THE DEVELOPMENT OF A MORE RISK-SENSITIVE & FLEXIBLE AIRPORT SAFETY AREA STRATEGY: Part II, Accident location analysis & airport risk assessment case studies

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Abstract

This two-part paper presents the development of an improved airport risk assessment methodology aimed at assessing risks related to aircraft accidents at and in the vicinity of airports and managing Airport Safety Areas (ASAs) as a risk mitigation measure. The improved methodology is more quantitative, risk-sensitive, flexible and transparent than standard risk assessment approaches. As such, it contributes to the implementation of Safety Management Systems at airports, as stipulated by the International Civil Aviation Organisation.

The second part of the paper presents the analysis of accident locations, including the plotting of Complementary Cumulative Probability Distributions for the relevant accident types. These were then used in conjunction with the improved accident frequency models to produce Complementary Cumulative Frequency Distributions that could be used to assess risks related to specific runways and determine Airport Safety Area (ASA) dimensions necessary to meet a quantitative target level of safety. The approach not only takes into account risk factors previously ignored by standard risk assessments but also considers the operational and traffic characteristics of the runway concerned. The use of the improved risk assessment technique and risk management strategy using ASAs was also demonstrated in two case studies based on New York LaGuardia Airport and Boca Raton Airport in Florida.

1. Introduction

The previous part of this paper has described the development of improved models for assessing the frequency of aircraft accidents occurring at and in the vicinity of airports. Nonetheless, without considering where in relation to the runway these

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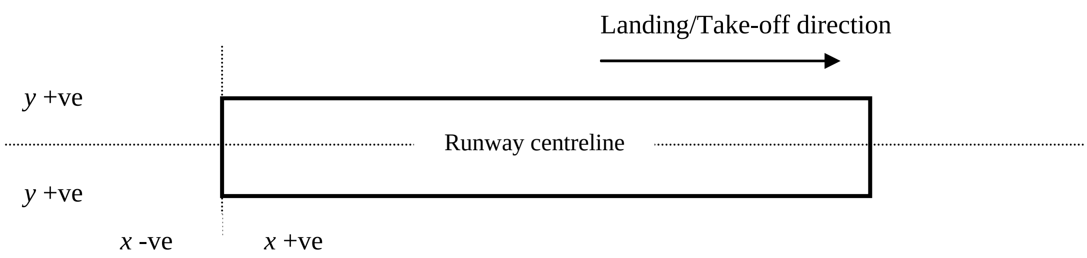
accidents are likely to occur, the frequency models, i.e. knowing the frequency of accident occurrence, are of limited use. This paper describes the analysis of accident locations and shows how it could be used in conjunction with the accident frequency models for practical airport risk assessment in two case studies. The case studies were carried out based on New York LaGuardia Airport and Boca Raton Airport in Florida. Other than demonstrating the application of the novel risk assessment techniques, the exercise also revealed important findings on the need of ASAs at the two airports.

2. Location Coordinate System

With the comprehensive accident database developed as described in part II of this paper, a more complete understanding of accident locations could be obtained versus previous airport risk assessment studies. The accidents' crash locations were recorded systematically using a coordinate system as shown in Figure 1.

Figure 1 Location coordinate system



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

A number of Dutch studies such as (Ale & Piers 2000) referenced accident locations to flight paths rather than the extended centreline. Although intuitively more accurate, the lack of accessibility to relevant flight path information from airlines or air traffic control authorities as well as the tendency of landing aircraft to align with the extended runway centreline at considerable distance from the threshold limit the benefits of referencing accident locations to flight paths (Davies & Quinn 2004).

3. Point of First Impact

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

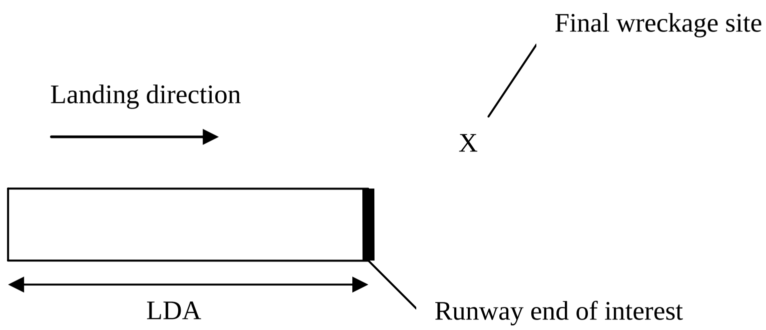
4. Crash Scenarios

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

4.1 Scenario 1 – landing overrun

Figure 2 depicts accident location scenario 1. After a landing overrun, the aircraft's final wreckage site lies beyond the runway end.

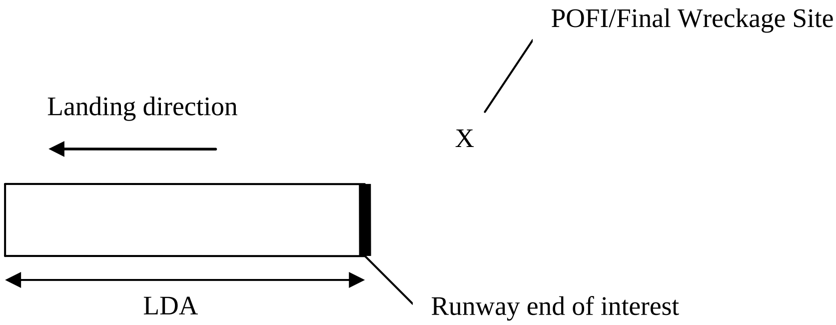
<u>Figure 2 Scenario 1</u>



4.2 Scenario 2 – landing undershoot

Figure 3 depicts accident location scenario 2. Before reaching the runway threshold, the aircraft undershoots and challenges an ASA. The x distances to the runway threshold from the POFI and final wreckage site were both measured. Critical x is the one with the largest negative x figure.

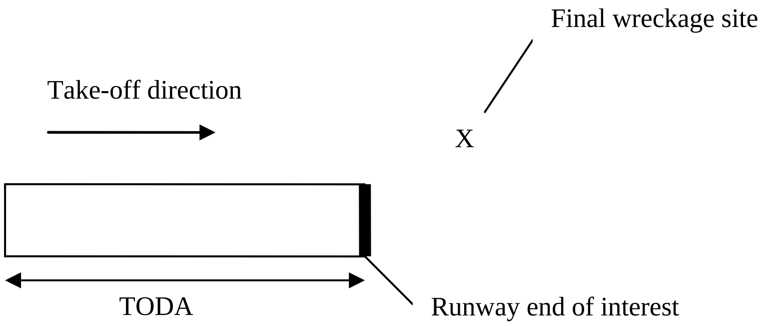
Figure 3 Scenario 2



4.3 Scenario 3 – take-off overrun

Figure 4 depicts accident location scenario 3. After a take-off overrun, the aircraft's final wreckage site lies beyond the runway end.

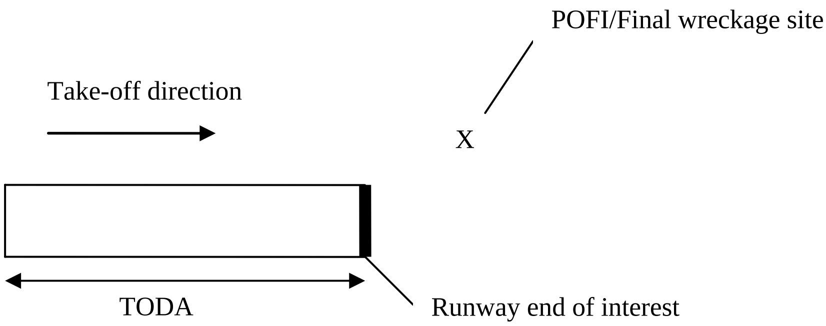
Figure 4 Scenario 3



4.4 Scenario 4 – crash after take-off

Figure 5 depicts accident location scenario 4. The x distances from the start-of-roll threshold to the POFI and final wreckage site were both measured. Critical x is the one with the largest x figure.

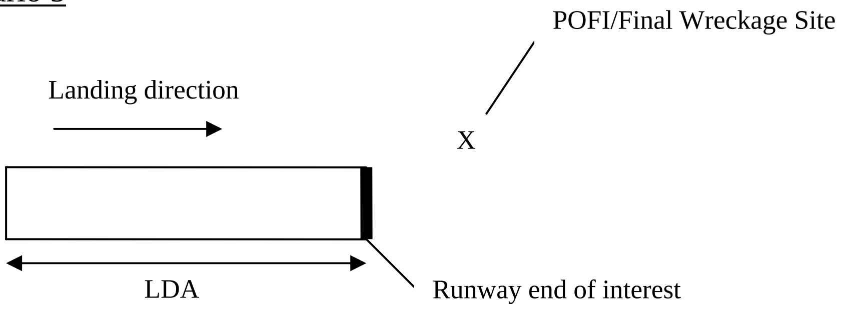
Figure 5 Scenario 4



4.5 Scenario 5 – landing undershoot (beyond runway end)

There are some cases of landing undershoots with POFIs and/or final wreckage sites beyond the runway threshold. These are classed as landing undershoots because their POFIs are off-runway. Scenario 5 considers such cases with POFIs or final wreckage locations beyond the runway end (Figure 6). This scenario also includes cases which, after a POFI before the runway threshold, the aircraft continued to a final wreckage site beyond the runway end.

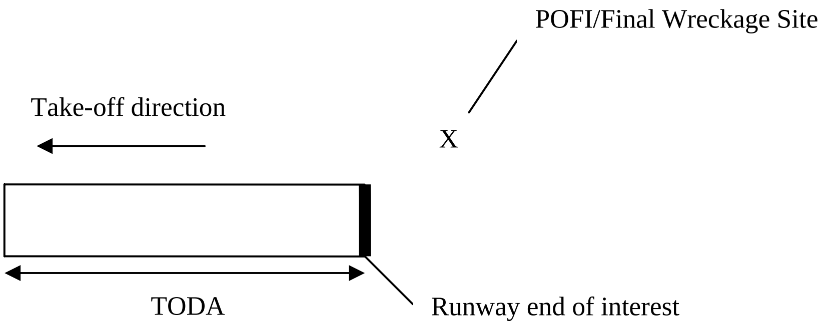
Figure 6 Scenario 5



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

Depicted in Figure 7, there are potentially cases of crashes after take-off that have POFIs and/or final wreckage locations with negative x distances. This is likely for flights that have made a sharp turn after lift-off towards the start-of-roll runway threshold before crashing.

Figure 7 Scenario 6



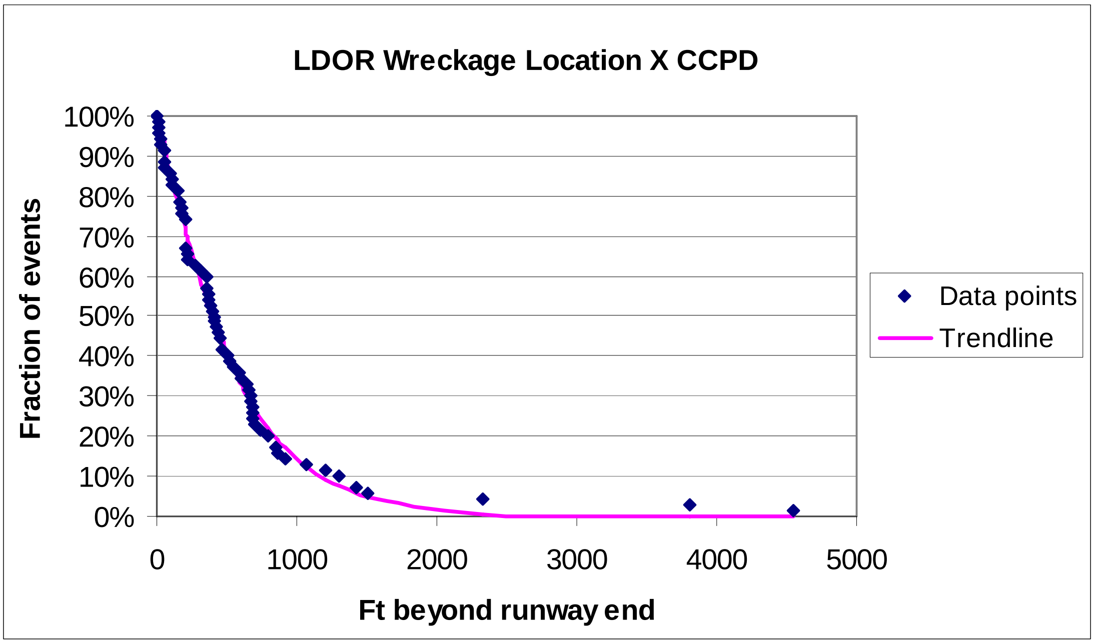
5. Complementary Cumulative Probability Distributions

For each of the accident scenarios described above, complementary cumulative probability distributions (CCPD) of the relevant x and y distances were plotted for the accident sample used in Part I of this paper. Eddowes et al. (2001) also used CCPDs to analyse overrun and undershoot distances. These CCPDs are essential to the application of the accident frequency models. The various CCPDs were be fitted into exponential functions as listed in Table 1 (see Section 6). The functions are also plotted in the relevant graphs (Figures 8-11) and labelled as 'Trendline'.

5.1 CCPD scenario 1 x distance

For scenario 1, the cases that challenge longitudinal ASAs are landing overruns with final wreckage sites beyond the runway end. Out of 133 landing overruns with known wreckage locations, 71 cases involved x locations beyond the runway end. The x distances from the runway end to the final wreckage sites were measured. One case that involved an x distance of over 19000ft was considered as an outlier and was removed. The remaining 70 cases were used to plot the CCPD, as shown in Figure 8.

Figure 8 Scenario 1 x distance CCPD

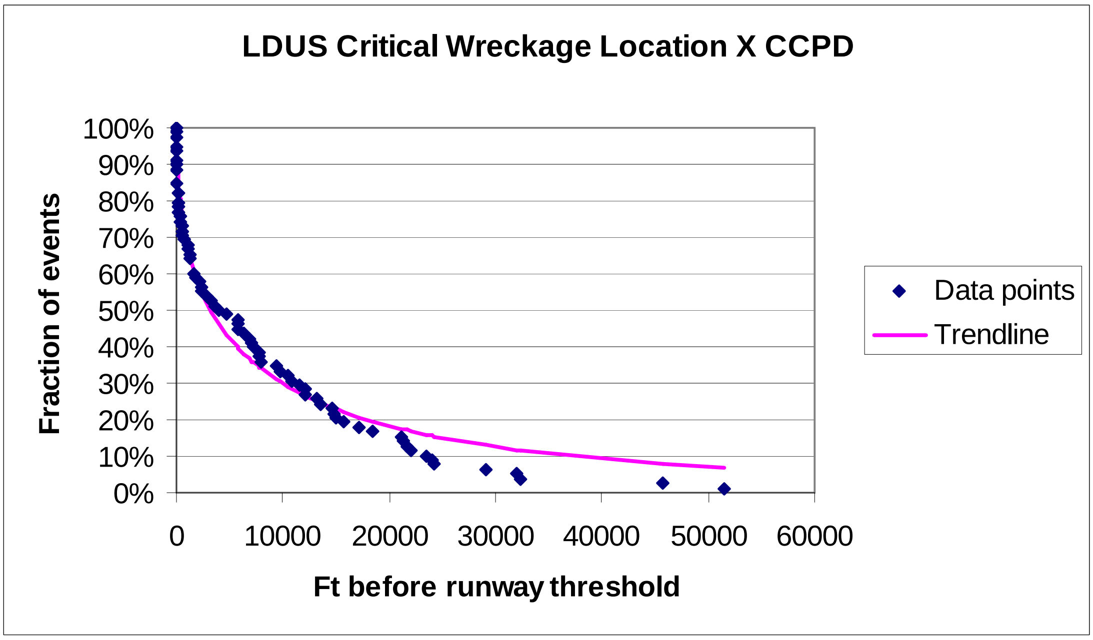


The CCPD shows that 80 percent of cases involve overrun distances of more than 150ft beyond the runway end. The plot also shows that 40 percent of cases involve overrun distances of 500ft or more beyond the runway end.

5.2 CCPD scenario 2 x distance

For scenario 2, the cases that challenge longitudinal ASAs are landing undershoots with POFIs and/or final wreckage sites before the runway threshold. Out of 105 landing undershoots with known wreckage information, 78 cases involved x locations before the runway threshold The critical x distances from the POFI/final wreckage site to the runway threshold were measured. All 78 cases were used to plot the CCPD, as shown in Figure 9.

Figure 9 Scenario 2 x distance CCPD



The CCPD shows that approximately 80 percent of cases involve undershoot distances of more than 100ft from the runway threshold. The plot also shows that a significant proportion of cases involve very large x distances. Roughly a third of cases involve undershoot distances of 10,000ft or more. The greater x distances compared to landing overruns were expected due to the airborne nature of undershoots. The trend line better fits data points closer to the runway threshold and tends to overestimate the proportion of events at large distances from the threshold.

5.3 CCPD scenario 3 x distance

For scenario 3, the cases that challenge longitudinal ASAs are take-off overruns with final wreckage sites beyond the runway end. Out of 37 take-off overruns with known wreckage locations, 21 cases involved x locations beyond the runway end. The x distances from the runway end to the final wreckage sites were measured and used to plot the corresponding CCPD. The CCPD shows that 80 percent of cases involve overrun distances of more than 245ft beyond the runway end. The greater overruns distances compared to landing overruns are probably due to the high energy nature of many take-off overruns. The plot also shows that roughly half of all cases involve overrun distances of 500ft or more.

5.4 CCPD scenario 4 x distance

For scenario 4, the cases that challenge longitudinal ASAs are crashes after take-off with POFIs and/or final wreckage sites beyond the runway end. Out of 57 crashes after take-off with known wreckage information, 26 cases involved x locations beyond the runway end. The critical x distances from the runway end to the POFI/final wreckage site were measured and the corresponding CCPD plotted. It shows that 80 percent of cases involve x distances of more than 1180ft beyond the runway end. Similar to landing undershoots, the plot also shows a significant proportion of accidents involve very large x distances. Roughly 15.4 percent of cases involve distances of 10,000ft or more. The greater x distances compared to take-off overruns were expected due to the airborne nature of crashes after take-off.

5.5 CCPD scenario 5 x distance

For scenario 5, the cases of concern are landing undershoots with positive x distances beyond the runway end. Out of 105 landing undershoots with known wreckage information, thirteen cases fall into this category. The critical x distances from the POFI/final wreckage site to the runway end were measured and used to plot the corresponding CCPD. It shows that approximately 80 percent of cases involve x distances of more than 3300ft beyond the runway end. The large x distances suggest that the majority of the cases involve occurrences far from the airports' immediate surroundings, where both POFIs and final wreckage sites are a distance away from the runway.

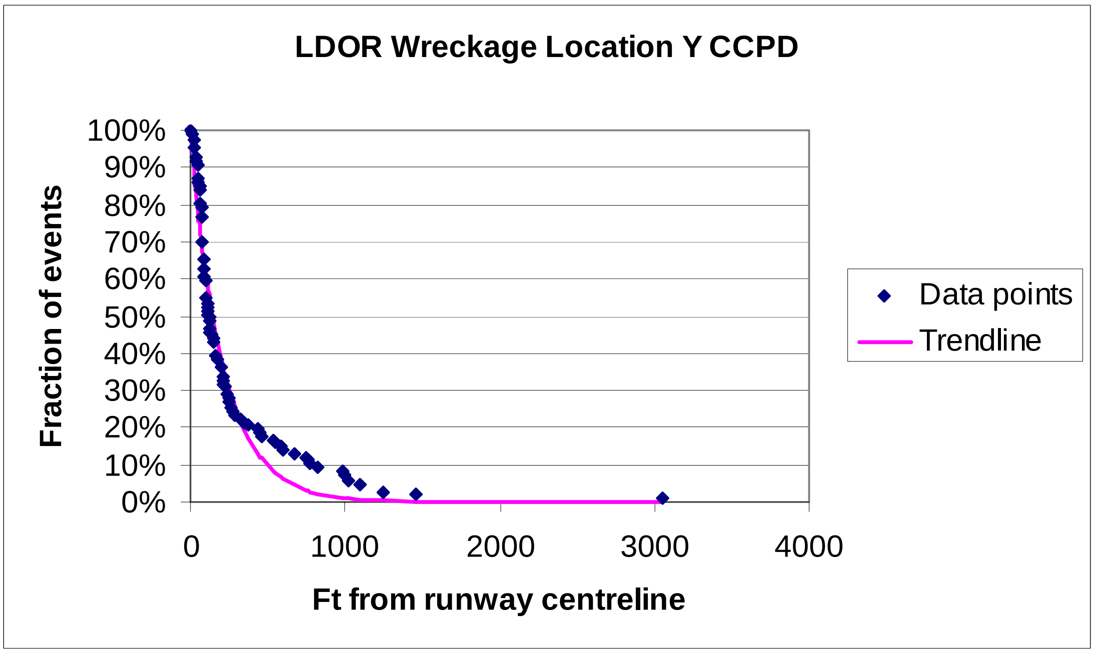
5.6 CCPD scenario 6 x distance

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

5.7 CCPD landing overrun y distance

The lateral deviations of all landing overruns were plotted in a single CCPD. Of the 133 cases with known y distances, 26 were recorded as zero[2]. These were removed for the purpose of plotting the CCPD. The plot, based on the remaining 107 cases, is shown in Figure 10.

Figure 10 Landing overrun y distance CCPD



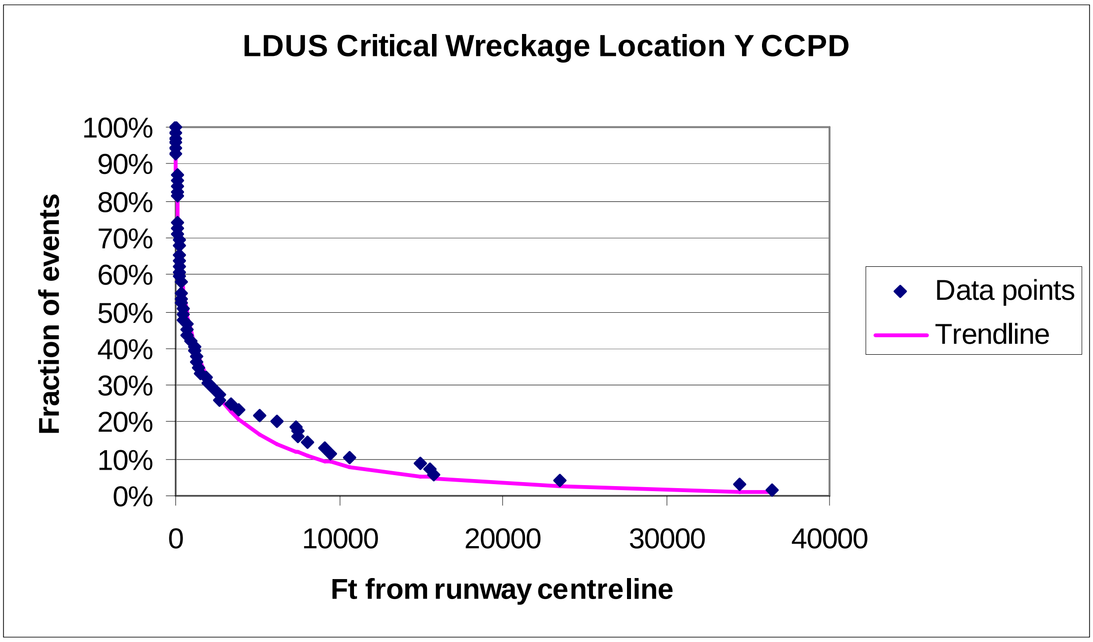
The CCPD shows that 80 percent of cases involve lateral deviations exceeding 65ft from the runway centreline. For a runway 150ft wide, the plot shows that 76.6 percent of landing overruns with non-zero y have final wreckage sites beyond the widths of the runway, i.e. y distances of over 75ft. Many runways, however, are legitimately less than 150ft wide. It is interesting to note that there is a clear discontinuity in data points approximately 300ft from the centreline, which is the strip width requirement for Code 4 runways. Whether the rule was derived from a similar analysis cannot be confirmed due to the opacity of current regulations.

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

5.8 CCPD landing undershoot y distance

The lateral deviations of all landing undershoots were plotted in a single CCPD. Of the 91 cases with known y distances, 22 were recorded as zero. These were removed for the purpose of plotting the CCPD. The critical y distances were identified and based on 69 cases the CCPD was obtained, as shown in Figure 11.

Figure 11 Landing undershoot y distance CCPD



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

5.9 CCPD take-off overrun y distance

The lateral deviations of all take-off overruns were similarly plotted in a single CCPD. Of the 37 cases with known y distances, eleven were recorded as zero. These were removed for the purpose of plotting the CCPD. It shows that approximately 80 percent of cases involve lateral deviations exceeding 53ft from the runway centreline. For a runway 150ft wide, the plot shows that approximately 75.3 percent of landing overruns have final wreckage sites beyond the widths of the runway. The findings are broadly similar with those of landing overruns, albeit based on far fewer data points.

5.10 CCPD crash after take-off y distance

The lateral deviations of all crashes after take-off were also plotted in a single CCPD. Of the 57 cases with known y distances, five were recorded as zero. These were removed for the purpose of plotting the CCPD. The critical y distances were identified and based on 52 cases the CCPD was obtained. It shows that approximately 80 percent of cases involve lateral deviations exceeding 150ft from the runway centreline. For a runway 150ft wide, the plot shows that approximately 94.2 percent of landing overruns have final wreckage sites beyond the widths of the runway. As such, crashes after take-off showed the largest lateral deviations. This is probably related to the high-energy and airborne nature of the accident type. Attempts to follow curved missed approach procedures may be a factor too.

6. CCPD Equations

The equations and corresponding R^2 values of the CCPDs are indicated in Table 1. It can be observed that the trend lines better fit data points that are close to the runway threshold/end/centreline than those that are far away. This conforms to the expectation that occurrences further away from the runway would be more ‘scattered’ than those with small deviation distances. The simple trend lines presented here are therefore more suited to assessing risk in an airport’s vicinity. It is inherently difficult to fit trend lines to a small number of scattered data points. Even more sophisticated trend line equations would only give a false sense of accuracy. The trend lines should therefore only be taken as indicative only for assessing a larger area such as in town or city level planning.

Table 1 CCPD Equations

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

7. Complementary Cumulative Frequency Distributions

With CCPDs, the fraction of accidents involving locations exceeding a given distance from the runway end or threshold could be estimated. When the CCPD is multiplied by the frequency of accident occurrence, a complementary cumulative frequency distribution (CCFD) is obtained. The latter quantifies the overall frequency of accidents involving locations exceeding a given distance from the runway end or threshold. In other words, multiplying the CCPDs by the accident frequency probabilities, as obtained using the accident frequency models, yields CCFDs with which ASA needs could be assessed. Eddowes et al. (2001) also used CCFDs to draw conclusions on Norwegian aerodrome design rules.

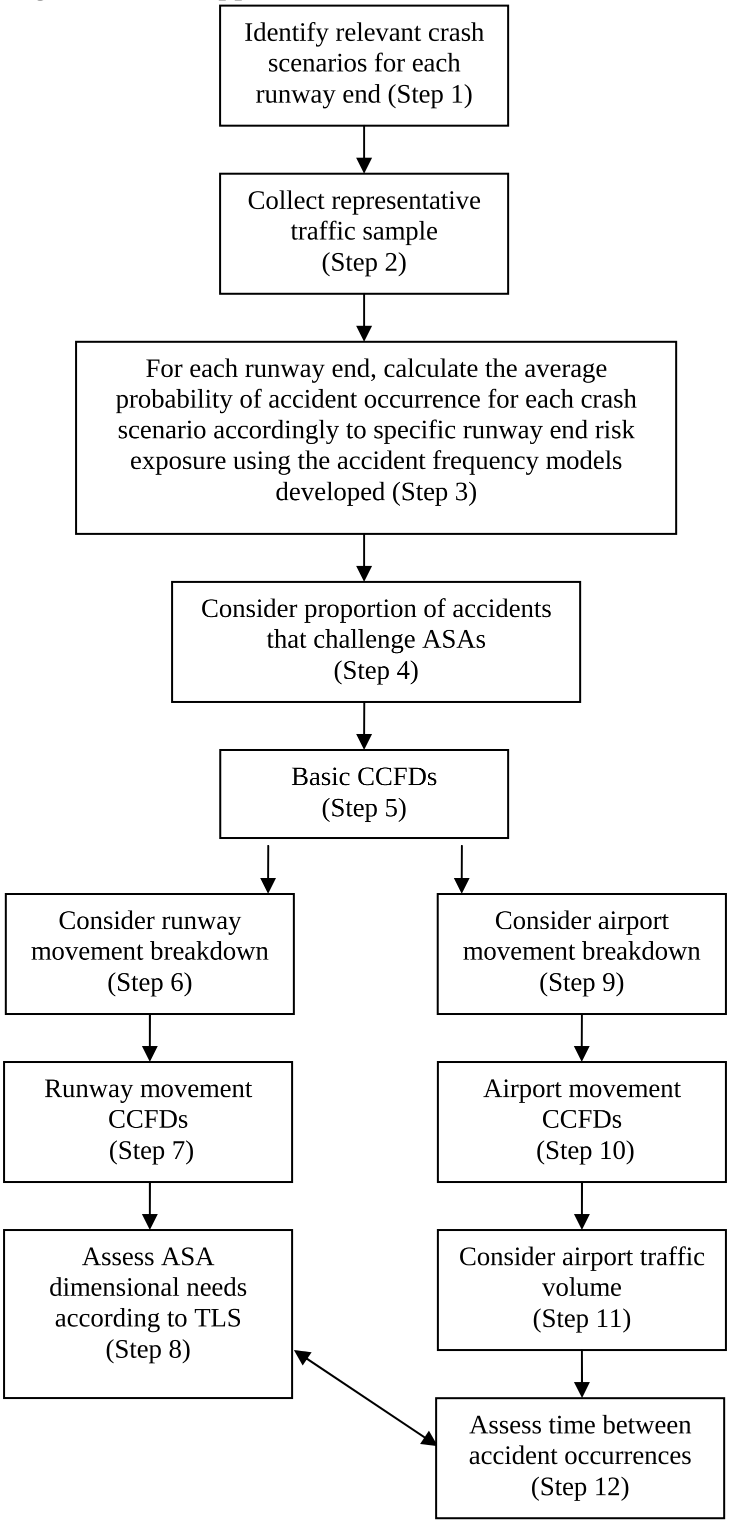
8. Case Study Airports

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

9. Model Application Demonstration – ASA Length

The length of ASA needed for each runway end was considered in turn, taking into account their specific accident frequency risk exposure, runway use patterns as well as traffic levels. The various stages involved are summarised in Figure 12.

Figure 12 Stages in model application



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

9.1 Identification of relevant crash scenarios (step 1)

In assessing the ASA needs of a specific runway end, each of the crash scenarios that challenge ASA length should be taken into account. Table 2 shows the crash scenarios that should be considered for the end of runway 4.

Table 2 Relevant crash scenarios to end of runway 4 risk assessment

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

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

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

Table 3 shows the relevant crash scenario probabilities. The probability of each crash scenario is the product of two distinct probabilities. The first is the probability of accident occurrence (the initial event) and the second is the probability of the specific ASA being challenged given the initial event occurred. The latter probability must be considered because the location CCPDs were calculated based only on cases that challenged ASAs, e.g. overrun wreckage sites beyond the runway end. Certain accidents would remain within the runway length, e.g. veer-offs with x distances smaller than the runway length.

Table 3 Crash scenario probabilities for ASA length assessment

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

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

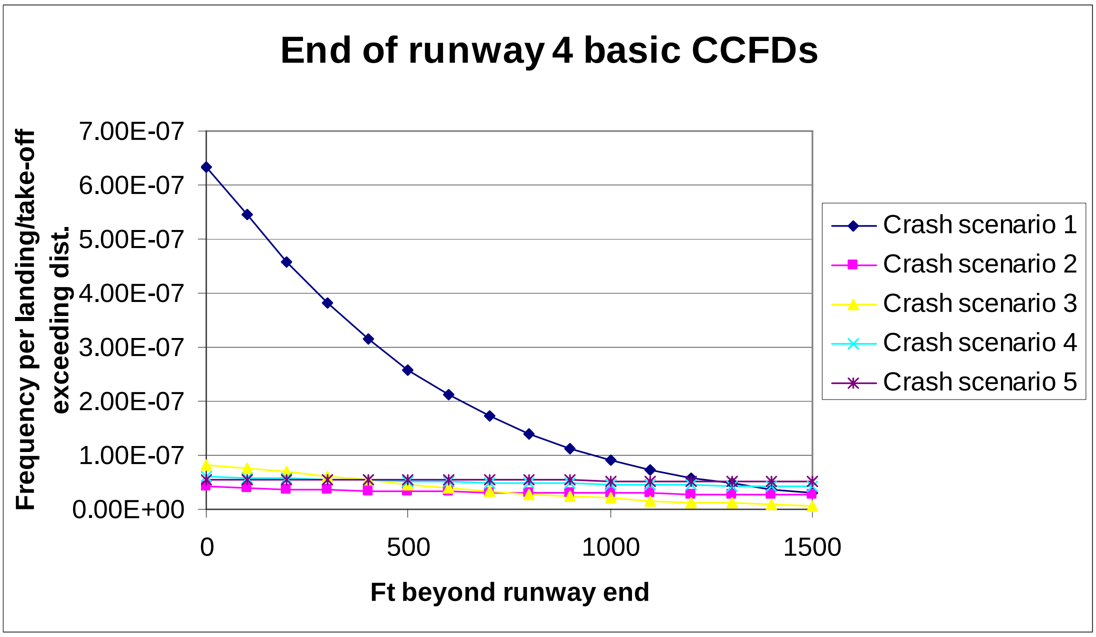
The above risk exposure breakdown by runway end was made possible by Aviation System Performance Metrics (ASPM) data identifying the take-off and landing runways in hourly segments. This information was coupled to the case study's traffic sample to identify the runway and direction used by each flight in the sample. The difference in risk exposure and accident probability between landings on runway 4 and runway 22 has highlighted the importance of differentiating risk at the runway end level, which is not standard international practice in airport risk assessment and not considered in the application of safety areas such as the ICAO's Runway End Safety Area or the FAA's Runway Safety Area. Unfortunately, ASPM only covers relatively large airports and so only average risks and probabilities could be calculated for BCT's runway ends. This would apply for any of the smaller airports not included in ASPM.

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

9.3 Basic CCFD (Step 5)

To obtain the CCFD from which the frequency of accidents involving locations exceeding a given distance from the end of runway 4 could be derived, the CCPDs of the relevant accident scenarios (given in section 5) were multiplied by the corresponding crash scenario probabilities (given in Table 3). For crash scenario 1, then, the CCFD is obtained by multiplying the CCPD equation $\exp(-0.000923x^{1.107653})$ by the crash scenario probability 6.344×10^{-7}. Figure 13 plots all the CCFDs related to the end of runway 4 up to a distance of 1500ft beyond the runway end.

Figure 13 End of runway 4 basic CCFDs



The frequencies depicted in Figure 13 relate to individual crash scenarios. Therefore, it is expected that an overrun of a landing on runway 4 entering the ASA beyond the runway end (crash scenario 1) occurs at a frequency of 6.34 x 10^{-7}. By inspecting the same plot, it is also estimated that a landing overrun on runway 4 in excess of 500ft occurs at a frequency of 2.58 x 10^{-7}. The other plots and frequencies are interpreted similarly. The graph also shows that the frequency of crash scenario 1 is several times higher than the other crash scenarios. The greater distances of airborne accidents such as undershoots and crashes after take-off are therefore overshadowed by the greater frequency of landing overruns on runway 4 as an initial event.

9.4 Runway movement CCFD (Step 6 & 7)

While Figure 13 reveals the CCFDs related to each of the crash scenarios affecting the end of runway 4, it does so without considering the runway use characteristics of runway 4/22 at LGA. Since runway 4/22 is principally used for landing on runway 22, the high frequency of landing overruns on runway 4 may not have as large an impact on the risk profile of the end of runway 4 as Figure 13 suggests. Table 4 shows the breakdown of operations on runway 4/22.

Table 4 Breakdown of runway 4/22 movements

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

In order to take into account the above runway use characteristics, the basic CCFDs of Figure13 were further multiplied by the operational breakdown statistics of Table 4, yielding a 'runway movement CCFD'. For example, the CCFD for crash scenario 1 was multiplied by 0.1285 to reflect the fact that 12.85 percent of movements on runway 4/22 are landings on runway 4. The runway movement CCFDs are shown in Figure 14. A composite CCFD was also calculated by summing the risks of the five crash scenarios at each of the considered distances from the runway end.

Figure 14 End of runway 4 runway movement CCFDs

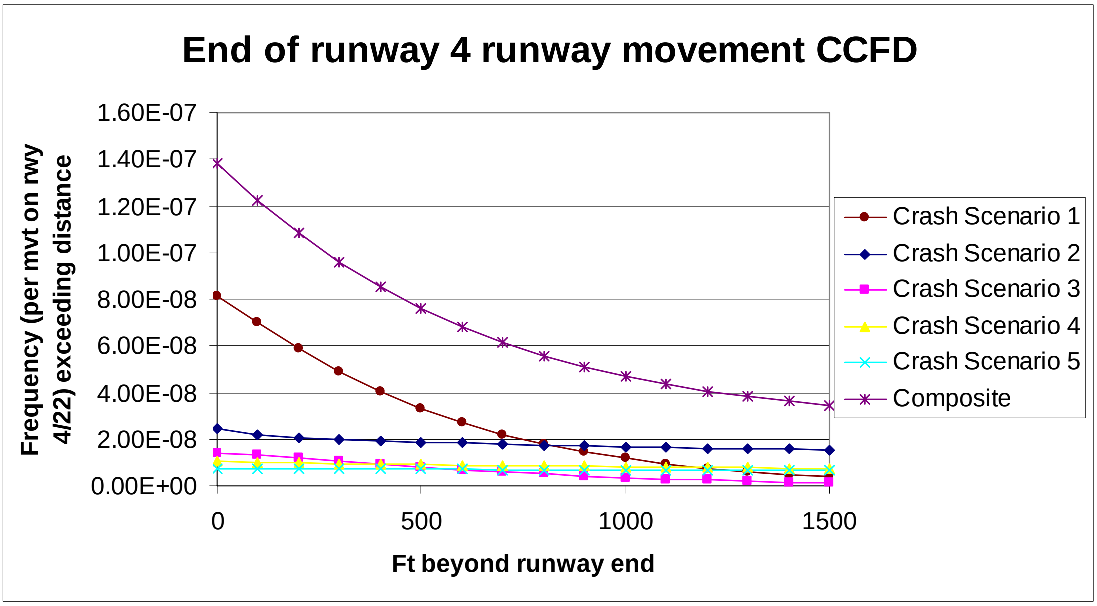


Figure 14 presents the CCFDs in the context of runway movements. These plots are more intuitive interpretations of the true risk posed by the crash scenarios. For instance, rather than noting the expected frequency of 2.58×10^{-7} for a landing overrun on runway 4 in excess of 500ft *per landing on runway 4*, Figure 13.3 provides the frequency of the same event *per movement on runway 4/22*, which is 3.31×10^{-8}.

By considering all scenarios which affect the end of runway 4, the composite plot could be used to determine the length of the ASA according to a predefined target level of safety. This is discussed in section 10 below. The application of the risk models to determine ASA width is similar to the process described above for ASA length.

10. Setting the Size of ASAs

10.1 Target level of safety

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

10.2 ASA lengths (Step 8)

With the methodology described above, the relevant CCFDs for all runway ends and widths at LGA and BCT were computed. Tables 5 highlights the residual risk at ASA lengths of 300ft, 600ft and 1000ft, which corresponds to the FAA Runway Safety Area length requirements for Airplane Design Groups II, III and IV respectively. The ASA lengths necessary to achieve a TLS of 10^{-7} and 10^{-8} are shown.

Table 5 ASA length requirements & residual risks

ASA length (ft beyond runway end)	**Residual risk within 95% Confidence Interval**
LGA end of runway 4	
300	9.605×10^{-8}
600	6.807×10^{-8}
1000	4.676×10^{-8}
267	*1.000×10^{-7}*
11690	*1.000×10^{-8}*
LGA end of runway 22	
300	6.640×10^{-8}
600	5.216×10^{-8}
1000	4.124×10^{-8}
N.A.	*1.000×10^{-7}*
16303	*1.000×10^{-8}*
LGA end of runway 13	
300	8.713×10^{-8}
600	6.838×10^{-8}
1000	5.174×10^{-8}
130	*1.000×10^{-7}*
9872	*1.000×10^{-8}*
LGA end of runway 31	
300	3.156×10^{-8}
600	2.509×10^{-8}
1000	1.975×10^{-8}
N.A.	*1.000×10^{-7}*
4730	*1.000×10^{-8}*
BCT runway end (average)	
300	1.772×10^{-7}
600	1.311×10^{-7}
1000	9.500×10^{-8}
927	*1.000×10^{-7}*
25302	*1.000×10^{-8}*

The results show the ASA needs of each runway end differ significantly. The end of runway 22 and runway 31 at LGA exceed the TLS of 10^{-7} even without ASAs beyond the runway end due to the low risk exposure of its operations. Figure 15 compares the average probability of accident occurrence for all accident types and runway ends. The principal crash scenarios that affect risk at the ends of runway 22 and 31, such as overruns of landings on runway 22 and 31 and undershoots of landings on runway 4 are all relatively low. The largest source of risk for the end of runway 31 is undershoots of landings on runway 13. However, this is offset by the rarity of landings on runway 13. Figure 16 shows the small proportion of landings that used runway 13 (0.73 percent).

Figure 15 Average accident occurrence probabilities

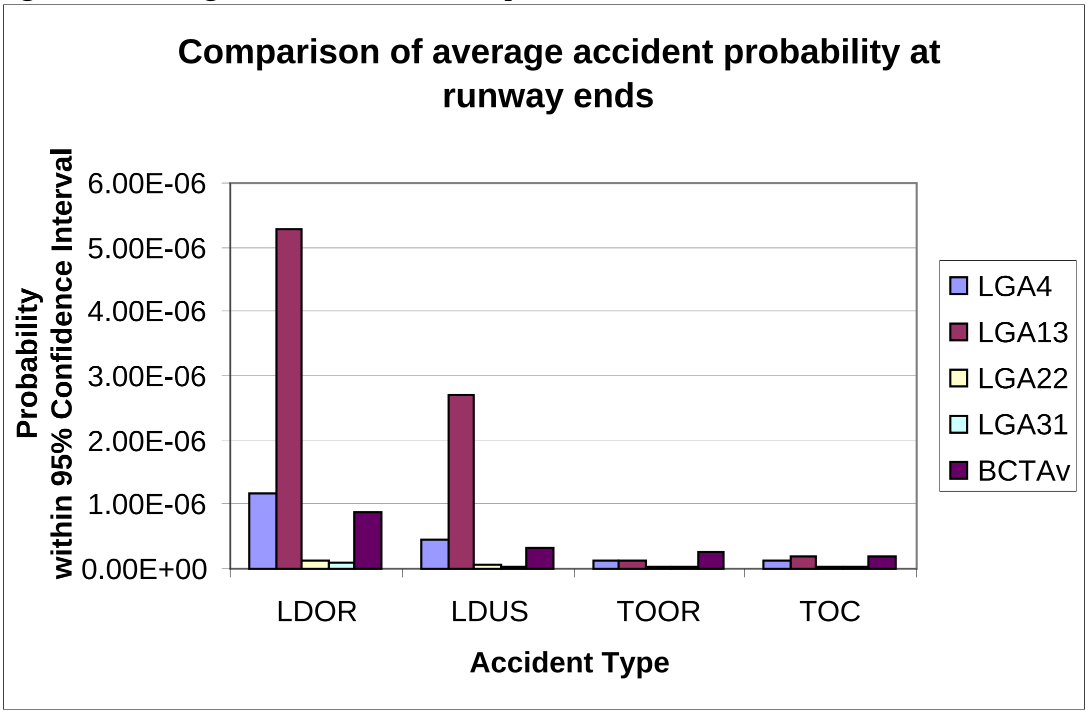
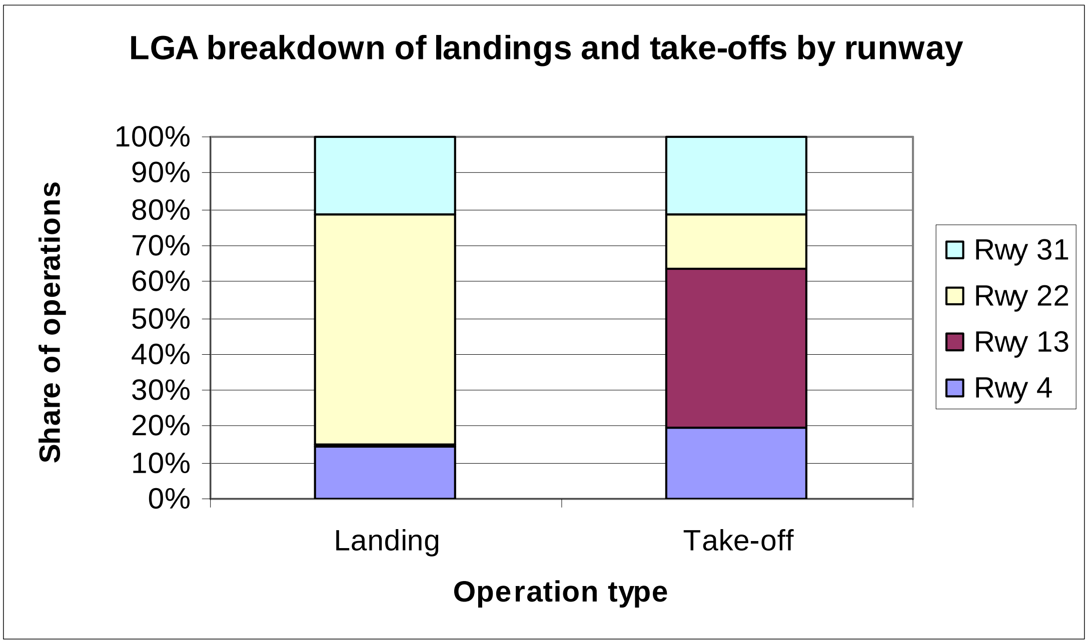


Figure 16 Breakdown of operations at LGA by runway



In contrast, the ends of runway 13 and 4 require ASA lengths of 130ft and 267ft respectively in order to achieve a TLS of 10^{-7}. Figure 14 showed that crash scenario 1 (overruns of landings on runway 4) contributes most to the composite risk at the end of runway 4. From Figure 15, it could be seen that the probability of overruns on runway 4 is the highest except accidents of landings on runway 13. The ASA requirement for the end of runway 4 still exceeds that of runway 13 or runway 31 (the runway ends affected by the high overrun and undershoot probabilities of landings on runway 13) because there are many more landings on runway 4 than 13. In fact, Figure 16 shows that there are almost 20 times as many landings on runway 4 than 13 (14.5 percent vs. 0.7 percent). As a result, the impact of high accident probabilities of landings on runway 13 is, to an extent, mitigated[3].

The smaller airport BCT has greater ASA requirement on average than any of LGA's runway ends. This contradicts the FAA's as well as ICAO's general policy of requiring larger ASAs at airports that serve large aircraft. The phenomenon can be traced to the traffic profile of BCT. The accident frequency models identify small aircraft and general aviation flights as high risk operations. Since BCT is a non-commercial service airport, 96 percent of its operations in the sample involve aircraft of 12,500 to 41,000lbs and 54 percent of flights are general aviation operations. As such, it would be expected that flights at BCT have a relatively high risk profile. The effect can be seen in Figure 15, where accident probabilities related to flights at BCT stand out, apart from the exceptionally high figures for landings on runway 13 and 4 at LGA. The appropriateness of providing larger ASAs at smaller airports is further discussed in section 10.5 where the level of traffic is considered.

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

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[3] Further investigation revealed that difference in adverse weather exposure is a key factor behind the particularly high accident probabilities of landings on runway 13. For example, all landings on runway 13 experienced fog.

10.3 ASA widths

Table 6 shows the results for ASA widths. The figures in the column on the left show the entire width of the ASA centred on the runway centreline. The middle column shows the associated residual risk on either side of the centreline. Since all runways at LGA and BCT are currently 150ft wide, the column furthest right indicates the additional ASA width required from the runway edge on either side of the runway to achieve the associated residual risk.

Table 6 ASA width requirements & residual risks

Total ASA width (ft)	**Residual risk either side of the centreline (within 95% Confidence Interval)**	**Width either side from edge of 150ft wide runway (ft)**
LGA runway 4/22		
100	1.186×10^{-7}	N.A.
150	1.083×10^{-7}	0
200	1.987×10^{-7}	25
197	*1.000×10^{-7}*	*24*
6180	*1.000×10^{-8}*	*3015*
LGA runway 13/31		
100	9.306×10^{-8}	N.A.
150	8.701×10^{-8}	0
200	8.177×10^{-8}	25
52	*1.000×10^{-7}*	*N.A.*
5542	*1.000×10^{-8}*	*2696*
BCT runway 5/23		
100	2.632×10^{-7}	N.A.
150	2.413×10^{-7}	0
200	2.222×10^{-7}	25
849	*1.000×10^{-7}*	*350*
13045	*1.000×10^{-8}*	*6448*

As with the ASA length results, Table 6 shows the dissimilar risks associated with each of the three runways. With no ASA and just the runway width of 150ft, runway 4/22 at LGA is close to meeting the TLS of 10^{-7} and runway 13/31 exceeds it. On the other hand, a simple runway of 150ft at BCT falls short of the same TLS. The key difference in risk between runway 4/22 and 13/31 lies chiefly in the crash location distributions of their associated operations. Even though runway 4/22 is the principal landing runway and is thus at risk from landing overruns which have the highest probabilities amongst accident types, the larger y distances of crashes after take-off dominate risks at runway 13/31, the main take-off runway, to the extent of eclipsing the relatively low probabilities of take-off accidents. The greater ASA width needs at BCT is attributed to the generally higher accident probabilities at the facility.

Once more, the results highlight the inconsistent margin of safety currently provided, at least in terms of accident frequency and location. Eliminating this mismatch between risk and safety margin would result in BCT having vastly wider ASAs than LGA, which again is contradictory to ICAO and FAA aerodrome design principles. Section 10.5 examines an additional factor that is pertinent to the subject.

10.4 ASA diagrams

The computed ASA sizes were also visually compared with the existing ASAs. The dimensions of ASAs necessary to achieve a TLS of 10^{-7} were overlaid in red onto maps of LGA and BCT as available from Google Earth in February 2007. Figure 17 shows the ASA requirements for LGA. It can be seen that current ASAs mostly exceed the TLS of 10^{-7} except the end of runway 4 where extra ASA length is needed, as shown in Figure 18. This would involve additional reclamation of Eastchester Bay.

Figure 17 LGA ASA Requirements (TLS 10^{-7})

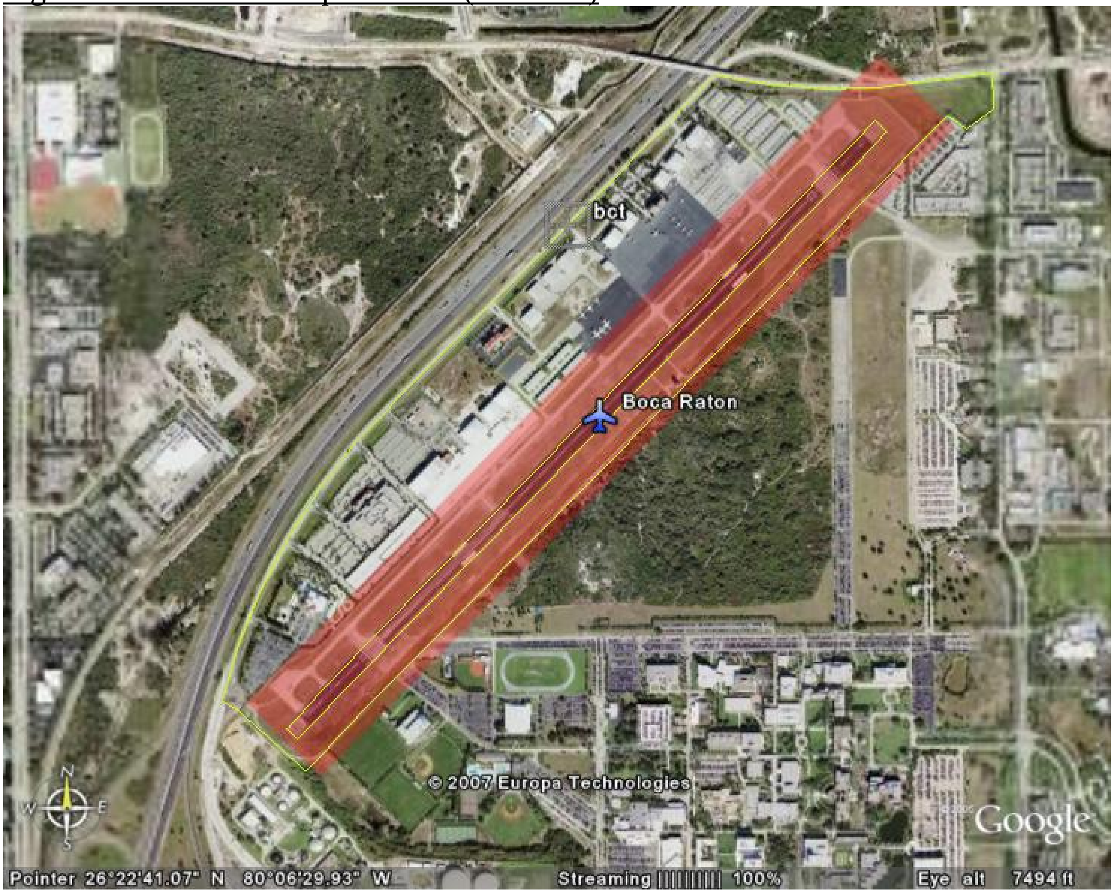
(Background map source: Google Earth)

Figure 18 LGA end of runway 4 ASA requirement (TLS 10^{-7})

(Background map source: Google Earth)

Figure 19 shows and compares the calculated and existing ASAs at BCT. Unlike LGA, current ASAs at BCT fail to provide a TLS of 10^{-7}. The required ASA would cover the parallel taxiway, parts of the airport apron, a building near the end of runway 5 as well as parts of the NW Spanish river boulevard and airport road. Figure 20 offers a close-up view of the area around the end of runway 5 with noticeable ASA infringements circled in black.

Figure 19 BCT ASA Requirements (TLS 10^{-7})



(Background map source: Google Earth)

Figure 20 BCT end of runway 5 ASA requirement (TLS 10^{-7})

(Background map source: Google Earth)

10.5 Impact of traffic level (Step 9-12)

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

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

For airports with multiple runways such as LGA, the use pattern between runways would affect the overall frequency of accident occurrence at the airport since the risk exposure of each runway end differs. 'Airport movement CCFDs' could be obtained by multiplying the basic CCFDs by the breakdown of airport movements. The breakdown of airport movements for LGA is given in Table 7.

Table 7 Breakdown of LGA movements

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

Using the breakdown of Table 7 and the basic CCFDs of each runway end, the airport movement CCFDs for all runway ends could be obtained and summed to give an overall CCFD for the airport. Figure 21 compares the overall CCFDs for LGA and BCT.

Figure 21 Overall airport movement CCFDs for LGA & BCT

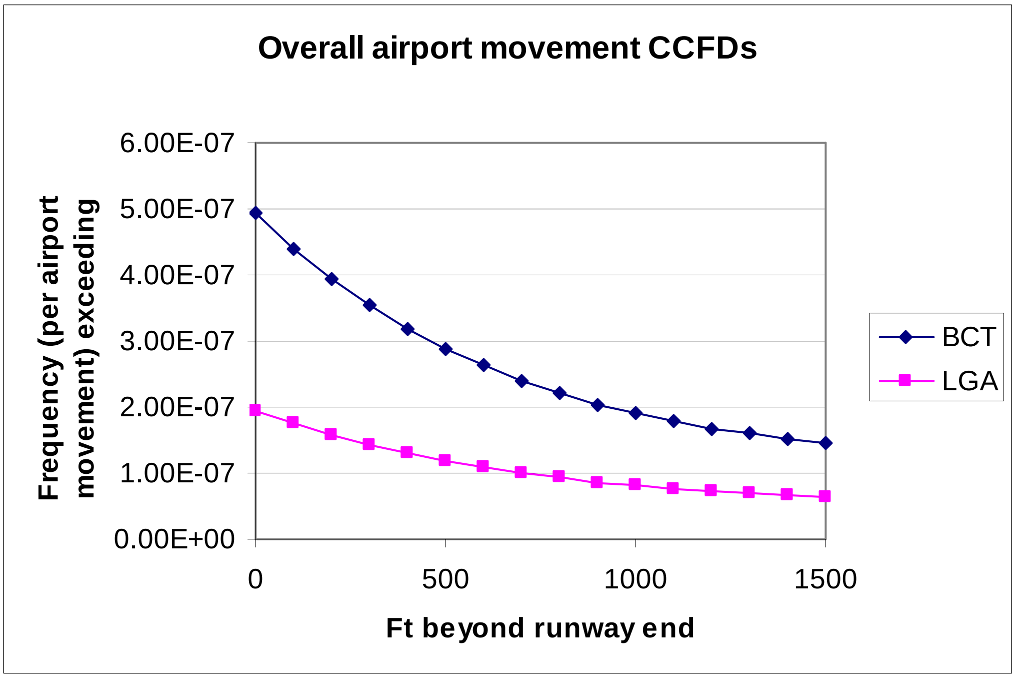
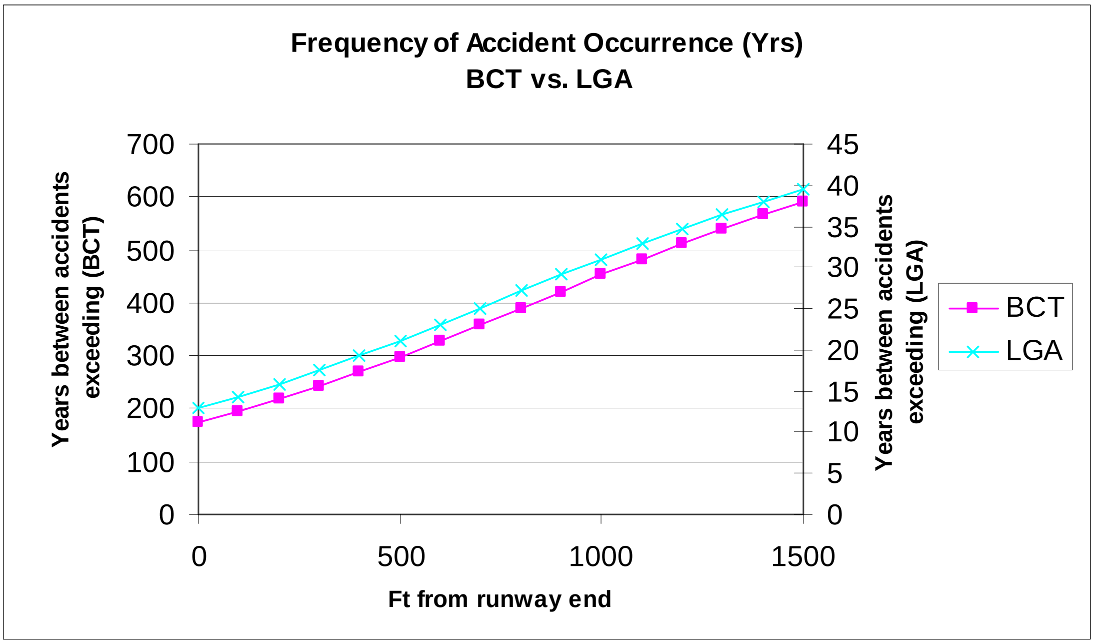


Figure 21 indicates the frequency of accidents that exceed a certain distance from the runway end. Given the traffic volumes of the airports, the frequency in terms of years between accident occurrences could be obtained, as shown in Figure 22.

Figure 22 Frequency of accident occurrence in years



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

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

ASA dimensional needs could therefore be adjusted with consideration for both criteria[4].

11. Conclusions

By considering the location of previous accidents and using the improved accident frequency models developed, this paper showed how a more systematic and risk-sensitive approach to airport risk assessment could be realised. This was demonstrated in two case studies. They showed that the methodology developed can be successfully applied to airports to quantify risk levels at individual runway ends, which form the basis for determining appropriate ASA dimensions. The case studies also illustrated the comprehensive approach of the proposed technique, in addition to its transparency and independence from qualitative judgements.

A number of advances that improve the effectiveness of airport risk assessment were made. Firstly, the dynamic interactions between diverse sources of risk are explicitly accounted for throughout the risk assessment process. Not only are the risks of individual flights assessed according to their respective risk exposure levels, but the usage pattern of the runway concerned is also considered. This is necessary so that the final ASA dimensions reflect not only the risk exposure but also the operational characteristics of the airport. For example, high risk landings are of less concern for a runway used predominantly for take-offs. These operational considerations have not featured in previous risk assessments but are intrinsic elements of the technique developed. Secondly, the proposed risk assessment methodology accounts for multiple dimensions of risk. Whereas the accident frequency models consider the frequency dimension of airport risk, accident locations are also incorporated through Complementary Cumulative Probability Distributions in the risk assessment process. ICAO and FAA ASA regulations may account for these separate aspects of risk implicitly but the current research does so explicitly and quantitatively.

The proposed risk assessment methodology allows the length and width of ASAs to be tailored according to the residual risk at individual runways, such that the margin of safety provided meets the Target Level of Safety (TLS). In terms of ASA size, the

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

case studies found that the TLS of 10^{-7} could be achieved and even exceeded relatively easily. However, the goal of attaining a TLS of 10^{-8} seems rather remote, especially if only on-airport ASAs were considered. The recommended ASA-sizing methodology also points to innovative solutions such as displacing runway thresholds and altering runway use patterns. The resulting change in risk exposure could be quantified with the proposed methodology to ensure that the residual risk does not exceed the risk budget afforded by the ASA available. This paper hence offers a far more dynamic and flexible approach to risk control and management than standard techniques.

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