED CRASH RATE

3.3.1 Airfield Related Crash Rate for the year 2013

The methodology used to calculate the airfield related crash rate is given in Appendix B. The calculation of the general airfield related crash rate for 2013 requires the airfield related incidents and the total number of movements for all airports in Great Britain for 1990 to 2013, both of which are given in Appendix D. These values are reproduced in Table 5, together with the calculated mean crash rate for small and large transport aircraft. The 95% confidence interval values are given in brackets. The other aircraft categories are not considered as they are not applicable to Heathrow and Gatwick airports. This is a general airfield related crash rate and is not specific to any airport.

Table 5 Estimates of the general airfield related crash rate ($\times 10^{-6}$ movement^{-1}) with the 95% confidence interval given in brackets

Rate calculation	*Small transport aircraft*	*Large transport aircraft*
Number of accidents	27	3
Number of movements*	7,184,749	36,185,856
Crash rate	3.8 (2.5, 5.5)	0.08 (0.02, 0.24)

*note that one movement is either a take-off or landing, each flight constitutes two movements, one or both of which may occur at an airport in Great Britain.

To understand the data presented in Table 5, the mean value calculated for the airfield related crash rate for small transport aircraft is 3.8×10^{-6} movement^{-1}. The lower confidence level is calculated as 2.5×10^{-6} movement^{-1} and the upper confidence level is 5.5×10^{-6} movement^{-1}. These two values give a measure of the uncertainty in the mean value and represent the 95% confidence interval, as described in Section 3.1.

From Boeing data (Boeing, 2014), 14% of all aircraft fatalities occur during take-off and 47% during landing. If it is assumed that the same proportions apply to airfield related crashes in general, then 23% (= 14/(14+47)×100%) of accidents occur during take-off and 77% during landing. The crash rates for small transport and large transport aircraft can be apportioned between take-off and landing accidents according to these percentages; the resultant crash rates are given in Table 6.

Table 6 Estimates of the general airfield related crash rate ($\times 10^{-6}$ movement^{-1}) apportioned between take-offs and landings with the 95% confidence interval given in brackets

Aircraft category	***Take-offs***	***Landings***
Small transport aircraft	1.7 (1.1, 2.5)	5.8 (3.8, 8.4)
Large transport aircraft	0.04 (0.01, 0.11)	0.13 (0.03, 0.37)

The annual numbers of movements for both categories of aircraft are required to calculate crash rates that are specific to Heathrow and Gatwick airports. These values are given in Table 7.

Table 7 Number of movements in 2013 at Heathrow and Gatwick airports

Airport/Aircraft category	***Take-offs***	***Landings***
Heathrow		
Small transport aircraft	10	11
Large transport aircraft	235,156	234,986
Gatwick		
Small transport aircraft	2	4
Large transport aircraft	122,222	122,278

The mean crash rates for Heathrow and Gatwick, and the 95% confidence interval, have been calculated using the methods described in Appendix B and are given in Table 8. The 95% confidence interval values are shown in brackets. The values listed in the following tables are the crash rates per year as the per movement rates have been multiplied by the annual number of movements. The values in the following tables are of the order of ($\times 10^{-3}$) as opposed to the ($\times 10^{-6}$) in the tables shown in the previous sections.

Table 8 Airfield related crash rates (× 10^{-3} yr^{-1}) for Heathrow and Gatwick airports in 2013 with the 95% confidence interval in brackets by take-offs and landings

Airport/Aircraft category	***Take-offs***	***Landings***
Heathrow		
Small transport aircraft	0.02 (0.01, 0.03)	0.06 (0.04, 0.09)
Large transport aircraft	9.0 (1.9, 26.2)	30.0 (6.2, 87.7)
Total	9.0 (1.9, 26.2)	30.1 (6.2, 87.8)
Gatwick		
Small transport aircraft	0.00 (0.00, 0.01)	0.02 (0.02, 0.03)
Large transport aircraft	4.7 (1.0, 13.6)	15.6 (3.2, 45.6)
Total	4.7 (1.0, 13.6)	15.6 (3.2, 45.7)

At Heathrow airport, take-offs are to the west 70% of the time and to the east 30% of the time. Landings are from the east 70% of the time and from the west 30% of the time. At Gatwick, take-offs are to the west 66% of the time and to the east 34% of the time. Landings are from the east 66% of the time and from the west 34% of the time. The crash rates for take-offs and landings have been amalgamated according to these percentages to determine a crash rate to the west of each airport and a crash rate to the east of each airport. These west and east crash rates are shown in Table 9, with the 95% confidence interval values shown in brackets.

Table 9 Airfield related crash rates (× 10^{-3} yr^{-1}) for Heathrow and Gatwick airports in 2013 by direction from the airport, with the 95% confidence interval in brackets

Airport/Aircraft category	***West***	***East***
Heathrow		
Small transport aircraft	0.03 (0.02, 0.05)	0.05 (0.03, 0.07)
Large transport aircraft	15.3 (3.2, 44.7)	23.7 (4.9, 69.2)
Total	15.3 (3.2, 44.7)	23.7 (4.9, 69.3)
Gatwick		
Small transport aircraft	0.01 (0.01, 0.01)	0.02 (0.01, 0.02)
Large transport aircraft	8.4 (1.7, 24.5)	11.9 (2.5, 34.7)
Total	8.4 (1.7, 24.5)	11.9 (2.5, 34.8)

The calculated crash rates to the west and east assume that landing crashes occur before the landing threshold, as opposed to overshooting the runway and crashing beyond the airport boundary. It is also assumed that take-offs and landings follow a straight line that is an extension of the runway centreline.

The different types of accident (e.g. overshoots, overruns, etc.) have been considered in the literature, together with curved flight paths. However, there is a large level of uncertainty associated with the modelling of these phenomena due to sparse data relating to the different types of accident observed and for the exact flight path locations. Data from other countries would have to be used, which may or may not be relevant to Heathrow or Gatwick. Statistical distributions would have to be applied to overseas data to determine the crash location, which would add an additional level of uncertainty to the calculations. As there is already a high level of uncertainty in the calculated crash rates (as shown by the range of values in the confidence interval), the different types of landing and take-off crashes have not been considered separately and neither have the different flight paths, especially as these are subject to change.

Consideration of these points is discussed further in Section 3.4. Even though the assumption that all landing crashes occur before the landing threshold may lead to an underestimate of the crash rate at the other side of the airport, it is considered that this discrepancy is small and is captured through the use of the confidence intervals.

The crash rates do not represent the risk to an individual on the ground. This will be several orders of magnitude lower, due to a number of factors including the size of the crash location, the local population within the crash location and the possible shielding effects from buildings.

3.3.2 Time trends in the data

Time trends have not been investigated for the airfield related crash data. There is insufficient data to be able to perform this analysis for the large transport aircraft category. Although there is more data for the small transport aircraft category, there are forecast to be no movements of this category of aircraft at either airport in the year 2050. Performing an analysis on the small transport aircraft data does not therefore add any useful information.

3.3.3 Airfield related crash rates for the year 2050

The crash rates shown in Table 6 (on Page 10) need to be multiplied by the forecast number of movements for each scenario to calculate the airfield related crash rate for Heathrow and Gatwick in the year 2050. The 2050 forecast aircraft movements are listed in Appendix E. Only the large transport aircraft crash rates in Table 6 are of relevance as this is the only category of aircraft projected to be flying from both airports in 2050. The forecast airfield related crash rates for Heathrow are shown in Table 10 and those for Gatwick airport are shown in Table 11. This assumes that the proportion of fatal accidents that occur during take-off and landing taken from Boeing (Boeing, 2014) apply in the year 2050.

Table 10 Airfield related crash rates (× 10^{-3} yr^{-1}) for Heathrow airport in 2050 by take-offs and landings, with the 95% confidence interval shown in brackets

Growth Scenario	*Expansion Scenario*	*Take-offs*	*Landings*
AoN CT	Do Minimum	9.0 (1.9, 26.3)	30.1 (6.2, 88.1)
	ENR	13.5 (2.8, 39.3)	45.1 (9.3, 131.7)
	NWR	14.3 (2.9, 9.9)	47.8 (41.7, 139.6)
AoN CC	Do Minimum	9.0 (1.9, 26.3)	30.1 (6.2, 87.9)
	ENR	13.6 (2.8, 39.6)	45.4 (9.4, 132.6)
	NWR	14.4 (3.0, 42.0)	48.1 (9.9, 140.5)
GGCT	Do Minimum	8.7 (1.8, 25.5)	29.2 (6.0, 85.4)
	ENR	13.5 (2.8, 39.5)	45.3 (9.3, 132.4)
	NWR	14.1 (2.9, 41.1)	47.1 (9.7, 137.6)

Table 11 Airfield related crash rates (× 10^{-3} yr^{-1}) for Gatwick airport in 2050 by take-offs and landings, with the 95% confidence interval shown in brackets

Growth Scenario	*Expansion Scenario*	*Take-offs*	*Landings*
AoN CT	Do Minimum	5.4 (1.1, 15.7)	18.0 (3.7, 52.7)
	2R	10.6 (2.2, 31.1)	35.6 (7.4, 104.2)
AoN CC	Do Minimum	5.4 (1.1, 15.9)	18.2 (3.8, 53.2)
	2R	9.1 (1.9, 26.5)	30.4 (6.3, 88.8)
LCIK CT	Do Minimum	5.2 (1.1, 15.3)	17.5 (3.6, 51.1)
	2R	10.6 (2.2, 31.0)	35.5 (7.3, 103.8)

The crash rates have been calculated for areas to the west and east of both airports. For Heathrow airport it is assumed that 70% of take-offs are to the west and 70% of landings are from the east. For Gatwick airport, it is assumed that 66% of take-offs are to the west and 66% of landings are from the east. These percentages are based on current movements and it is assumed that the proportions will remain unchanged in the year 2050. The airfield related crash rates to the west and east of the airports are shown in Table 12 for Heathrow airport and in Table 13 for Gatwick airport.

Table 12 Airfield related crash rates (× 10^{-3} yr^{-1}) for Heathrow airport in 2050 by direction from the airport, with the 95% confidence interval shown in brackets

Growth Scenario	*Expansion Scenario*	*West*	*East*
AoN CT	Do Minimum	15.3 (3.2, 44.8)	23.8 (4.9, 69.5)
	ENR	22.9 (4.7, 67.0)	35.6 (7.3, 104.0)
	NWR	24.3 (5.0, 71.0)	37.7 (7.8, 110.2)
AoN CC	Do Minimum	15.3 (3.2, 44.7)	23.7 (4.9, 69.4)
	ENR	23.1 (4.8, 67.5)	35.8 (7.4, 104.7)
	NWR	24.5 (5.1, 71.5)	38.0 (7.8, 111.0)
GGCT	Do Minimum	14.9 (3.1, 43.5)	23.1 (4.8, 67.4)
	ENR	23.1 (4.8, 67.4)	35.8 (7.4, 104.5)
	NWR	24.0 (4.9, 70.1)	37.2 (7.7, 108.6)

Table 13 Airfield related crash rates (× 10^{-3} yr^{-1}) for Gatwick airport in 2050 by direction from the airport, with the 95% confidence interval shown in brackets

Growth Scenario	*Expansion Scenario*	*West*	*East*
AoN CT	Do Minimum	9.7 (2.0, 28.3)	13.7 (2.8, 40.1)
	2R	19.1 (4.0, 56.0)	27.1 (5.6, 79.3)
AoN CC	Do Minimum	9.8 (2.0, 28.6)	13.9 (2.9, 40.5)
	2R	16.3 (3.4, 47.7)	23.1 (4.8, 67.6)
LCIK CT	Do Minimum	9.4 (1.9, 27.5)	13.3 (2.8, 38.9)
	2R	19.1 (3.9, 55.8)	27.0 (5.6, 79.0)

For Heathrow, the scenario with the highest crash rates is the “additional northwest runway” (NWR) option with the “Assessment of Need – Carbon Capped” (AoN CC) growth rate. The mean crash rate for this scenario is 24.5 × 10^{-3} yr^{-1} to the west of the airport and 38.0 × 10^{-3} yr^{-1} to the east of the airport. The increase, assuming the mean values, compared to the “Do Minimum” scenario, or the 2013 base case is calculated as 9.2 × 10^{-3} yr^{-1} in the west direction and 14.3 × 10^{-3} yr^{-1} to the east.

The total crash rate at Heathrow under the "Assessment of Need – Carbon Capped" (AoN CC) growth rate with the "additional northwest runway" (NWR) is lower than the crash rate calculated as part of the Terminal 5 Inquiry (Vandermeer, 2000). The projected crash rate for 2016, both with and without Terminal 5, was 1 in 14 years, which is approximately 71×10^{-3} per year. This can be compared to a total rate from Table 12 of 63×10^{-3} per year, or 1 in 16 years, and represents a difference of more than 10%.

The Gatwick scenarios need to be compared to the "Do Minimum" cases as the number of movements is projected to increase, regardless of whether or not a second runway is built. The "Do Minimum" scenario with the highest crash rates is the "Assessment of Need – Carbon Capped" (AoN CC) growth rate. In this case, the crash rates are 9.8×10^{-3} yr^{-1} to the west and 13.9×10^{-3} yr^{-1} to the east. The increase in the crash rate under this scenario assuming a second runway is built is 6.5×10^{-3} yr^{-1} to the west and 9.2×10^{-3} yr^{-1} to the east of the airport. The scenario with the highest crash rates in 2050 with a second runway is the "Assessment of Need – Carbon Traded" (AoN CT) option. In this case, the crash rates are 19.1×10^{-3} yr^{-1} to the west and 27.1×10^{-3} yr^{-1} to the east of the airport.

The "Do Minimum" scenarios for Heathrow airport are equivalent to the 2013 situation as Heathrow is already at a full capacity. The mix of aircraft categories may change slightly in the future but this only has a minimal impact on the crash rates. The crash rates are therefore generally the same as the 2013 rates for the 2050 "Do Minimum" scenarios. In the case of the "Global Growth – Carbon Traded" (GGCT) growth scenario, the 2050 "Do Minimum" rates are lower than those calculated for 2013. The "Do Minimum" scenarios for Gatwick airport all see a small increase in the number of flights and hence the airfield related crash rates increase by between 12% and 15%.

The scenario for Heathrow with the highest crash rates represents an increase of 60% in the crash rate compared to 2013. At Gatwick airport, the crash rate is more than doubled in the scenario with the highest rates when compared to both 2013 and the "Do Minimum" 2050 scenarios.

3.4 DISCUSSION

The results presented in the previous sections provide an estimate of the aircraft crash rate in the vicinity of either Heathrow or Gatwick airport. The results represent the outputs from the first two steps identified in the methodology described in Appendix B. The final two steps in the methodology involve producing statistical distributions for the crash location and estimating the risk to an individual on the ground. These calculations have not been performed in this report due to the reasons presented in Appendix B.

The risk to people in the vicinity of the airports will be orders of magnitude lower than the aircraft crash likelihood. This is because the additional two steps to calculate the risk to an individual near the airports would involve multiplying the aircraft crash rates by the probabilities output from the statistical distributions to determine the crash locations and harm impacts on people on the ground. These additional calculations mean that the likelihood of people near the airports being affected by an aircraft crash is much less than the simple aircraft crash likelihoods calculated in this study.

It is possible to perform some form of location analysis (the third step of the standard methodology identified in Appendix B) but any location analysis is associated with a high level of uncertainty, particularly at distances further away from the airport. There is already a high level of uncertainty associated with the crash rates, as shown by the range of values in the 95% confidence intervals. Trying to identify the likely crash locations would add to that uncertainty.

Including a crash location analysis could give a false sense of accuracy in the results, which is not achievable given the data available.

Although an explicit crash location analysis has not been performed, it is possible to provide indications of the areas for which the crash rate will be highest. The background crash rates given in Section 3.2.1 and 3.2.3 apply at distances of greater than approximately 10 km from the airports (~5 nautical miles). These rates are associated with aircraft that are cruising and not with aircraft that are landing or taking off at any airport.

Within the 10 km radius of Heathrow and Gatwick airports, the dominant crash rate is the airfield specific crash rate, based on aircraft taking off and landing at the airports. The airspace above the airports also contains traffic that is associated with other nearby airports and also includes aircraft cruising at high altitudes. The background crash rate should be added to the airfield related crash rate within the 10 km radius of both Heathrow and Gatwick to account for the aircraft within this airspace that are not associated with either of these airports. It must be considered that the background rate is per km^2 per year whilst the airfield related crash rate is per year. In practice, however, the background crash rate is approximately three orders of magnitude lower than the airfield related crash rate and has a negligible impact on the crash likelihood calculated for areas around the airport. The background crash rate is not considered further in relation to the areas around the airports.

The airfield specific crash rates, or more accurately, proportions of the airfield specific crash rates (given in Sections 3.3.1 and 3.3.3) apply within the 10 km radius of the airports. The areas of greatest risk are along the extended centrelines of the runways to both the west and east. There are effectively corridors to the west and east of the airports, out to a distance of approximately 10 km, where the risk of an aircraft crashing is highest.

The effective current likelihoods of an aircraft crashing along these west-east corridors are approximately the rates given in Table 9, Section 3.3.1 calculated from the 1990 to 2013 data. The maximum likelihood of a crash is calculated to be to the east of both airports.

As Heathrow airport is currently at full capacity, the “Do Minimum” crash rates for 2050 are unchanged, or decrease slightly when compared to the current crash rates.

The number of movements at Gatwick airport is assumed to increase, whether or not a second runway is built. This has the effect of increasing the crash rates in 2050 when compared to 2013, even without an additional runway as can be seen from Table 13 in Section 3.3.3. The largest “Do Minimum” crash rates for Gatwick airport occur with the “Assessment of Need – Carbon Capped” growth forecast.

The aircraft crash rates along these west-east corridors for the year 2050 are approximately those shown in Table 12 and Table 13 in Section 3.3.3. Again, the maximum calculated crash likelihoods are to the east of both airports, for specific expansion and growth scenarios. The largest increases at Heathrow airport are seen with the “Assessment of Need – Carbon Capped” growth forecast and the addition of a third runway. At Gatwick airport, the highest crash rates occur with the “Assessment of Need – Carbon Traded” growth forecasts but the largest increase when compared to the “Do Minimum” scenario occurs with the “Low Cost is King – Carbon Traded” growth forecast.

The total crash rates under all growth and expansion scenarios at Heathrow airport are lower than those predicted for 2016 as part of the Terminal 5 Inquiry.

For areas away from the west-east corridors along the runway centrelines and within the 10 km radius circle of the airports, the crash rate depends on whether an area is beneath an arrival or departure route, or beneath a holding stack. These routes and stacks are subject to change and so it is not possible to define these areas exactly.

Within areas that lie beneath an arrival or departure route, the crash rate is approximately the landing or take-off crash rates for the particular airport. These are in Table 8 in Section 3.3.1 for 2013 and in Table 10 for Heathrow airport and Table 11 for Gatwick airport in Section 3.3.3 for 2050. The crash rates for landing accidents are higher than for take-off accidents.

The largest crash rates, and increases in crash rates, for take-offs and landings follow the same pattern as the west-east crash rates. This is to be expected as they represent different interpretations of the same total values.

The holding stacks have not been modelled specifically as they are subject to change and, as in the case of modelling the crash locations, there would be a high level of uncertainty associated with the modelling of these locations. The crash rate for locations below the holding stack is higher than the general background rate, but is significantly lower than the rates for areas below the arrival and departure routes.

The aircraft crash rate for areas within the 10 km radius circle from the airports that are not along the extended runway centreline, below the arrival or departure routes, or below the holding stacks have a lower crash rate than for any of these locations. The risk of a crash at a location reduces with distance from any of these higher risk areas (i.e. west-east aircraft corridor; arrival, departure routes; holding stack). The risk within the 10 km radius of each airport is not as low as the background rate as, if an aircraft encounters a problem, it may deviate from prescribed paths and crash outside of these higher risk areas.

The aircraft crash rates discussed in this section do not provide an estimate of the risk to an individual on the ground. The risk to the general public is significantly lower than the rates given here, by orders of magnitude. This is because the aircraft will impact on a relatively small area (even allowing for potential mid-air break up which could lead to parts of the aircraft landing in different locations). In a built-up area, buildings will absorb some of the impact of a crash, although they are likely to incur significant damage. In more rural areas, there is a lower population that can be affected and the crash debris may land in surrounding fields.

The magnitude of the likelihood of an aircraft crash can be compared to other statistics, although the rates themselves are not directly comparable as they are not estimating the same end results (i.e. the statistics presented represent a fatality or injury). According to Cancer Research UK (Cancer Research UK website), the lifetime risk of developing cancer is a 1 in 2 chance i.e. 0.5 per lifetime. The lifetime risk of dying in a car crash is 1 in 240 i.e. a risk of around 4×10^{-3} per lifetime (Bandolier, 2015). The annual risk of dying in a car crash in Great Britain in 2012 was 3×10^{-5} per year, the annual risk of being seriously injured in a car crash was 4×10^{-4} per year, and the annual risk of being injured in a car crash was 3×10^{-3} per year (Department for Transport, 2013 and assuming a population of 62 million).

In the UK, there are approximately 250,000 falls down stairs that result in a visit to a doctor's surgery or hospital (Scott, 2005). This equates to an approximate rate of 4×10^{-3} per year (assuming a population of 64 million). There are almost as many deaths each year from accidents in the home as traffic accidents, and a quarter of these are falls from stairs.

From a review of the general statistics, the calculated aircraft crash risk is of a similar order of magnitude to some common risks. Given that the risk of injury or death from an aircraft crash is several orders of magnitude lower than the aircraft crash rate, the overall risk of a fatality to a person on the ground from an aircraft crash is likely to be significantly lower than the risk of being killed from falling down the stairs or in a car accident.

3.5 SUMMARY OF RESULTS

The forecast aircraft crash likelihoods are largest to the east of both Gatwick and Heathrow airports and are greater for landings than take-offs.

The largest increases in the crash likelihoods for either airport occur under the "Assessment of Need – Carbon Capped" growth forecast for Heathrow airport and with the addition of a third runway (the "additional northwest runway" (NWR) scenario).

At Gatwick airport, the largest crash rates occur with the "Assessment of Need – Carbon Traded" growth forecast and the addition of a second runway (the "2 runways" (2R) scenario).

The largest increase in crash rates for Gatwick, however, occurs under the "Low Cost is King – Carbon Traded" growth forecast and the addition of a second runway.

4 CONCLUSION

The Health and Safety Laboratory (HSL) were asked by the Airports Commission to assess the likelihood of an aircraft crash in the vicinity of Heathrow and Gatwick airports. The Airports Commission were interested in the relative likelihoods of an aircraft crash in the year 2050 from potential expansion at either Heathrow or Gatwick compared to there being no expansion at either airport. The aircraft crash likelihoods for three different growth scenarios for each airport for the year 2050 were compared with no expansion taking place at either airport.

HSL reviewed literature, detailed in Appendix A, to identify a methodology and potential data to use in the assessment. The chosen methodology is described in detail in Appendix B. Additional data for the calculations was provided by the Airports Commission and the Civil Aviation Authority (CAA).

A background crash rate was calculated for the year 2013 (the latest year for which full data is available) and for the year 2050. The background rate applies to areas beyond a 10 km (~5 nautical miles) radius from the airports. The results indicate that there is only a small change in the background rate when the number of movements is increased at either airport. On average, a crash could be expected once every 20,000 years, approximately over any given square kilometre in England.

An airfield related crash rate, specific to either Heathrow or Gatwick airport, has been derived for the years 2013 and 2050. The results show that the maximum airfield related crash rate for Heathrow airport is lower than the rate predicted as part of the Terminal 5 Inquiry (Vandermeer, 2000). The airfield related crash rates for Gatwick airport are lower than for Heathrow.

The airfield related crash rates have been apportioned according to take-offs and landings, and according to the location relative to the airport i.e. west or east. The crash rates for landings are higher than for take-offs and the rates to the east of the airports are higher than to the west. This is true for both Heathrow and Gatwick airports.

A narrative description of where the crash rate is highest in the areas around the airports has been given, considering the impacts of flight paths and holding stacks, as it has not been possible to model these explicitly.

Confidence intervals have been given for the results calculated for all the scenarios modelled for both 2013 and 2050. These confidence intervals provide an indication of the uncertainty surrounding the calculations. The large variation in the values between the upper and lower bounds of the intervals are a reflection of the lack of data used in the derivation of the crash rates. Crashes, for large transport aircraft in particular, are rare, making the calculation of a representative crash rate difficult. The statistical methods used, however, together with the 95% confidence intervals, allow some confidence to be placed on the results produced.

The risk to people on the ground from an aircraft crash has not been considered as this study was to calculate the likelihood of an aircraft crash only, where an aircraft crash is defined as an uncontrolled landing or mid-air break-up leading to serious damage to the aircraft and/or at least one fatality. The fatality relates to people on board the aircraft, not to people on the ground, due to how the data is recorded. The aircraft crash likelihoods calculated in this study do not consider how an aircraft crash could lead to fatalities on the ground. This would require additional data and a number of further assumptions and modelling to determine impact areas, harm criteria and human vulnerability, and other factors to calculate the risk of a fatality to a person on the ground from an aircraft crash. Taking all of the additional elements into consideration means that the risk of a fatality on the ground is likely to be orders of magnitude lower than the aircraft crash rates calculated and described in this report.

5 APPENDIX A: LITERATURE REVIEW

5.1 INTRODUCTION

Literature was reviewed to ascertain what methods and data have been used previously to assess aircraft crash likelihoods and risks. This was to determine the applicability of any existing methods and data for the scenarios identified for Gatwick and Heathrow. Relevant data or applicable elements of methodologies have been used to inform the development of the methodology used in this analysis.

The literature search was conducted to identify published methodologies and data for calculating aircraft crash risk in the vicinity of an airfield or airport. The references that were identified as being of most relevance to this project were investigated and are summarised in the subsequent sections.

5.2 MODELS

5.2.1 Wong *et al* (2009a)

The paper by Wong *et al* (2009a) is concerned with assessing risks related to aircraft accidents at, and in the vicinity of, airports. It is also concerned with managing Airport Safety Areas (ASAs) as a risk mitigation measure. There are two types of ASA: aerodrome design ASAs and land-use planning ASAs. They are designed to protect passengers and nearby communities from accidents that occur during take-off and landing. In the USA, the aerodrome ASAs are defined as Runway Safety Areas, which, according to the Airport Cooperative Research Program (ACRP, 2008), are essentially areas that an aircraft can run into without causing damage to the aircraft or injury to the occupants. The land-use planning ASAs restrict the type of development that can occur in the vicinity of the airport. This paper describes the development of an accident frequency model used in assessing the ASAs.

A comprehensive accident database was developed that covered US incidents between 1982 and 2002. Accidents that resulted in hull loss due to take-off and landing overruns, undershoots, veer-offs and crashes after take-off, up to a distance of 10 km from the landing or take-off threshold, were included in the database. Normal operations data (NOD) were also included i.e. non-accident flight data, for example, to assess the effect of meteorological conditions or human factors on the risk.

The final database contained 440 cases; 199 landing overruns, 122 landing undershoots, 52 take-off overruns and 67 crashes after take-off.

Multivariate analysis in the form of logistic regression was used to model the risk of accident occurrence. This allowed the NOD data to be considered along with the accident data. The final equations included information on the type of aircraft, if they were owned by foreign operators, the visibility, wind information, snow and ice conditions, etc.

5.2.2 Wong *et al* (2009b)

This paper (by Wong *et al*, 2009b) is a continuation of the work described in Section 5.2.1 and is concerned with defining Airport Safety Area (ASA) dimensions. It describes a crash location model. Six scenarios were considered: landing overrun, landing undershoot, take-off overrun, crash after take-off, landing undershoot (beyond runway end) and crash after take-off (before start-of-roll threshold i.e. the wreckage is found behind the start of the runway and occurs when flights have made a sharp turn after lift-off).

For each of the scenarios, complementary cumulative probability distributions (CCPD) of the relevant x and y distances from the runway were plotted using the accident sample in Part I of the paper (Wong *et al*, 2009a). The CCPDs were fitted to exponential functions. It was shown that approximately one third of the landing undershoot cases involved distances of 10,000 ft (~3000 m) or more, whereas there were only a few overruns that extended beyond 1000 ft (~300 m) of the runway. Most of the take-off overruns occur before the aircraft has become airborne, thereby limiting the excess distance that is travelled. Landing undershoots, however, can occur at some distance from the runway as the aircraft is airborne immediately prior to touchdown.

It appears that most of the landing undershoots (beyond the runway end) occurred away from the airfield (approximately 80 incidents in total). Two incidents fell into the last category (crash after take-off before the start-of-roll threshold). Both of these appear to have occurred outside the airport boundary.

The trend lines fitted to the data are most accurate close to the runway threshold/end/centreline. Incidents further away are likely to be more scattered, and there are far fewer points to generate a trend line. As there is too much uncertainty with the use of the trend lines at distances further away from the airport, then it is suggested that the trend lines are only used as indicative when assessing larger areas around an airport.

Two case studies were considered, using the methodology described in this paper and in Part I of the paper.

5.2.3 Airport Cooperative Research Program, ACRP (2008)

The aim of the report by the Airport Cooperative Research Program (ACRP, 2008) was to develop a method for assessing aircraft overruns and overshoots, which would allow analysis of Runway Safety Areas (RSAs). These are rectangular-shaped areas surrounding the runway that are graded and obstacle-free and "should be capable, under normal (dry) conditions, of supporting airplanes without causing structural damage to airplanes or injury to their occupants".

Three models were developed to assess the risks. These covered landing overruns, landing undershoots and take-off overruns. Each model calculated a probability of occurrence, the location, and the consequences.

A database of aircraft overrun and undershoot incidents and accidents was created, which also contained normal operations data (NOD). This allowed specific factors to be considered such as weather conditions. Accident and incident data was taken from areas of the world that have accident rates comparable to the US namely, the US and Canada, Western Europe (Joint Aviation Authorities (JAA) countries), Oceania and a few countries in Asia. In addition, only fixed wing, multiple engine aircraft were considered with a certified maximum gross weight of 6000 lbs (~2.7 te) or more. Undershoots and overruns that were more than 2000 ft (~600 m) beyond the threshold were excluded as it would be unfeasible to have an RSA this large.

Accidents and incidents from 1982 to 2006 were included in the database, although some events prior to 1982 were also included. This led to a total of 459 incidents, of which 274 were landing overruns, 93 were landing undershoots and 92 were take-off overruns. As incidents that occurred beyond 2000 ft (~600 m) of the runway threshold were not included then the database is of limited use for the current analysis as these types of incidents are relevant for this study. The NOD data consisted of information on the aircraft, the airport and the consequences, together with flight data, any obstacles or terrain that was hit, and the weather.

A normalisation procedure was used to transform the data to a standard normal airport, as it was recognised that the incidents would have occurred at airports with different operating conditions and levels of risk. The "normal" airport was defined as an airport situated at the International Standard Atmosphere (ISA) conditions, with level surrounding terrain or obstacles and an infinitely long, hard runway.

Overrun and undershoot risk models were developed to allow specific factors relating to the existing operational conditions to be considered in the analysis of RSAs. The probability distributions for wreckage location in the proximity of the runway threshold were modelled. This was both for the longitudinal and lateral deviation from the runway centreline.

Logistic regression, discriminant analysis and probit analysis were used to develop the statistical models for accident/incident occurrence probability. This allowed a number of variables to be considered such as visibility, crosswind, precipitation, etc. The location model was in the form of an exponential equation, based on the accident locations in the database. The distribution of accident locations relative to the runway was modelled through the use of statistical functions.

5.2.4 Airport Cooperative Research Program, ACRP (2011)

The report by the Airport Cooperative Research Program (ACRP, 2011) is an update to that described in Section 5.2.3, with the aim of improving the models used for assessing Runway Safety Areas (RSAs).

Five types of incident were considered, as opposed to the three considered in the earlier report (ACRP, 2008). These were: landing overruns, landing undershoots, landing veer-offs, take-off overruns and take-off veer-offs. Appendix B of the report contains a list of accidents and incidents used for the model development. Plots are given showing the number of each type of incident by the distance from the runway.

The event probabilities were calculated using backward stepwise logistic regression. This allowed a number of variables to be taken into consideration including visibility, crosswind, precipitation, etc.

The location models were based on historical accident data for aircraft overruns, veer-offs and undershoots. The location for overruns depended on whether or not an arrest system was installed in the RSA, which reduces the distances travelled. Five sets of complementary cumulative probability distribution (CCPD) models were developed. These calculated the fraction of accidents that involved locations exceeding a given distance from the runway end or threshold. When multiplied by the frequency of accident occurrence, a complementary cumulative frequency distribution (CCFD) was obtained. This quantified the overall frequency of accidents involving locations exceeding a given distance from the runway boundaries. The models were exponential functions.

The models were validated by comparing the results with historical accident rates for a sample of eight airports. None of the airports were part of the sample used to develop the risk models. Good agreement was shown, although the sample size was small.

The work was heavily based on that by Wong (2009a, 2009b).

5.2.5 Ayres *et al* (2013)

This work (Ayres *et al*, 2013) builds on that reported by Wong *et al* (2009a, 2009b) and ACRP (2011), which developed accident and incident frequency models for different types of take-off and landing events. It is referred to subsequently as the Loughborough model. The paper aims to summarise the work on the models of aircraft crash location and consequence. The events were: landing overruns, landing veer-offs, landing undershoots, take-off veer-offs and take-off overruns. Data from a number of different sources was used, representing 11 countries. The full list is in Appendix B of ACRP (2011).

Plots are given for the number of each type of incident and the distance from either the runway centreline or the lateral distance from the runway edge. Most incidents occurred within a short distance of the runway (and so it can be assumed that they were contained within the airfield).

The location models from Airport Cooperative Research Program (ACRP, 2011) are described together with consequence models. The main emphasis of the paper is on Runway Safety Areas (RSAs), as in the case of the earlier reports, and so it appears that the bulk of the data represents incidents that occurred within the airfield boundaries. The overruns, for example, appear to assume that the aircraft has touched down/ not taken off as the location model depends on whether the terrain is paved or unpaved.

5.2.6 Phillips (1987)

The report by Phillips (1987), for the Atomic Energy Authority (AEA), describes a model for use in assessing the risk from an aircraft crash onto a nuclear site. In particular, two separate crash distributions for crashes around airfields were developed, one for commercial/military traffic, and one for light aircraft. These were based on USA and Canadian data.

5.2.7 Byrne (1997)

The report by Byrne (1997) aimed to develop a methodology to assess aircraft crash risks at any location on the UK mainland. The crash risk calculation was divided up into a number of stages and was split according to five aircraft categories. These were:

- Light civil aircraft: fixed wing aircraft of less than 2.3 te maximum take-off weight authorised (MTWA). It includes military light aircraft used for training that are less than 2.3 te MTWA;
- Helicopters: all civil and military helicopters;
- Small transport aircraft: fixed wing aircraft in the MTWA range of 2.3 te to 20.0 te, including civil and transport military aircraft;
- Large transport aircraft: any other civil or military fixed wing aircraft not covered in the other categories;
- Military combat and jet trainers: all military fixed wing aircraft with MTWA up to 40 te to 50 te used for, or capable of, aerobatic style flying.

A background crash rate was calculated for England, Scotland, Wales and the UK mainland as a whole. (NB crashes occurring over the Isle of Man, the Scottish Islands and Jersey appear to have been included so the rate should be reported as the rate for Great Britain, rather than the UK mainland). The background rate was calculated for each aircraft type, using a Poisson process and assuming a 50% confidence level, where crash data for the period 1985 to 1994 was used. The data source used for civil aircraft was the Civil Aviation Authority (CAA) annual reports of accidents to UK registered aircraft and to foreign registered aircraft in UK airspace (CAA, 1985 to 1991).The primary source of information for military aircraft accidents was the Royal Air Force (RAF) Inspectorate of Flight Safety. Other sources were used for non-RAF accidents.

The military category was considered further, with the country being divided up into areas of high crash concentration and low crash concentration. Different background rates were calculated for these areas, with a further formula being applied to the transition zone from the high to the low concentration.

Note that, although Byrne refers to the UK mainland in the calculation of the background crash rate, crashes occurring on the Scottish Islands, the Isle of Man and Jersey have been included.

A method for calculating airfield related crash rates was described, where the crashes were associated with the take-off and landing phases of flight. Distributions were used to determine the location of the crash in relation to the runway. Reliabilities, in terms of crashes per movement, were quoted from a previous report and were at the 50% confidence level.

A method was given for calculating the crash rate below an airway. This was dependent on the in-flight reliability of each class of aircraft, and the number of movements on the airway.

Methods for calculating impact frequencies for individual buildings or other sites of interest were given. This took into account descent angles and calculated effective target areas. Impact mass probability distributions for different types of aircraft were also calculated.

Other aspects of aircraft crash were also considered, such as aircraft fuel fires, debris falling from moving aircraft and in-flight break-up of an aircraft.

The data within the Byrne model has been updated in 2002 and 2008. The reports are not in the public domain, however, and cannot be used.

5.2.8 Cowell *et al* (1997)

The aim of the report by Cowell *et al* (1997) was to describe an aircraft crash location model developed by National Air Traffic Services (NATS) that could be used as part of the development of Terminal 5 at Heathrow Airport. Different models were created to determine the wreckage location for take-off overruns, landing overruns, take-off non-overruns and landing non-overruns (i.e. accidents that did not involve the aircraft overrunning the runway). In addition, models for the point of first impact for take-off non-overruns and landing non-overruns were also created. The models were based on data from 464 airport accidents.

The model was updated in 2000 but the report on the update is not in the public domain and therefore cannot be used.

5.2.9 Evans *et al* (1997)

The report by Evans *et al* (1997) produced individual risk contours around five sample UK airports (Heathrow, Gatwick, Birmingham, Manchester and Leeds Bradford) using various models, to review the Department of Transport policy on Public Safety Zones (PSZs). A PSZ is an area of land adjacent to the end of a runway in which development is restricted. The calculation of the contours required the crash frequency (annual probability of a crash occurring near a given airport), a crash location model (the distribution of the crashes with respect to location) and a consequence model (the size of the crash area and the proportion of people likely to be killed within the area).

Appendix A of the report contains information on where accident data and movement data was obtained. It also compares the recorded movement data with actual data from Heathrow and Manchester airports to determine the veracity of the movement data for the other airports.

Details are given of how the worldwide historical crash and movement data were subdivided to form generic aircraft groups. The crash data came from the Airclaims CASE database (now the Ascend database) and the movement data from the Official Airline Guide (OAG). Only data from first world countries was considered, although it is not clear if this referred to the country where the crash occurred, the country of registration of the aircraft, or the country of location of the aircraft operator. The data was split as follows:

- Class I western airliner jets;
- Class II-IV western airliner jets;
- Eastern jets;
- Executive jets;
- Western airliner turboprops delivered in and after 1970;
- Western airliner turboprops delivered before 1970;
- Unclassified turboprops;
- Piston-engine aircraft.

The western airliner jets were subdivided into two classes based on Boeing's classifications; Class I, which represents the oldest jets, and Class II-IV, which covers all other jets. The authors stated that significant differences in crash rates were seen between Class I and the other classes, with much smaller differences seen between classes II, III and IV. More recent data also shows a significant difference in accident rate between classes II and IV so this statement in the report is no longer supported by the data.

The crash rates for all the categories other than executive jets, unclassified turboprops and piston-engine aircraft were estimated using the Airclaims crash data and the OAG movement data. These rates were then multiplied by the number of movements of that category of aircraft at the airport of interest to get a predicted crash frequency.

The rates for western airliner jets and western airliner turboprops were based on scheduled passenger (SP) flights only due to available data constraints. Rates for unclassified turboprops could not be derived due to insufficient data and so the rate for the western airliner turboprops delivered before 1970 was used. The eastern jets crash rate had an associated high level of uncertainty, but this type of jet represented a small proportion of the number of flights at the airports of interest and so was unlikely to have much influence on the overall crash frequency.

The crash rate for western airliner turboprops delivered in and after 1970 was used for the executive jets as there was insufficient data to derive a separate rate. The proportion of flights using executive jets was low so any inaccuracies in the use of this value was not likely to significantly affect the overall crash frequency.

A crash rate, taken from the literature, of 3 crashes per million movements was used for piston-engine aircraft as data was not recorded in the Airclaims database for this aircraft category. The same rate was used for other non-commercial flights, which made up a small proportion of all flights. These types of flights did not occur at all airports. All other flight types that did not fall into any of the listed categories were assigned the rate of 3 crashes per million movements; these flight types only represented a small proportion of all flights.

An average crash rate at each airport was calculated based on the calculated crash frequency for each aircraft type and the total number of movements at the airport.

To assess sensitivity to the crash rates, tests were performed:

- using worldwide crash data, rather than first world data;
- using additional data for overruns;
- assuming the crash rate for non-SP jets was twice that of SP jets.

Significant differences were seen in the results from all three tests, with the largest difference being from the use of worldwide data.

A number of crash location models were discussed, although the National Air Traffic Services (NATS) location model (Cowell *et al*, 1997) was chosen to perform the analysis as it was based on the largest dataset and the distributions are in the public domain. The NATS location model was based on data for aircraft with maximum total weight authorised (MTWA) of 4 te or more. Most aircraft below this weight are likely to be non-commercial, with different crash location distributions due to their flying activity differing from commercial aircraft activity. The model contained four distributions for:

- landing overruns including veer-offs;
- landing crashes from flight;
- take-off overruns including veer-offs;
- take-off crashes from flight.

No account was taken of curved flight paths due to a lack of information on this aspect. It was assumed, therefore, that the arriving and departing aircraft maintain the extended centreline of the runway. As light aircraft were not included in this model, the Atomic Energy Authority (AEA) model (Phillips, 1987) was used for light aircraft in the calculations.

The average aircraft crash rate at each airport was split into the four accident types from NATS according to data recorded in the Airclaims database. This indicated that 20% of relevant incidents were take-off crashes from flight, 8% were take-off overruns, 52% were landing crashes from flight and 20% landing overruns. The crash rate was apportioned accordingly.

Although sensitivity tests were performed, no estimations were made for the levels of uncertainty around the data and the methods used, e.g. by the use of confidence levels.

5.2.10 Hillestad *et al* (1993)

The report by Hillestad *et al* (1993) is a study regarding safety at Schipol Airport in the Netherlands as a result of an aircraft crash. The first few sections concern management at the airport, the operations performed and consultations with the public regarding the perception of safety. Chapter 5, however, reviews worldwide aviation accidents and causes, whilst Chapter 6 describes a method for evaluating the safety at the airport.

Chapter 5 gives a list of sources used to populate a database of aircraft accidents, with further details being given in Appendix B. These include the Civil Aviation Authority (CAA), Boeing Commercial Airplane Group and the International Civil Aviation Organisation (ICAO). In particular, the authors looked at hull loss data to determine the factors that could influence third-party risk near Schipol. The incidents dated from 1959 through to 1991. The number of aircraft movements appears to have been obtained, although this is not explicitly stated.

The data was interrogated to determine if the accident could have occurred at Schipol, given that the conditions at airports around the world vary considerably. Any that were considered to be unlikely to occur, e.g. crashes due to air shows and formation flying, were excluded from the database. Others, that appeared unlikely e.g. a crash due to blowing sand, were included as the mechanism of the crash was reduced visibility, which could occur at Schipol due to fog.

The causes of the crashes were identified, where possible, and potential prevention/mitigation measures were discussed.

Trends of the data over time indicated that aviation safety has improved. It also showed that newer aircraft have a lower accident rate than older aircraft after an initial introductory period.

In Chapter 6, the authors describe a model to evaluate the safety at Schipol airport. They obtained data on:

- the movements by aircraft type;
- whether they were taking off or landing;
- the runway used;
- Standard Instrument Departure, SID (departure route) or Standard Terminal Arrival Route, STAR (arrival route);
- business or non-business hours.

Hull loss data for 1987 to 1991 for all accidents that were applicable to Schipol was assembled for the types of aircraft used at the airport.. Only hull loss incidents were considered, as there have only been a negligible number of accidents that led to third-party fatalities outside the airport that did not result in a hull loss. Incidents that occurred within the grounds of the airport or far from the airport were also excluded. This allowed an accident rate to be derived.

The expected number of crashes that could contribute to the external risk was calculated by multiplying the number of movements by the accident rate for each type of aircraft. The distribution of the crashes was calculated as a function of the longitudinal distance along the intended flight path and the lateral distance from the flight path using crash data defining the x and y location of crashes relative to the runway. Assumptions were made allowing estimates of mortality to be derived for the surrounding population. This varied according to the time of day, assuming business and non-business hours.

Projections were made for the aircraft movements by aircraft size, time of day, etc. for 2003 and 2015, allowing any change in the risks from the airport to be assessed. Adjustments were made to derive rates for take-offs and landings separately.

A number of changes that could occur at the airport and in its environs between 1993 and 2015 were considered, including changes in fleet mix, growth in population, changes in population distribution and the addition of a fifth runway.

The authors highlighted the uncertainty surrounding any risk calculations when the underlying data (number of crashes) is small. They calculated the group risk around the airport (defined as the annual expected number of fatalities among a population of people living or working near, but outside the airport) for the different years. The results were given as the number of fatalities per year. The variance and standard deviation around this figure were given in each case, as an indication of the uncertainty. The results were compared to the expected number of fatalities in the area from car accidents.

The method used by the authors allowed them to consider measures that could be taken to improve the safety around the airport, thereby reducing the projected number of fatalities from an aircraft incident each year.

5.2.11 Couwenberg (1995)

This paper by Couwenberg (1995) is concerned with the development of an aircraft crash location model around Schipol airport. Three crash location models are developed for:

- take-offs;
- landing accidents that occur before the runway threshold;
- landing overshoot accidents.

All three models use curvilinear coordinates relative to the ground track of the intended flight path.

5.2.12 Piers *et al* (1998)

Piers *et al* (1998) provide an overview of risk modelling around airports, which builds on the work of Couwenberg (1995). In particular, they describe a general methodology which is broken down into three main elements:

- calculating the probability of an aircraft crash in the vicinity of the airport;
- creating an accident location probability model to indicate where the crash will occur;
- assessing the consequences to people in the vicinity.

The combination of these three elements allows the individual and societal risk to be calculated.

To calculate the aircraft accident rate, the authors emphasise the need to only use accident data that are relevant to the airport in question. They suggest that data must be collected from a number of different sources, including international sources, but that this data must be matched to the conditions at the airport that is to be assessed. A statistical fitting process can be used to calculate the accident rate, or an average rate over a number of years can be calculated. The authors suggest that separate accident rates should be calculated for take-offs and landings and for different categories of aircraft.

The paper states that accident location models are difficult to develop due to a general lack of accurate data, but that they need to be developed to determine the individual and societal risk around an airport. The authors define three categories of accident location models that have been used previously, providing examples of each and a review of the general techniques used to develop these models.

The first category of accident location model is relatively simple, and provides an estimate of the crash location based on historical data, over broad, geographical locations.

The second category of aircraft crash location model generate two-dimensional probability density functions to describe the crash location probability as a function of the Cartesian coordinates for a particular location relative to the runway. Separate functions are provided for take-offs and landings. The models often consider the x-distribution and y-distribution functions to be independent, which is not necessarily borne out when statistical tests are performed on the data.

The third category of accident location model aims to model the accident locations in curvilinear coordinates to consider the aircraft routes in the calculations. This category of model aims to consider the curved approaches and take-offs at the airport. A minimum of three separate location probability models are required for this category:

- take-offs;
- landings;
- landing-overruns.

The authors note that the data is scarce, implying that it is difficult to develop such models with any degree of certainty.

Descriptions are given of different types of consequence models and of the data required to undertake a full risk assessment. An overview of the results that can be obtained from the models is given in terms of the individual and societal risk. There is a separate discussion on the need to consider uncertainty as part of the modelling process.

5.2.13 Pikaar *et al* (2000a)

This report by Pikaar *et al* (2000a) describes a model to calculate the risk around Schipol airport and is based on earlier work by Couwenberg (1995) and Piers *et al* (1998). It was developed for the Netherlands National Aerospace Laboratory (NLR). A selection method for the accident data is used, which identifies airports around the world with similar characteristics to Schipol. The accidents that have occurred at these airports are used in the derivation of an accident rate. The method reduced the number of airports from 5000 to 40, and includes both Heathrow and Gatwick. The final set consists of airports that are all within Europe or North America.

The authors list a number of sources for accident data and identify 850 aircraft accidents related to the 40 airports, with no double counts. A number of criteria were used to screen the identified accidents (e.g. only incidents between 1980 and 1997 are considered as the documentation regarding earlier incidents is less detailed and movement data are either incomplete or unavailable at those times), reducing the total to 75 incidents.

Movement data was obtained from the Official Airline Guide (OAG) database. The database contains data on the scheduled movements of aircraft heavier than 5.7 te for all commercial airports worldwide. The validity of the database was checked by comparing the number of movements given in the database for Schipol with those given in the Statistical Annual Reviews of Amsterdam Airport Schipol. It was found that the difference was, on average, less than 0.3%, which was considered negligible. The OAG database does not contain non-scheduled flights but the number of such flights at Schipol is low.

Accident rates for different ages of aircraft, and for take-off or landing overruns, overshoots or veer-off were calculated, together with the values assuming a 95% confidence interval. Statistical significance for the difference by age of aircraft was calculated. It was found that only the take-off veer-off and take-off overshoot accidents did not display differences in accident rate by generation of aircraft that were statistically significant.

Five datasets were used to ascertain the distribution of accident locations, assuming that an accident occurs. The distribution of locations is dependent on the phase of flight. The data was subdivided into:

- overshoots;
- take-off overruns;

- undershoots;
- landing overruns;
- veer-offs.

It was found that the lateral distance, y, from the runway centreline was linearly dependent on the longitudinal distance, x.

The Weibull distribution was used to model the longitudinal distribution of locations whilst the lateral distribution was modelled using the generalised Laplace function. A Gaussian distribution was used for the lateral distribution of locations on the extended centreline.

Distributions were applied for each of the accident types e.g. overruns, overshoots, etc. The parameters of the distributions were estimated from the accident location data using the maximum likelihood method.

The various distributions and accident rates formed part of an accident consequence model that calculated the number of fatalities should an accident occur. It was used to evaluate third party risk for two scenarios, which are detailed in the report. This provides examples of how to use the model.

5.2.14 Pikaar *et al* (2000b)

This paper by Pikaar *et al* (2000b) appears to be a high level overview of the work described in Pikaar *et al* (2000a). It does not contain any useful additional information.

5.2.15 Sandquist *et al* (1995)

This paper provides an overview of the Aircraft Crash Risk Assessment (ACRA) model for performing aircraft crash risk assessments and demonstrates the method by assessing the risk at Salt Lake International Airport (SLIA). In general terms, the annual frequency of aircraft crashes in a particular location, *F*, is given by:

$$F = \Sigma NPfA \tag{3}$$

where:

N = annual number of aircraft operations which could impact a ground facility;
P = frequency of an aircraft crashing per operational measure (usually expressed as the crashes per distance flown, or hour flown, or per flight);
f = the distribution of crashes from the runway threshold and the centreline of the approach or departure path, or the centreline of the airway; and
A = effective surface area of a building or facility exposed to an aircraft crash.

ACRA contains a number of databases of historical crash information and geographical information. The area in the far field from the airfield in question, in this case SLIA, is divided up into a regular grid and the ground features (e.g. buildings) are averaged within each cell. The population is also recorded in each cell. In the near field, the grid cells are finer. The aircraft crash risk is calculated for each cell.

5.2.16 Kimura *et al* (1996)

The report by Kimura *et al* (1996) from Lawrence Livermore National Laboratory (LLNL) describes the data development that was used in the Aircraft Crash Risk Analysis Methodology (ACRAM), which was subsequently used as part of the US Department of Energy (DOE) standard on aircraft crash risk around hazardous sites (DOE, 2006). An earlier version of this model was used in the Salt Lake International Airport assessment described in Sandquist *et al* (1995).

The incidents included in the analysis were those that resulted in destruction or substantial (major) damage to the aircraft. It was not based on fatalities or injuries as a substantial number of fatal accidents or those that incur injury do not involve significant damage to the aircraft (e.g. ground accidents, severe air turbulence).

A number of tables are given in Section 2 of Kimura *et al* (1996) that describe the number of crashes, and the calculated crash rate. The first 16 of these tables are for air carriers. The time period 1973 to 1994 was used and data was obtained from the National Transportation Safety Board (NTSB). Some of the tables distinguish by the phase of flight, although a number of assumptions have been made to derive statistics in this manner. In particular, a "typical" flight was used, which was defined as lasting 1.4 hours, having a distance of 570 miles, and 407 miles/hour average velocity. Further tables distinguish between all accidents that satisfied the criteria, and those which then entailed the plane being written off. Later tables adjust the values such that only accidents that occurred off the airport are considered.

A similar process was undertaken for air taxis. In this instance, data from the NTSB for years 1980 to 1993 was used.

Location distributions for commercial aircraft are given that model the off-runway impact location, angle and velocity, and the heading and deceleration after impact. A database of commercial aircraft accidents between 1950 and 1990 was used. Separate distributions are described for take-off and landing accidents.

The accidents used in the commercial aircraft analysis are given in an Appendix to Section 2 of the report.

Section 3 of the report provides tables of data that were used to derive crash rates for the general aviation category, divided into a number of subcategories. Tables of crash rates by flight phase for subdivisions of the general aviation category are presented. A formula is given for the location distribution. A table of values for crash location probabilities for general aviation take-offs is given, together with one for landings.

Two analyses were performed to derive military aviation crash frequencies, described in Section 4 of the report. The first analysis was based on a review of brief summaries of incidents provided by the Air Force/Army safety agencies and covered the time period up to 1994. The second analysis used the Air Force mishap database. The crash location distributions were based on data from the Air Force mishap database between 1976 and 1994.

5.2.17 US Department of Energy, DOE (2006)

This is a US standard from the Department of Energy (DOE, 2006) to evaluate and assess the effect of aircraft crash onto a hazardous facility. It covers the risk of crash and the offsite and onsite consequences. The process is divided into four phases, of which the first, to determine the frequency of aircraft impact into a facility, is of relevance to this project. It aims to provide conservative results rather than calculating levels of uncertainty associated with a best guess estimation.

The emphasis of the standard is on estimating the extent to which aircraft crash is of concern to a hazardous site. This does not require an accurate estimate of the risk as it is sufficient to determine whether or not it is larger than other risks to the site.

Generic crash rates for various aircraft categories are given in Table B-1 in Appendix B of the standard. They have been based on data from the Federal Aviation Authority (FAA) or National Transportation Safety Board (NTSB) for civilian aircraft and the US military for military aircraft. Different rates are given for take-offs and landings.

Crash location probabilities were calculated from FAA/NTSB data for civilian aircraft and from US Air Force data for military aircraft. They are given per square mile in tabular form in Appendix B, assuming x and y coordinates from the runway centre, for different categories of aircraft. Each probability value reflects the conditional probability that, given a crash, the crash will occur within a specific one square mile bin in the vicinity of an airport.

An expected number of crashes per square mile per year for incidents not associated with airports is given. Due to the limited number of historical in-flight crashes, particularly for larger aircraft, this represents an average value across the US. Maximum and minimum values are also given for commercial and military operations.

The details of how the tables were generated are given in Kimura *et al* (1996).

5.2.18 Trotta (2012)

This report by Trotta (2012) was in response to an application for Lydd airport in Ashford to increase the passenger throughput and to enable landing and take-off of larger aircraft. ESR Technology used the Byrne method (Byrne, 1997) to assess the impact of the proposed changes at the airport on the risk associated with aircraft crashing at Dungeness nuclear power plant. Trotta reviewed the ESR report, investigated the method and concluded there were a number of shortcomings with the technique, which were highlighted. The most pertinent of these are as follows:

- The background crash probability is affected by the confidence level chosen and on the statistical method adopted. Byrne assumed a confidence level of 50%, as opposed to a more conservative value of 1% (2.5% is more widely adopted). This has the effect of increasing the background crash rate for the small transport category by a factor of 2;

- Curved flight paths were not assessed by the Byrne methodology. Instead, it was assumed that the aircraft follow the runway centreline;

- Imprecise details of the crash locations lead to an underestimate of the crash probability at locations further away from the runway centreline. There is little data available at further distances from the runway, and functions were fitted to this data which rely largely on extrapolation. This leads to a high degree of uncertainty in the exact location, which is not considered by Byrne;

- The crash reliabilities, as in the case of the background crash rate, were evaluated at the 50% confidence level, which is considered to be insufficiently conservative.

The conclusion of the report is that the results obtained by ESR Technology were neither robust nor accurate.

5.3 DATA IN THE LITERATURE

5.3.1 Boeing (2013)

Boeing (2013) provides a number of statistics for worldwide commercial jet airplanes that are heavier than 60,000 pounds (~27 te) gross weight. Two groups are excluded, namely:

- airplanes manufactured in the Commonwealth of Independent States or the Union of Soviet Socialist Republics due to a lack of operational data;
- commercial airplanes operated in military service.

A table is given of the airplane accidents that occurred in 2013, which includes:

- the airline;
- the aircraft type;
- the type of operation;
- accident location;
- the phase of flight;
- an event description;
- whether it entailed a hull loss.

In total, there were 31 accidents, with 13 hull losses.

Graphs are given that show an upward trend from 1994 to 2013 in the number of flight hours, the number of departures and the number of airplanes.

A summary table is given of the number of accidents worldwide since 1959 by type of operation. In addition, there is a graph showing the trend in the overall accident rate, the fatal accident rate, onboard fatalities and the hull loss accident rate since 1959. This indicates an initial sharp decline in the rates, followed by a gradual, continual decrease, although some variation is seen from year to year.

Statistics are presented for the fatal accidents and onboard fatalities by phase of flight for 2004 to 2013. For the fatal accident rate these statistics indicate that 14% of the accidents occur in the take-off and initial climb phases of flight, and 47% occur in the final approach and landing phases. This makes a total of 61% of accidents occurring during take-off and landing.

5.3.2 Civil Aviation Authority, CAA (2011)

The report by the Civil Aviation Authority (CAA, 2011) covers UK aviation safety statistics for the period 2000 to 2009. It provides statistics on the number of different types (large aeroplanes, small aeroplanes, helicopters and balloons) of UK registered and UK operated aircraft involved in accidents around the world and includes a calculated accident rate. The data is also split between public flights and non-public flights (e.g. aerial survey, construction work, line inspections, etc.).

5.3.3 Civil Aviation Authority, CAA (2013)

This report by the Civil Aviation Authority (CAA, 2013) contains a large number of statistics. Of particular interest from the worldwide data are:

- In the 10-year period 2002 to 2011, the number of flights flown worldwide increased by 22%, equivalent to an average annual growth rate of 1.9%. The equivalent values for hours flown were 36% for overall growth and 3.0% for average annual growth;

- There was a decreasing trend in the overall rate of fatal accidents and onboard fatalities;

- On average, the fatal accident rate for turboprops was four times that for jets, based on flights flown, or nine times greater when considering hours flown;

- On average, the fatal accident rate for aircraft with Maximum Take-off Weight Authorised (MTWA) below 15 te was three times that for aircraft with MTWA above 27 te, based on flights flown, and nine times greater based on hours flown;

- On average, the fatal accident rate for cargo flights was eight times greater than for passenger flights, based on flights flown, and seven times greater based on hours flown;

- North America had the lowest fatal accident rate of all the regions. The fatal accident rate for African operators was over seven times greater than for all operators combined.

5.3.4 International Air Transport Association, IATA (2012)

This is the 2012 annual review of worldwide aviation from the International Air Transport Association (IATA, 2012). It is stated that the hull loss accident rate for western built jets (WBJ) was 0.37 per million flights in 2011. This was the lowest in aviation history. Over the previous 10 years, there was a 61% improvement in safety for western built jets, although there was significant regional variation in this figure.

5.3.5 National Transportation Safety Board, NTSB (2011)

This report by the National Transportation Safety Board (NTSB, 2011) provides high level statistics for US civil aviation accidents for the years 2007 to 2009 that were investigated by the NTSB. It includes the number of accidents that included a runway excursion (overrun or undershoot) or collisions on take-off or landing.

5.4 DISCUSSION

From the literature it would seem that a general methodology for calculating aircraft crash risk can be described.

The first part of this methodology involves calculating a background crash rate from historical data that can be specific to the country of interest. The background rate is the likelihood that a crash will occur over any location during the cruise phase of flight, and is not applicable at, or close to, airports. The rate can be subdivided into different classes of aircraft. In some models, confidence intervals are included to model the uncertainty associated with the scenario.

The next part of the methodology is to calculate an airfield specific crash rate. This considers the take-off and landing phases of flight (including the initial climb and final descents). It is based on historical data, which is normally specific to the country in question. Data for the specific airfield is normally too sparse to generate this crash rate. In some models, different types of accident are considered, e.g. landing overruns or undershoots, and crash rates are calculated for each type. Some models attempt to take into consideration operational data such as the age of the aircraft and the meteorological conditions at the time of the accident. In these cases, formulae are developed that allow the user to input the types of conditions that can be found at the airport in question. Confidence intervals on the values obtained are provided in some of the models.

The airfield specific crash rate is calculated by multiplying the generic airfield crash rate by the number of movements at the airport in question.

The third part of the methodology is to calculate where the crash is located, assuming a crash occurs during take-off or landing. Distributions are derived based on historical data. The literature varies as to what data should be used to derive the distributions. It can be worldwide accidents or a subset of these accidents that satisfy some criteria. Distributions may be calculated for the different types of accident (e.g. take-off overruns) or the distributions may just depend on whether the aircraft is taking off or landing, or on the aircraft type. Some criticisms have been made in the literature (e.g. Trotta, 2012) when curved flight paths have not been considered.

The fourth phase in the calculation is to consider the effect that a crash has on the ground i.e. the consequences of the crash. As the aim of this study is to calculate a likelihood of an aircraft crashing, the consequences are not required for this analysis. This aspect of the modelling is therefore not considered further.

Although the inclusion of operational data in the calculation of the airfield specific crash rate allows more specific aspects of the airfield in question to be modelled, there are a number of disadvantages with this approach. In the first instance, it relies on the information being recorded, and recorded accurately, for each accident that is used to build up the crash rate. Statistical techniques have to be employed to relate each of the elements of the operational data to the crash rate, which leads to further uncertainty. In some instances, some of the parameters in the final equations seem hard to justify, such as the meteorological ceiling height. To calculate the crash rate, numerous different combinations of weather conditions and aircraft parameters need to be considered and multiplied by the number of movements that would satisfy all of the specified criteria. The movement data is not recorded at this level of detail. Given the general levels of uncertainty surrounding the whole modelling process, there is the risk that the approach will imply a greater level of confidence in the final results than is actually there.

The use of confidence intervals on the likelihoods obtained appears essential. In some cases the data is sparse, leading to a high level of uncertainty surrounding the crash risks obtained. This uncertainty needs to be quantified in some manner, and confidence intervals are an accepted way of quantifying the uncertainty.

The general lack of data means that aircraft types can only be divided up into coarse categories. Trying to refine the aircraft types into more categories, as in the case of the National Air Traffic Services (NATS) model (Evans *et al*, 1997), reduces the number of incidents that have occurred in each category, which leads to an increase in the uncertainty surrounding the final calculations. There appears to be little benefit in trying to distinguish between different types of aircraft, beyond a broad categorisation process.

The location distributions have been primarily used to determine the risk associated with an airfield at a specific site, normally nuclear power plants. They have also, in the case of Schipol Airport, been used to try and quantify the risk around a major airport. There are a number of potential issues with using this approach, however. The first is ensuring that only data relevant to the airfield in question are used. Worldwide data, or a subset of this data, has to be used as there is insufficient information that is specific to the airport in question. This raises a number of questions, including whether the crash locations will vary according to the take-off and landing routes at the airport or whether they will be randomly distributed due to the loss of control. Whenever possible, pilots will attempt to avoid built-up areas and this could affect the crash locations.

Location distributions require assumptions that the recordings of the first point of impact and the final debris location are accurate. Relatively small errors in these may impact on the accuracy of the final distributions. Meteorological conditions, the age of the plane, the aircraft maintenance regimes, pilot training, the number of hours that the pilot has flown on that flight, the experience of the pilot etc. can all influence the crash location (as they will affect the responsiveness of the aeroplane and the actions that the pilot will take).

It could be argued that modelling a crash location can lead to a high degree of confidence that the final results are definite values when, in reality, there is a large level of uncertainty surrounding these calculated values. Criticisms of this method have appeared in the literature previously (e.g. Trotta, 2012), particularly at locations further away from the airfield, as the data is generally too sparse to allow for confidence in the final predictions.

An alternative method to that generally described in the literature, is to generate look-up tables of the total crash rate by distance from the airfield, as in the case of the US Department of Energy model (DOE, 2006), which provides tables of risk against distance. The actual process to derive the look-up tables would be similar to the general method already described, however, and so there appears to be no additional advantage to using this method.

The DOE values cannot be used directly as they use data that may not be applicable to the UK and they have been derived for a generic airport. The aim of this project is to derive likelihoods of an aircraft crash that are specific to Heathrow and Gatwick airports. The DOE values will have included information from aircraft that are not applicable to these two airports, and from airfields that are different from Heathrow and Gatwick.

In a number of cases within the literature, the aim of the modelling has been to consider the risk to a specific site from aircraft crashing. The aim of this project is to consider the likelihood of an aircraft crash around Heathrow and Gatwick airports. The two aims are subtly different. A generic method is required to calculate the risk to a specific site from an aircraft crash that can be applied to any site of interest. The aim of this study is to create a model specific to Heathrow and Gatwick. In practical terms, the differences between the two approaches may be small but it means that some scenarios that are considered in the general case, may not need to be considered in the specific case for this study. It also can have an impact on the data used. In the generic case, a wider range of data may be used to develop the crash rates than would be the case when looking at a specific airport.

In terms of the data reviewed, although some interesting statistics are provided, there is generally insufficient information to perform any calculations. Some of the information may be used but additional data is also required.

6 APPENDIX B: METHODOLOGY

6.1 INTRODUCTION

A standard approach to modelling aircraft crash risk has been described in the literature reviewed (Section 5.4). This approach can be summarised as:

- Calculate background crash rate:
  This is the crash rate for anywhere in the country caused by an accident in an aircraft flying overhead. It is not associated with any specific airfield and can relate to aircraft that do not take-off or land in this country;

- Calculate airfield specific crash rate:
  This is the crash rate associated with aircraft taking-off or landing at a specific airfield. It is not associated with aircraft in the cruise phase of flight;

- Derive distributions of crash locations:
  This refers to statistical distributions defining the location of a crash, assuming a crash has occurred on either take-off or landing. It is associated with a specific airfield and is not associated with aircraft in the cruise phase of flight;

- Estimate the consequences on the ground:
  When an aircraft crashes, it can cause damage to buildings and harm to people. This stage of the process estimates how many people are likely to be killed or injured should an aircraft crash. It is associated with a specific airfield as it refers to crashes that occur during take-off or landing.

The background crash rate and the airfield specific crash rate are calculated for Heathrow and Gatwick airports as described in the literature. Issues have been identified for the derivation of crash location distributions for this case, including:

- A high level of statistical uncertainty in the crash location distributions calculation;

- Take-off and landing routes around the airports being subject to change in the future, which would affect the distributions.

Given these issues, the crash location distributions are not being used as part of this analysis. However, whilst the crash locations are not modelled explicitly, a discussion regarding which areas will be subject to the greatest likelihood of a crash is included in this report. This discussion considers areas up to and beyond 10 km from both airports under consideration.

The Airports Commission asked HSL to determine the likelihood of an aircraft crashing in the vicinity of Heathrow and Gatwick. The consequences of a crash, the final stage of the risk calculation, described in the literature is not required to calculate this likelihood.

The chosen method, therefore, consists of two stages:

- Calculation of a background crash rate, which applies to areas away from the airport;

- Calculation of an airfield specific crash rate that applies to areas in the vicinity of the airport.

The different stages in the methodology are discussed in more detail in the subsequent sections.

6.2 BACKGROUND CRASH RATES

Background crash rates are calculated for five categories of aircraft, as described in Byrne (1997). The five aircraft categories are:

- Light civil aircraft: fixed wing aircraft of less than 2.3 te maximum take-off weight authorised (MTWA). It includes military light aircraft used for training that are less than 2.3 te MTWA;
- Helicopters: all civil and military helicopters;
- Small transport aircraft: fixed wing aircraft in the MTWA range of 2.3 te to 20.0 te, including civil and transport military aircraft;
- Large transport aircraft: any other civil or military fixed wing aircraft not covered in the other categories;
- Military combat and jet trainers: all military fixed wing aircraft with MTWA up to 40 te to 50 te capable of aerobatic style flying.

The crash events are represented as a Poisson process (Ross, 2000) with rate parameter λ (i.e. the number of background crashes per year for a chosen area). The maximum likelihood method (Hazewinkel, 2001) has been used to estimate the value of λ, as it is a standard method for estimating the parameters of a statistical model. This method selects the parameter value maximising the probability of obtaining the observed data. For a Poisson process, the maximum likelihood estimate of λ is:

$$\hat{\lambda} = \frac{1}{n}\sum_{i=1}^{n} k_i \qquad (4)$$

where k_i is the number of crashes observed in year i, and n is the number of years of observations.

The benefit of using a Poisson process is that the chi-squared distribution can be used to determine the rates per km^2 expressed at any specified confidence level. The chi-squared distribution (Ulm, 1990) has been used to calculate 95% confidence intervals for the background rates: if r is the number of crashes occurring over time period t, the chi-squared distribution relates the probability α that the mean crash rate is greater than or equal to a value of θ, where:

$$\theta = \frac{\chi^2_{\{1-\alpha,2r\}}}{2t} \qquad (5)$$

or:

$$\theta = \frac{\chi^2_{\{1-\alpha,2(r+1)\}}}{2t} \qquad (6)$$

A 95% confidence interval is a standard interval to use for statistical purposes and the calculations for the upper and lower ends of the confidence interval, given in Equations 5 and 6, are the accepted method to use.

The area of land over which crashes could occur is required to calculate the background crash rates per unit area. The land areas for Great Britain are:

- England 1.304×10^5 km^2
- Scotland 0.788×10^5 km^2
- Wales 0.208×10^5 km^2
- Great Britain total 2.300×10^5 km^2

Screening criteria have been used to identify relevant data for the background rate assessment. In line with previous reports, the accident must have occurred over land or within 2 miles of the coast to be included in the background rate analysis (including the Isle of Man, the Scottish Islands and the Channel Isles). The accidents must be away from an airfield, as incidents close to airfields are included in the airfield crash rate analysis. The accident must have led to serious damage to the aircraft and/or fatalities. This ensures that minor accidents, such as injuries sustained during turbulence, are excluded. Accidents have been further excluded if they satisfy the following criteria:

- The aircraft was clearly involved in the take-off or landing phases of flight, or was involved in some other airfield related activity such as flying “in circuit”. In general, this means that accidents that occur within approximately 5 nautical miles (nm) of an airfield are excluded. For light aircraft, however, the accident may occur within a distance of 5 nm from the airfield and still be classed within the background crash rate as shorter distances are required for the initial climb and final descent when compared to larger aircraft;

- The accident occurred as a result of a forced landing in which the pilot had some degree of control over the choice of landing site. The pilot, in these situations, will generally try and avoid built-up areas or large structures. In reality, this leads to the exclusion of a number of light aircraft and helicopter accidents, but does not have a significant impact on the number of accidents that fall in the other categories;

- The accident was associated with crop-spraying and it occurred within, or close to the area being sprayed;

- The accident involved a helicopter hovering close to the ground.

Data on the number and location of crashes have been detailed previously in a report that is not currently available to the public, for light aircraft, helicopters, small transport aircraft and large transport aircraft between 1985 and 2006. These data sets have been extended by investigating Air Accidents Investigation Branch (AAIB) bulletins that are available on the internet (AAIB website). Data from the years 1990 to 2013 are used in this analysis, and details of the crashes for the four categories are given in Table 14 to Table 17 in Appendix C.

Although information is available on the AAIB website for 2014, it is possible that incidents that occurred towards the end of 2014 have not been fully investigated and have not yet appeared on the website. Use of this data could lead to an underestimate of the number of incidents that have occurred in 2014. Data up to and including 2013 has been used in this analysis. Any other data required as part of the analysis is up to and including 2013, where this has been possible.

Information on military aircraft crashes has been detailed in Byrne (1997) and two subsequent reports that are not available to the public. In total, the years 1985 to 2006 have been covered by these reports. The data was obtained from the Ministry of Defence and has been updated to 2013 by analysing information available from Service Inquiries and Board of Inquiries into military incidents that are published on the government website (Government website). Additional information has been obtained directly from the Royal Air Force (RAF, 2015). Details of the crashes that fall under this category are given in Table 18 in Appendix C.

Time trends for the data have been investigated, where this is possible. Data is too sparse for this analysis to be undertaken for the large aircraft category.

There is a perception that the risk of a crash would increase around Heathrow and Gatwick if additional runway capacity was developed at either airport, even though there is no evidence from previous studies to indicate that increasing the number of movements increases the background crash risk. This is likely to be due to safety systems on aircraft and on the ground having been improved as flight numbers have increased. Despite this lack of evidence, the background rates for the small and large transport aircraft categories have been factored up for each scenario by the increased number of aircraft movements in both of these categories to ensure that this possibility has been fully considered in the analysis. This gives a “worst case” scenario for the areas around Heathrow and Gatwick.

The non-UK military accident data have not been updated since 2006 as the relevant information is not readily available. The omission of this data will not affect the final results as it is the change in aircraft crash likelihood that is being assessed; as there are no military flights from Heathrow and Gatwick airports, the same military aircraft background crash rate will apply for all scenarios.

6.3 AIRFIELD RELATED CRASH RATE

The airfield related crash rate has been derived for two categories of aircraft, small and large transport aircraft. The light aircraft, helicopters and military categories used in the background crash rate analysis are not applicable for Heathrow and Gatwick airports. It is not possible to further refine the categories due to the sparsity of the accident data. Any attempt to do so would increase the uncertainty associated with the final results.

Screening criteria have been used to ensure that the historical accidents used within the analysis are relevant. In particular, only accidents that led to significant damage to the aircraft and/or major injury or fatality to crew or passengers were included. An accident was assumed to be airfield-related if it met the following criteria:

- The crash occurred within 5 nm of the runway threshold during approach or take-off;
- The crash resulted from significant loss of control, meaning that the pilot may not have been able to avoid impacts with buildings or structures. For the small and large aircraft categories used in this analysis, this did not lead to the exclusion of many incidents;
- The aircraft overshot or skidded beyond the boundaries of the airport.

Accidents that occurred on the ground e.g. when taxiing or during towing were explicitly excluded, as were fires on the ground, hard landings, veer offs, minor impacts or landing gear failures.

Data on the number and location of crashes have been obtained from sources such as the Air Accidents Investigation Branch (AAIB) bulletins on the AAIB website. The accidents used within the analysis are listed in Table 19 and Table 20 in Appendix D. Data from 1990 to 2013 will be used in the analysis.

The numbers of movements in each aircraft category for each year are also required to calculate the airfield related crash rates. This information has been obtained from the Civil Aviation Authority (CAA) for all major UK airports and is shown in Table 21 in Appendix D. This may slightly underestimate the number of movements in the small aircraft category, as there may be airfields not covered in the CAA data from which small aircraft were able to take-off and land. The effect of any omission of this data is likely to be minor, however, and potentially leads to a slight overestimation in the airfield related crash risk for this category of aircraft as the accident data covers all airfields within the UK mainland.

It has been assumed that the aircraft crash events can be represented by a Poisson process, as has been assumed for the background crash rate. The maximum likelihood method is used to calculate the airfield related crash rate per flight movement (see Equation 4 in Section 6.2). The chi-squared distribution (Ulm, 1990) has been used to calculate 95% confidence intervals for the airfield related crash rate: if r is the number of crashes occurring from N flight movements, the chi-squared distribution relates the probability α that the mean crash rate is greater than or equal to a value η, where:

$$\eta = \frac{\chi^2_{[1-\alpha,2r]}}{2N} \tag{7}$$

or:

$$\eta = \frac{\chi^2_{[1-\alpha,2(r+1)]}}{2N} \tag{8}$$

Equation 7 states that there is a 97.5% probability that the actual mean crash rate is greater than or equal to the calculated value (η). Equation 8 states that there is a 2.5% probability that the actual mean crash rate is greater than or equal to the calculated value.

The airfield crash rate is expressed as a rate per movement, which differs from the background crash rate, expressed as a rate by area. This airfield rate is not split by take-offs or landings, but data from Boeing (Boeing, 2013) has been used to apportion the rate between take-offs and landings.

An analysis has been undertaken to determine if there are any statistical trends to the data for small transport aircraft. It is not possible to do this analysis for the large transport aircraft category as there have been so few incidents historically.

The airfield crash rates specific to Heathrow and Gatwick require the crash rate calculated for both aircraft categories (small and large transport) to be multiplied by the number of movements for take-offs and landings for the proportion of movements that occur in each direction (e.g. west to east, or east to west).

This results in four crash rates for each airport:

- take-offs to the west;
- take-offs to the east;
- landings to the west;
- landings to the east.

The four crash rates can be combined so that overall likelihood so aircraft crashing to the east or west of both airports can be calculated.

The change in the airport specific accident rates have been calculated by comparing the values obtained from each of the specific scenarios to the “Do Minimum” scenario, i.e. where no expansion takes place at either airport.

Although the location of the crashes have not been analysed, it is possible to relate the likelihood of a crash to broad geographical areas, out to a radial distance of 20 miles from the airport.

7 APPENDIX C: BACKGROUND RATE DATA

This appendix contains tables of the crash data used in the analysis of the background crash rate. The locations of the incidents in these tables use the distance units (e.g. nautical miles, miles, kilometres, etc.) as recorded in the data. An aircraft crash is defined as an uncontrolled landing or mid-air break-up leading to serious damage to the aircraft and/or at least one fatality.

Table 14 Light aircraft background crashes, 1990 to 2013

Year (number of crashes)	***England***		***Scotland***		***Wales***	
1990 (5)	24.03.90	3 miles E of Mere	20.11.90	Dunbar Common, near Edinburgh		
	03.05.90	Chadlington				
	19.05.90	M25, Reigate				
	19.05.90	M25, Reigate				
1991 (5)	18.04.91	Stanmore Common			15.05.91	Llangollen
	19.05.91	Aldermaston				
	20.05.91	Near Lancaster				
	17.08.91	Ashampstead				
1992 (7)	13.02.92	Skiddaw	03.04.92	Loch Muick		
	15.02.92	M25/A13 near Thorrock	22.08.92	Isle of Jura		
	07.04.92	Consett				
	15.07.92	Forest of Bowland				
	09.12.92	8 miles W of Luton				
1993 (4)	21.03.93	Near Shrivenham	18.03.92	3 miles SW of Maybole		
	20.07.93	Shadoxhurst	15.09.93	SW of Sanquhar		
1994 (6)	08.01.94	Wrekin				
	17.01.94	Thirlmere				
	20.01.94	Near Bloxwich				
	20.03.94	Near Wellesbourne Mountford				
	09.10.94	5 miles SW of Binbrook				
	20.11.94	3 miles N of Worthing				
1995 (3)	04.03.95	Near Malden, Essex				
	21.03.95	Knottingkey, Yorks				
	13.10.95	Sileay Ruy, Isle of Man*				

Year (number of crashes)	***England***	***Scotland***	***Wales***
1996 (7)	05.05.96 Near Westcott 06.06.96 Pebworth, near Evesham 15.06.96 Buxton 22.07.96 Tockington Park Farm, near Almondsbury, Bristol 25.09.96 2 nautical miles W of Southport Pier 26.10.96 Dover VOR	16.10.96 18 nautical miles NW of Perth	
1997 (3)	27.11.97 1.8 miles NW of Shobdon Airport, Herefordshire	06.05.97 3 nautical miles N of Cumbernauld Aerodrome 21.12.97 Near Ben House, Gatehouse of Fleet, Galloway	
1998 (3)	26.07.98 Bentworth, Hampshire 20.10.98 Mow Cop House, Staffordshire		23.05.98 Tryfan, North Wales
1999 (7)	21.01.99 300 metres from western edge of Mattersey, Nottinghamshire 29.04.99 Near Selby, Yorkshire 04.07.99 Near Easingwold, Yorkshire	09.05.99 2 kilometres S of Cromarty, Black Isle, Highlands	12.02.99 Berwyn Mountain, mid Wales 02.08.99 Moel Hebog mountain, near Beddlegert, North Wales 29.08.99 Sarn, near Newtown, Powys
2000 (5)	15.05.00 Hambledon Hill, 15 miles N of Leeds Bradford Airport 16.07.00 Near Upper Cumberworth, West Yorkshire	30.11.00 Fortingall, Perthshire 13.12.00 En route Inverness to Benbecula	11.09.00 20 miles N of Swansea
2001 (6)	24.02.01 Near Sharpthorne, West Sussex 12.05.01 Osea Island, Essex 23.06.01 Nash, Shropshire 22.07.01 Near Lichfield, Hampshire 15.08.01 Halesworth, Suffolk	25.01.01 10 nautical miles South of Braemar, Grampian	

Year (number of crashes)	*England*		*Scotland*		*Wales*	
2002 (4)	27.02.02	Hannington, Hampshire			01.04.02	2 miles W of Cwmbran
	25.08.02	Devils Chair, Stiperstones, Shropshire			18.05.02	12 nautical miles west of Brecon VOR
2003 (2)	05.01.03	2 miles NE of Towcester, Northamptonshire				
	13.04.03	Clitheroe, Lancashire				
2004 (4)	13.03.04	Hotham, South Cave, Humberside	22.10.04	37 miles NW of Inverness		
	27.06.04	Beacon Village, near Honiton, Devon				
	04.07.04	offshore, in Liverpool Bay, 2 nautical miles N of Wallasey				
2005 (7)	25.05.05	Near Pottersbury, 6 miles NW of Milton Keynes	19.05.05	Approx. 20 miles N of Dundee	04.09.05	Irish Sea, 5 nautical miles NW of Stumble Head, Pembrokeshire
	15.06.05	Near Wolton-under-Edge, Gloucestershire				
	18.08.05	Remenham (Berkshire)				
	17.11.05	Near Bugbrooke, Northamptonshire				
	18.12.05	Moreton in Marsh, Gloucestershire				
2006 (3)	16.07.06	Hoxne, Suffolk			11.09.06	Near Bethesda, Gwynedd
	25.08.06	Near Bramley, South Yorkshire				
2007 (4)	03.02.07	Sea close to Blackpool beach	09.04.07	9 nautical miles south of Oban	01.06.07	Near Magar, Gwent
	16.12.07	Near Rugely, Staffordshire[1]				
2008 (3)	13.02.08	Rutland Water, near Empingham, Leicestershire	05.04.08	Cairn Gorm, the Cairngorms		
	23.02.08	Farthing Common, Kent				

Year (number of crashes)	***England***		***Scotland***		***Wales***	
2009 (5)	02.01.09	Colwich Junction, near Little Haywood, Staffordshire			11.02.09	Near Porthcawl
	10.04.09	Near Steep, Petersfield, Hampshire				
	14.06.09	Near Drayton, Oxfordshire				
	08.07.09	Bishop Norton, Lincolnshire				
2010 (4)	19.06.10	Castleford, W. Yorkshire			26.11.10	Brecon Beacons
	10.07.10	Near Rotherfield Peppard, Oxfordshire				
	04.09.10	Near Ryde, Isle of Wight				
2011 (3)	21.03.11	Ingleborough, N. Yorkshire				
	28.04.11	Near Malden, Essex				
	15.05.11	Near Witchampton, Dorset				
2012 (1)	16.08.12	Near Bruera, Cheshire				
2013 (1)	30.09.13	Near Bristol				
Total (102)	**73**		**16**		**13**	

*Isle of Man has been included as a British Crown Dependency

[1]This was a crash involving a light aircraft and a small transport aircraft. A corresponding entry has been made in Table 16

Table 15 Helicopter background crashes, 1990 to 2013 (*military crashes in italics*); only years with crashes shown

Year (number of crashes)	***England***		***Scotland***		***Wales***	
1990 (3)	28.03.90	1 mile W of Chinnor	24.01.90	Giffnock	*12.02.90*	*10 kilometres NW of Valley*
1991 (1)	08.09.91	Welford-on-Avon				
1992 (4)	23.02.92	Royton				
	28.03.92	Coalport				
	29.05.93	Near Latimer				
	14.08.92	Crowthorne				
1993 (5)	23.06.93	Near Kendal			20.11.93	Near Brecon
	11.12.93	Near Wimborne			*12.08.93*	*Llyn Padarn Lake*
	20.07.93	*Stanford Training Area*				
1994 (3)			07.12.94	Ballachulish	22.05.94	Colwyn Bay
			02.06.94	*Mull of Kintyre*		
1995 (2)	*07.04.95*	*Yarcombe, Somerset*				
	05.10.95	*Wye Valley, Chepstow*				
1996 (3)	*23.04.96*	*1 nautical mile S of Portesham, Dorset*				
	19.10.96	Near Cauldron Lowe, Staffs				
	22.10.96	Middlewich, Cheshire				
1997 (3)	16.03.97	Gravesend near Albury, Heartfordshire				
	11.08.97	Adjacent to M6 motorway at Nether Kellet, nr Lancaster				
	14.11.97	Cocking, near Chichester				
1998 (3)	19.04.88	900 metres SW of Gumley				
	26.07.88	Near Rochester Airport				
	01.08.88	Near Six Mile Bottom, Cambridgeshire				
1999 (1)	*18.05.99*	*Tilton-on-Hill, E of Leicester*				

Year (number of crashes)	***England***		***Scotland***		***Wales***	
2000 (6)	01.02.00 08.03.00 21.08.00 23.08.00	2 nautical miles E of Chorley, Lancashire Near Twyford, Berkshire Dartford Marshes, Kent Streatley, Berkshire	*27.10.00*	*Inner sound between Island of Rona and Applecross*	21.04.00	Coryton Drive, Cardiff
2001 (1)	*16.11.01*	*Brunton*				
2002 (3)	13.07.02 19.10.02	Hampton Magna, Warwickshire Wooferton, Shropshire	17.02.02	Near Muirkirk, East Ayrshire		
2003 (4)	17.01.03 10.04.03 02.12.03	Cudham, Kent Brightling, Sussex Hurstbourne Tarrant, near Andover	30.07.03	Carlenrig, Teviothead, near Hawick		
2004 (1)	11.11.04	Cophams Hill Farm, Bishopton, Warwickshire				
2005 (1)	*23.02.05*	*Salisbury Plain Training*				
2007 (3)	01.05.07 03.08.07 *08.08.07*	Near Thornhaugh, Peterborough Near Kendal, Cumbria *Near Catterick, Yorkshire*	15.09.07	Lanark		
2008 (3)	26.01.08 *28.05.08* 01.11.08	Harrogate, North Yorkshire *Kingscott Valley, Devon* Winchcombe, Gloucestershire				
2009 (2)	22.09.09 15.11.09	Near Stalmine, Lancashire Macclesfield, Cheshire				
2011 (1)	08.03.11	Keswick, Cumbria				
2012 (1)	06.01.12	Near Ely, Cambridgeshire				
2013 (2)	16.01.13	Near Vauxhall Bridge, London	29.11.13	Glasgow		
Total (57)	**35 (*44*)**		**6 (*8*)**		**3 (*5*)**	

Table 16 Small transport background crashes, 1990 to 2013; only years with crashes shown

Year (number of crashes)	***England***		***Scotland***		***Wales***	
1993 (3)	13.01.93	Sellafield				
	11.06.93	Peak District, Broomhead Moor				
	15.08.93	Near Guildford, Surrey				
1995 (1)	24.05.95	6 miles NE of Leeds/Bradford Int. Airport				
1998 (2)	28.11.88	Owlacombe Cross, Near Bickington, Devon (foreign registered)				
	24.12.88	1 nautical mile from the coast near Bradwell-on-Sea				
1999 (1)	01.88.99	Woolaston, Gloucestershire				
2000 (2)	18.08.00	Eastbourne, East Sussex				
	09.12.00	4 nautical miles NW Louth, Lincolnshire				
2003 (1)					01.06.03	Borth, North Wales
2007 (1)	16.12.07	Near Rugeley, Staffordshire[1]				
2010 (1)	15.01.10	Bladon, Oxfordshire				
Total (12)	**11**		**0**		**1**	

Note: It is known that five of the six crashes that occurred between 1998 and 2003 involved privately owned ex-military jets (Hawker Hunter, two Jet Provosts, a Strikemaster and an Aero Vodochody Delfin).

[1]This incident was a crash involving a light aircraft and a small transport aircraft. A corresponding entry has been made in Table 14.

Table 17 Large transport background crashes, 1990 to 2013; only years with crashes shown

Year (number of crashes)	*England*	*Scotland*	*Wales*
1990		30.04.90 30 feet below summit of Maodel, Isle of Harris	
1993		27.05.93 8 nautical miles NW of Blair Atholl	
1994	25.02.94 Near Uttoxeter		
Total (3)	**1**	**2**	**0**

Table 18 Military aircraft background crashes, 1990 to 2013; only years with crashes shown

Year (number of crashes)	*England*	*Scotland*	*Wales*
1990 (5)	09.01.90 Near Hexham, Northumberland 05.02.90 The Wash 10.04.90 North Dorchester, Dorset 02.05.90 Wells-next-the-sea, Norfolk		06.02.90 Capel-y-Ffyn, Powys
1991 (3)	25.09.91 Near Great Driffield, Yorkshire		10.05.92 Chepstow, Monmouthshire 29.08.91 Near Llanidloes, Powys
1992 (1)	02.04.92 Barton Hartshorn, Buckinghamshire		
1993 (2)	28.06.93 Heckington, Lincolnshire 21.10.93 Near Barnard Castle, County Durham		
1994 (2)	14.01.94 Aston Somerville, Worcestershire	01.09.94 Killin, Stirling	

Year (number of crashes)	*England*		*Scotland*		*Wales*
1996 (5)	10.02.96	Conningsby, Lincolnshire[1]			
	10.02.96	Conningsby, Lincolnshire[1]			
	23.02.96	6 nautical miles S of Taunton, Somerset			
	13.05.96	4 nautical miles W of Driffield, Yorkshire			
	28.09.96	Blackpool, Lancashire			
1997 (1)			03.06.97	3 nautical miles SW of Castle Douglas, Dumfries and Galloway	
1998 (1)	18.12.98	2.5 nautical miles W of Staindrop, County Durham			
1999 (6)	21.01.99	Everton, near Retford, Nottinghamshire	14.07.99	7 nautical miles E of Coldstream, Berwickshire	
	09.07.99	22.5nautical miles ENE of Cottesmore, Rutland	17.11.99	1 nautical mile E of Torness, East Lothian	
	14.10.99	1.5 nautical miles SE of Kirkheaton, West Yorkshire			
	22.10.99	10 nautical miles S of Penrith, Cumbria			
2000 (2)	18.10.00	Lowick, Northumberland	27.10.00	5 nautical miles NE of Dumfries	
2001 (2)			26.03.01	Ben McDui, Cairngorms[1]	
			26.03.01	Ben McDui, Cairngorms[1]	
2002 (1)	17.05.02	Humber Estuary near Brough			
2003 (1)	23.07.03	5 miles NW of Pickering, North Yorkshire			
2004 (1)	29.06.04	10 miles SW of Boscombe Down, Wiltshire			
2009 (1)			02.07.09	Glen Kinglas, Argyll	

Year (number of crashes)	***England***	***Scotland***	***Wales***
2011 (2)	20.08.11 River Stour, Southampton	27.01.11 Off Stornoway	
2012 (1)		03.07.12 Moray Firth	
Total (37)	**24**	**10**	**3**
[1]Mid-air collision, counted as two separate impacts as ground impacts are different			

8 APPENDIX D: AIRFIELD RATE DATA

The data used in the calculation of the airfield related crash rates are listed in the subsequent tables.

Table 19 Small transport airfield related crashes, 1990 to 2013; only years with crashes shown

Year (number of crashes)	***England***		***Scotland***		***Wales***
1991 (2)	19.05.91	Brimpton Airfield, near Aldermaston, Berkshire			
	30.06.91	Audley End, Essex			
1992 (2)	27.06.92	Woodford, Manchester	06.10.92	Prestwick, South Ayrshire	
1995 (3)	13.03.95	Near Andover, Hampshire			
	24.05.95	Near Leeds Bradford Airport			
	11.08.95	Fyfield, near Andover, Hampshire			
1996 (4)	14.07.96	Duxford Airfield, Cambridgeshire	19.05.96	Griesta, near Lerwick	
	21.07.96	Near Barton Airfield, Manchester			
	01.09.06	Crosland Moor Airfield, Huddersfield			
1998 (1)	05.06.98	Dunsfold Airfield, Surrey			
1999 (1)			03.09.99	near Glasgow Airport	
2000 (3)	08.04.00	Goodwood Airfield, Chichester, West Sussex			
	14.06.00	Mersey Estuary, near Liverpool Airport			
	23.12.00	Near Blackbushe Airport, Hampshire			

Year (number of crashes)	*England*		*Scotland*		*Wales*
2001 (3)	02.06.01	Biggin Hill Airfield, Kent			
	03.06.01	Biggin Hill Airfield, Kent			
	06.06.01	About 1 nautical mile east of Isle of Man Airport*			
2002 (3)	04.01.02	Birmingham International Airport	24.12.02	Aberdeen Airport	
	02.06.02	Duxford Airfield, Cambridgeshire			
2006 (2)	05.08.06	Derham Green, Buckinghamshire			
	06.09.06	Duxford Airfield, Cambridgeshire			
2008 (2)	30.03.08	Romsey Close, Farnborough, Kent			
	17.08.08	Near Coventry Airport			
2011 (1)	10.07.11	Near Duxford Aerodrome, Cambridgeshire			
Total (27)	**24**		**3**		**0**

*Isle of Man has been included as a British Crown Dependency

Table 20 Large transport airfield related crashes, 1990 to 2013; only years with crashes shown

Year	*England*	
1994	21.12.94	Coventry
1999	22.12.99	Near Stanstead
2008	17.01.08	Heathrow

Table 21 Number of movements and accidents for small and large transport aircraft for all major Great British airports, 1990 to 2013

Year	*Small transport*		*Large transport*	
	Number of movements	*Number of accidents*	*Number of movements*	*Number of accidents*
1990	433,073	0	1,008,799	0
1991	448,331	2	959,437	0
1992	491,146	2	1,022,750	0
1993	375,547	0	953,800	0
1994	371,117	0	914,213	1
1995	382,031	3	974,702	0
1996	400,651	4	987,406	0
1997	344,525	0	1,049,038	0
1998	336,401	1	1,111,094	0
1999	323,119	1	1,203,737	1
2000	317,489	3	1,283,816	0
2001	305,282	3	1,395,012	0
2002	305,607	3	1,482,379	0
2003	324,214	0	1,552,876	0
2004	307,411	0	1,609,350	0
2005	279,958	3	1,636,419	0
2006	269,197	2	1,711,681	0
2007	288,890	0	1,800,839	0
2008	293,717	2	1,915,802	1
2009	309,379	0	1,946,788	0
2010	280,795	0	1,997,535	0
2011	264,147	1	1,959,003	0
2012	249,258	0	1,783,611	0
2013	226,036	0	1,688,761	0
Total	**7,184,749**	**27**	**36,185,856**	**3**

9 APPENDIX E: FORECAST MOVEMENTS IN 2050

This appendix contains the forecast number of movements for Heathrow and Gatwick airports under all the different scenarios for 2050, where the scenarios are as specified by the Airports Commission:

- AoN CT: Assessment of Need – Carbon Traded
- AoN CC: Assessment of Need – Carbon Capture
- GGCT: Global Growth – Carbon Traded (Heathrow only)
- LCIK CT: Low Cost is King – Carbon Traded (Gatwick only)

It should be noted that only large transport aircraft are forecast to use both airports in the future.

The forecast movements for Heathrow airport are shown in Table 22 and those for Gatwick airport in Table 23 for the different expansion options

- Do minimum: no expansion;
- ENR: extended northern runway at Heathrow;
- NWR: additional northwest runway at Heathrow; and
- 2R: 2 runways at Gatwick.

The movements listed in the tables are required for the calculation of both the background crash rate and the airport specific crash rate.

Table 22 Forecast number of movements for Heathrow airport in 2050

Growth Scenario	***Expansion Scenario***	***Number of movements***
AoN CT	"Do Minimum"	472,090
	ENR	705,969
	NWR	748,080
AoN CC	"Do Minimum"	471,074
	ENR	710,795
	NWR	753,269
GGCT	"Do Minimum"	457,872
	ENR	709,575
	NWR	737,561

Table 23 Forecast number of movements for Gatwick airport in 2050

Growth Scenario	***Expansion Scenario***	***Number of movements***
AoN CT	"Do Minimum"	282,535
	2R	558,449
AoN CC	"Do Minimum"	285,272
	2R	475,755
LCIK CT	"Do Minimum"	273,939
	2R	556,388

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