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Research Project:

Study on models and methodology for safety assessment of Runway End Safety Areas (RESA)

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Final Report

Client: European Aviation Safety Agency

Rotterdam, 30 July 2014

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Summary

A significant part of all aircraft accidents and serious incidents occurs during takeoff and landing. Many of these events involve a runway overrun or undershoot of the runway. The normal protection for an aircraft and its occupants to these type of events is provided by so-called runway end safety areas (RESAs). Often airports do not have sufficient land to accommodate standard recommendations for RESAs. Airports that pursue this approach face expensive and controversial land acquisition or a reduction of takeoff/landing distances. The European Aviation Safety Agency EASA therefore states that for applicable runways where the RESA does not extend to the recommended distance, as part of their Safety Management System, aerodromes operators should assess the risk and implement appropriate and suitable mitigation measures as necessary. EASA currently does not provide any methodology to assess this risk.

This report presents the development of a probabilistic method to evaluate alternative RESA dimensions when the recommended RESA for an existing or planned runway cannot be met. Based on information gathered from historical overruns and undershoots, risk models that consider relevant aerodrome related operational factors are developed in this study to assess the likelihood for such events occurring. The overall output of the models is an estimation of the probability that an aircraft does not end up in the RESA. The user of the models can evaluate alternatives (e.g. reduced runway length, different RESA sizes, changes in runway usage, installation of landing aids etc.) that are most effective to obtain an acceptable level of risk. The need of such models follows from a Preliminary Regulatory Impact Assessment that is conducted a part of this study.

1 Introduction

1.1 Background

A significant part of all aircraft accidents and serious incidents occurs during takeoff and landing. Many of these events involve a runway overrun or undershoot of the runway. An undershoot can be seen as a condition that occurs during an approach to landing that results in an inadvertent landing or contact with the ground short of the runway, normally due to misjudgement of distance, speed, and/or altitude on final approach. An overrun is the continuation of an aircraft movement beyond the end of the runway; i.e., overrunning the intended landing or takeoff area. The normal protection for an aircraft and its occupants to these type of events is provided by so-called runway end safety areas (RESAs). This is an area symmetrical about the extended runway centre line and adjacent to the end of the strip. It is primarily intended to reduce the risk of damage to an aeroplane undershooting or overrunning the runway. RESAs are an important element of the implementing measures the Agency is developing as part of the common European regulatory framework for aerodromes. In doing so, the Agency needs to take into account the relevant developments in ICAO Annex 14. Also there are observations and developments in airport operations experience and in technology that the Agency needs to take into account, in accordance with paragraph 6 of article 8a of the Basic Regulation.

Several safety studies as well as recent overrun and undershoot accidents in Europe and other parts of the world show that the risks associated with undershoots and – in particular – overruns continues to be significant and shows no clear signs of declining, especially in those cases where a RESA did not meet the ICAO requirements. A number of recent fatal overrun and undershoot accidents has re-emphasised the importance of a properly designed RESA to mitigate the consequences of such accidents.

EASA has recently published Certification Specifications (CS) and Guidance Material (GM) for Aerodromes Design CS-ADR-DSN. This provides requirements equal to ICAO Annex 14 on RESA dimensions for instrument runways. For a variety of reasons, a significant part of the aerodromes falling within the scope of the Basic Regulation do not (fully) comply with the RESA requirements. Many aerodromes were constructed before requirements for RESAs were introduced[1]. EASA therefore states that for applicable runways where the RESA does not extend to the recommended distance, as part of their Safety Management System, aerodromes operators should assess the risk and implement appropriate and suitable mitigation measures as necessary[2]. Whatever length of RESA is provided, it is important to ensure that the likelihood of, and potential impacts arising from an overrun or undershoot are minimised as far as reasonably practicable.

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1 A 2009 study by the Agency involving a sample of large and medium sized aerodromes across Europe shows that 34 out of 51 aerodromes do not fully meet the ICAO recommendations and 7 out of 51 do not meet the ICAO standards.

2 Certification Specifications (CS) and Guidance Material (GM) for Aerodromes Design CS-ADR-DSN Initial Issue 27 February, GM1 ADR-DSN.C.210 paragraph a, and GM1 ADR-DSN.C.215.

1.2 Project objectives and scope

Within the scope of the Basic Regulation, adequate models and methodologies for assessing the probability and the location of overrun and undershoot events at any given aerodrome are developed in this study. The developed models and methodologies should allow to take into account the relevant characteristics and operating conditions of each aerodrome, as well as other factors (e.g. weather conditions), which have been found to be associated with aircraft overrun and undershoot occurrences.

It is important that the method for risk assessment of undershoots and overruns is easy to use on the one hand but captures the most important elements on the other in order for it to become a valuable tool for the targeted end-users (e.g. aerodrome operators or competent authorities). As specified in the call for tender, the development of methods for evaluating the consequences of overrun and undershoot events falls beyond the scope of the project.

The results of the project are the inputs for a preliminary regulatory impact assessment concerning the provision of RESA including for non-instrument runways and any future rulemaking actions of EASA regarding the certification specifications and/or other related EASA regulatory material in RESA field, in order to ensure that the essential safety requirements contained in the Basic Regulation are met.

1.3 Organisation of the report

The general approach of the study is discussed in section 2. Collection of data on overruns and undershoots is presented in section 3. In section 4 an initial analysis of these data is given. Development of location probability models is discussed in section 5. The development of the undershoot and overrun probability models is discussed in section 7. Basic application of the models is given in section 6. The pre-RIA and the application of the models to three example aerodromes is presented in section 8. Section 9 provides conclusions and recommendations. Finally section 10 lists the references used.

2 Approach

2.1 Introduction

In assessing a complex risk such as the risk of an undershoot or overrun event and in developing models to support such assessments, it can be difficult to strike the right balance between reliance on detailed quantitative analysis on the one hand, and the use of Subject Matter Expert (SME) input on the other hand, to conduct the various steps in the assessment. Account must be taken of the probabilities involved, the potential consequences of the outcome for decision-making and also of the skills and resources needed to carry out the risk assessment. Based on NLR's experience in developing similar models, see e.g. [Pikaar et. al., (2000)], a quantitative approach is developed here. In this approach, models for calculating the probability of an overrun or undershoot, combined with models for calculating the probability of the location of the aircraft relative to the runway are developed. There are sufficient data and information available with regard to the risk associated with undershoot and overrun occurrences to develop quantitative models.

2.2 Development steps

The work is conducted in four consecutive steps.

The first step is to collect factual historical data on undershoot and overrun occurrences. A data-taxonomy is defined in this step that covers relevant factors related to undershoot and overrun occurrences. This work is presented in section 3.

The second step is to analyse the data collected. This analysis will, among other things, identify and quantify those factors that are important with regard to the risk associated with undershoots and overruns. A data-taxonomy will be defined that covers all relevant factors related to undershoot and overrun occurrences. This work is presented in section 4.

The third step in the approach is to convert the results of the analysis into a method of assessing the risks of undershoots and overruns. This encompasses the development of models for calculating the probability of an overrun or undershoots, combined with models for calculating the probability of the location of the aircraft relative to the runway. Based on these models a method will be developed that can be used by the end-users to assess the undershoot and overrun risks in relation to the available or foreseen RESA dimensions and specific characteristics of the aerodrome and runway. The development of the location probability models is presented in section 5. The models for the occurrence probability are presented in section 6. The models are summarised in section 7.

The fourth and final step is a preliminary regulatory impact assessment and an application of the assessment concept to a number of aerodromes.

3 Data collection

3.1 Introduction

This section discusses the data collection process. Data sources, data taxonomies, and collection period are discussed.

3.2 NLR Air Safety Database

NLR-ATSI maintains one of the largest databases in the world with data related to aviation safety. Air safety data are all data that characterise activities of the air transport system. The NLR-ATSI Air Safety Database is updated frequently with data from reliable sources such as official reporting programs, insurance claims, accident investigation boards, aircraft manufacturers, civil aviation authorities, ICAO, EASA, and other credible sources. The NLR-ATSI Air Safety Database contains detailed information on accidents and serious incidents of fixed-wing aircraft and helicopters including commercial operations, general aviation etc. from 1960 onwards. Currently, it contains information on more than 70,000 accidents and serious incidents that occurred worldwide. This database was used to determine the datasets for overrun and undershoot events as part of WP-1. The NLR-ATSI Air Safety Database also contains a large collection of worldwide non-accident related data, e.g. flight exposure data (hours and cycles), airport movements, airport weather data, fleet data, and more. Also different sets of flight data (FDM) are available for e.g. landings and takeoffs. These exposure data can be related to factors in the occurrence data. For instance the number of non-accident landings under a certain tailwind condition can be linked to the occurrences that have occurred with the same tailwind. This will be important in developing the probability models (see sections **1** and **1**).

3.3 Data coverage period

The data presented here are used to develop the probability models. For the development of such models it is important to have a large data sample to obtain a high level of statistical accuracy. This would mean that the time-period to be covered by the database should be as large as possible. However, older data are not always representative of the current and near future situation. For instance, the level of flight safety has evolved over time due to improved certification standards, improved and more reliable technology, better training of pilots, improved operational procedures etc. This would require selecting a shorter (very) recent period of time for the data. However this could be in conflict with the need to have sufficient data to develop statistically robust probability and location models. As the models should take into account the various factors associated with overruns and undershoots a sufficiently large amount of data are also needed to be able to identify these factors.

In similar previous studies on undershoots and overruns NLR looked at several different time periods starting as early as 1970. In the more recent safety studies conducted by NLR the selected period typically started at 1990. The time period from 1990 onwards reflects high and consistent safety levels and is also characterised by the operation of mainly modern aircraft types like the B767, B737 classics/NG, B747-400, Fokker 50, ATR42, Citation 550, etc. as examples of so-called generation 3 aircraft and B777, A320/A330/A340, EMB170/190 etc. as examples of so-called generation 4 aircraft. These generation 3 and 4 aircraft have shown a much better safety performance than older generation aircraft. For the above mentioned reasons the present study limits the data for the probability models to the time period from 1990 to 2012. As the data for 2013 are incomplete occurrence that took place in 2013 are not considered.

The period from 1990 to present is particularly relevant with regard to the development of the probability model, since this model is critically dependent on recent data representative for the safety levels found in modern aviation.

For the development of the occurrence location models it is less relevant what the generation of aircraft was [Pikaar, de Jong, and Weijts (2000)]. A longer period can therefore be selected to increase the data sample upon the location models are based.

3.4 Selection criteria

The occurrences considered for the analysis are either an overrun event that occurred during takeoff or landing, or an undershoot event that occurred during the approach. An overrun is defined as an occurrence in which the aircraft was not able to stop on the runway and departed the end of the runway with its nose wheel. An undershoot is an event in which the aircraft touched the ground surface within 500 meters in front of the threshold during the approach.

The following selection criteria are applied to the data:
- Fixed wing aircraft with a maximum takeoff mass of 2250 kg or higher;
- Occurrences related to sabotage are excluded;
- Occurrences that took place in EASA countries, North America or Australia (Australia data were limited to aircraft with a MTOW>5670 kg);
- Occurrences cover all types of civil aircraft operations (e.g. passenger, cargo, business, general aviation, etc.). Military operations are excluded.

3.5 Data taxonomy

For each occurrence the following information was collected:
- date of occurrence;
- aerodrome;
- location relative to the runway;
- aircraft type;
- approach type;
- visual approach guidance system;
- type of operation (e.g. commercial passenger, cargo, business);
- weather conditions (wind, visibility etc.);
- runway conditions (e.g. wet, snow covered etc.);
- runway length;
- number of fatalities & injuries;
- damage to the aircraft;
- third party damage;

- runway slope;
- airport elevation;
- light conditions;
- causal/contributing factors.

These (mostly aerodrome related) factors were selected on the basis of previous safety studies and expert judgement. In some studies it was shown that these factors could be associated with a higher risk of an occurrence like overrun or undershoot. Analysis of the data should reveal the actual importance and relevance of these factors. It is realised that overruns and undershoots are associated with other factors. However these are typically not directly related to the aerodrome itself or are not under the control of the aerodrome (e.g. training of the crew).

4 Analysis of overrun and undershoot occurrences

4.1 Analytical process employed

The data were evaluated through a straightforward single-variable analysis. This included developing frequency distributions of different factors considered and a short analysis of main causal/contributing factors.

A central objective is to estimate the risk associated with the various operational factors that could be used for the development of the probability models. It is not sufficient to conclude from occurrence data alone that if a certain factor occurs in a significant fraction of the data sample that it must be an important element of the events leading to the accidents. The equivalent fraction for all non-occurrence flights should be determined to enable assessment of the significance of the fraction found in the accident sample. An estimate of the risk of having an overrun or undershoot with a particular factor present was accomplished by calculating a risk ratio. This risk ratio provides insight on the *association* of a factor on the risk in an overrun or undershoot. The risk ratio is the rate of the accident probability with the factor present over the accident probability without the factor present. The risk ratio is given by the following formula:

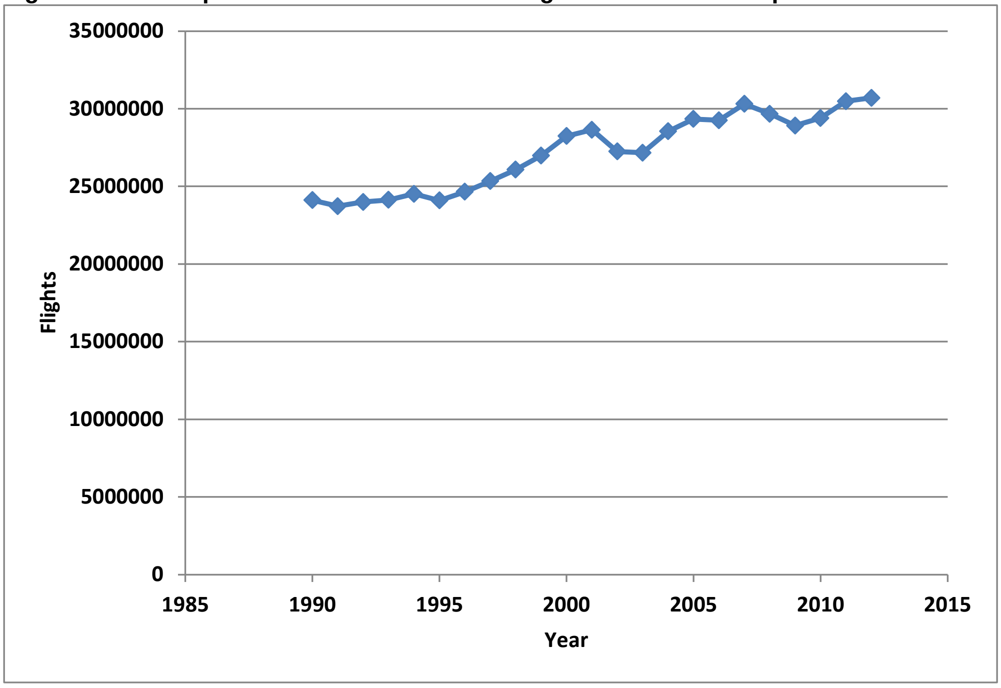
$$\mathit{Risk\ Ratio}\quad (RR) = \frac{\left(\dfrac{\text{Occurrences with presence of a risk factor}}{\text{normal takeoffs/landings with presence of a risk factor}}\right)}{\left(\dfrac{\text{Occurrences without presence of a risk factor}}{\text{normal takeoffs/landings without presence of a risk factor}}\right)}$$

Risk ratio values greater than 1 indicate an increase level of risk due to the presence of a particular factor. A risk ratio of 4 means that the probability of an occurrence with the risk factor present is 4 times higher than the risk without its presence. Note that positive associations between a factor and overruns or undershoots show that a demonstrated association exists. However it does not prove causation.

4.2 Exposure data

The exposure data (number of flights) were obtained from the NLR Air Safety database. This encompasses sources like official time tables, published airport movements, cycles per airframe etc. Figure 4.1 shows the annual number of flights in the data sample.

Figure 4.1 Development of annual number of flights in the data sample



4.3 Univariate analysis

4.3.1 Overruns

A total of 605 overrun accidents were found that met the data inclusion criteria with 125 occurring during the take-off and 480 during landing. This corresponds to 0.48 overruns per million movements. Figure 4.2 and Figure 4.3 show the main (causal) factors that were identified in the landing and takeoff overruns respectively. The percentages are based on the number of overruns with known cause(s). Note that more than one factor could be present in a single occurrence. The factors identified here are comparable to those found in other studies on runway overruns.

Table 4.1 to Table 4.11 list the frequency distributions of the different factors present in the overrun data sample.

Figure 4.2 Main causal factors for landing overruns as percent of landing overruns with known causes

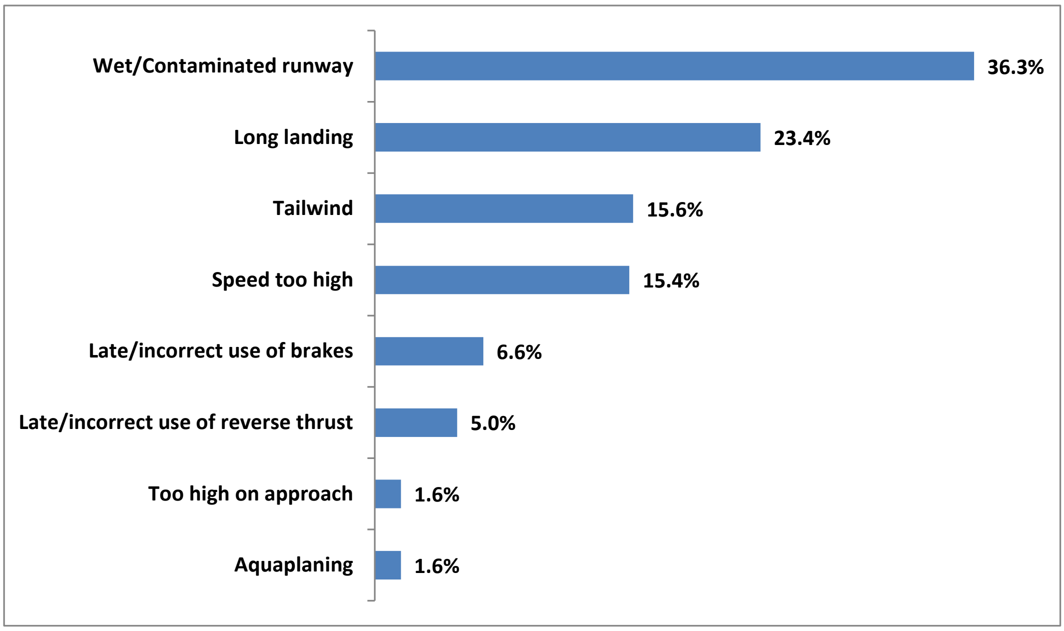


Figure 4.3 Main causal factors for take-off overruns as percent of take-off overruns with known causes

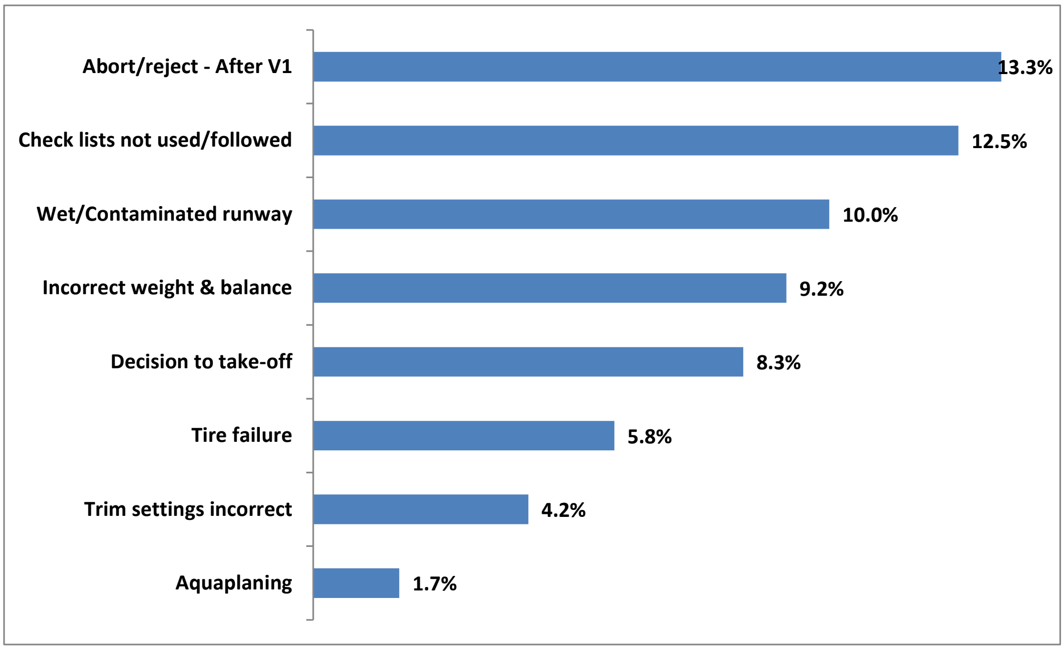


Table 4.1 Distribution of mass categories in the overrun sample

Mass category	Count
2 250 to 5 670 Kg	246
5 671 to 27 000 Kg	215
27 001 to 272 000 Kg	124
> 272 000 Kg	20

Table 4.2 Distribution of lights conditions in the overrun sample

Light conditions	Count
Daylight	481
Night/dark	124

Table 4.3 Distribution of approach types in the landing in the overrun sample

Approach type flown	Count
Precision	177
Non-precision	61
Visual approach	242

Table 4.4 Distribution of the general weather condition in the overrun sample

Weather conditions	Count
IMC	272
VMC	333

Table 4.5 Distribution of the flight phases in the overrun sample

Flight phase	Count
Landing	479
Take-off	126

Table 4.6 Distribution of the runway conditions in the overrun sample

Runway condition	Count
Dry	329
Ice Covered	19
Snow covered	78
Standing water covered	30
Wet	149

Table 4.7 Distribution of longitudinal wind in the overrun sample

Tailwind present	Count
No	409
Yes	196

Table 4.8 Distribution of the visibility in the overrun sample

Visibility (m)	Count
0: 249	16
250: 499	10
500: 749	2
750: 999	8
1000: 1249	12
1250: 1499	1
1500: 1749	22
1750: 1999	3
2000: 2249	8
2250: 2499	8
2500: 2749	4
2750: 2999	4
3000: 3249	15
3500: 3749	2
4000: 4249	9
4500: 4749	1
4750: 4999	13
5000: 5249	8

Visibility (m)	Count
5250: 5499	1
5500: 5749	2
6000: 6249	12
6250: 6499	11
7000: 7249	1
8000: 8249	12
9000: 9249	2
9500: 9749	7
9750: 9999	2
>=10000	409

Table 4.9 Distribution of the runway slope in the overrun sample

Runway slope	Count
Down	110
Up or zero	495

Table 4.10 Distribution of the airport elevation in the overrun sample

Elevation (m)	Count
<0	7
0: 249	439
250: 499	97
500: 749	25
750: 999	3
1000: 1249	8
1250: 1499	4
1500: 1749	10
1750: 1999	8
2000: 2249	4

Table 4.11 Distribution of visual approach guidance systems in the overrun sample

Visual approach guidance (PAPI/VASI)	Count
Installed	230
Not installed	250

4.3.2 Undershoots

A total of 168 undershoot occurrences were found that met the data inclusion criteria. This corresponds to 0.27 undershoots per million landings. Figure 4.4 shows the main (causal) factors that were identified in the undershoot occurrences. The percentages are based on the number of undershoots with known cause(s). Note that more than one factor could be present in a single occurrence.

Table 4.11 to Table 4.19 list the frequency distribution of the different factors present in the undershoot data sample.

Figure 4.4 Main causal factors for landing undershoots as percent of all undershoots with known causes

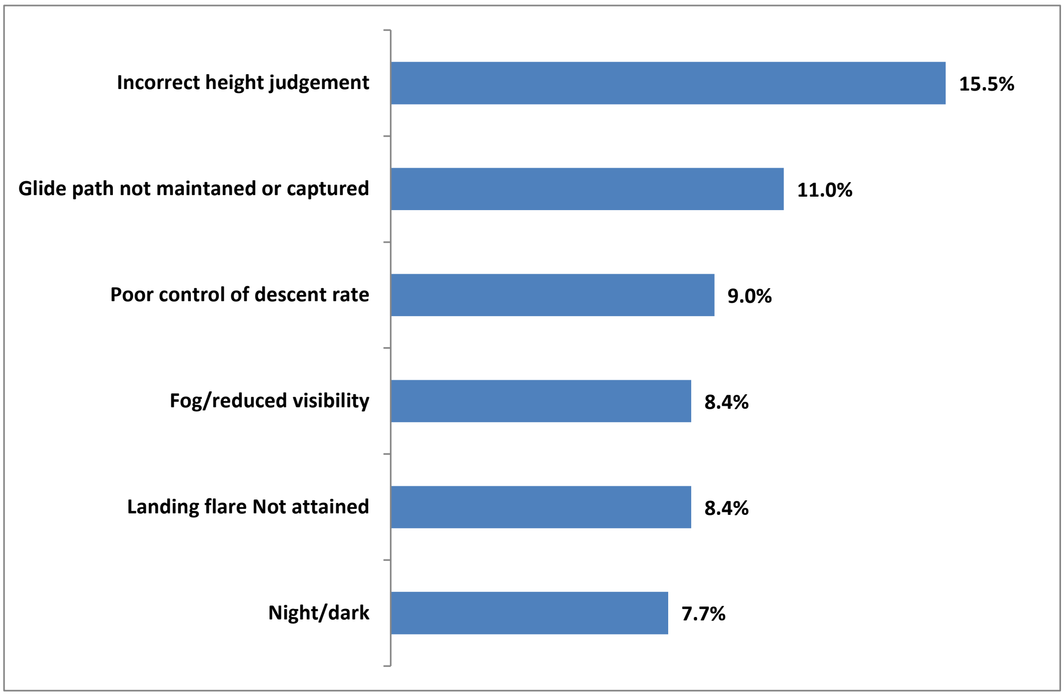


Table 4.12 Distribution of the mass category in the undershoot sample

Mass category	Count
2 250 to 5 670 Kg	118
5 671 to 27 000 Kg	24
27 001 to 272 000 Kg	23
> 272 000 Kg	3

Table 4.13 Distribution of the general weather conditions in the undershoot sample

Weather conditions	Count
IMC	74
VMC	94

Table 4.14 Distribution of the light conditions in the undershoot sample

Light conditions	Count
Daylight	127
Night/dark	41

Table 4.15 Distribution of the approach type in the undershoot sample

Approach type	Count
Non-precision	14
Precision	41
Visual	113

Table 4.16 Distribution of the runway slope in the undershoot sample

Runway slope	Count
Down	23
Up or zero	145

Table 4.17 Distribution of the visibility in the undershoot sample

Visibility (m)	Count
0: 249	3
250: 499	8
500: 749	1
750: 999	6
1000: 1249	2
1250: 1499	1
1500: 1749	6
2000: 2249	3
2250: 2499	2
2750: 2999	1
3000: 3249	4
4000: 4249	2
4750: 4999	4
6250: 6499	1
8000: 8249	4
9500: 9749	1
9750: 9999	1
>10000	118

Table 4.18 Distribution of the elevation in the undershoot sample

Elevation (m)	Count
0: 249	118
250: 499	28
500: 749	9
750: 999	1
1000:1249	1
1250:1499	3
1500:1749	5
1750:1999	2
2000:2249	1

Table 4.19 Distribution of visual approach guidance systems in the undershoot sample

Visual approach guidance (PAPI/VASI)	Count
Installed	85
Not installed	83

4.4 Bivariate analysis

In order to estimate risk ratios as defined in section 4.1, the number of landings or takeoffs with or without a particular factor of interest absent should be known. Different approaches were followed to obtain these operational data. For instance, detailed movement data from airports were related to weather data from METAR databases. The approach type flown was estimated from the NLR Air Safety Database which contains information regarding precision, non-precision and visual approaches by airport. The actual runway conditions at airports (e.g. wet, snow covered etc.) are not well recorded. Therefore the number of landings or takeoffs conducted on the different runway conditions were estimated from historical hourly precipitation observations at airports and operator surveys. The fact that it, for instance, rains does not automatically mean that the runway is wet. This depends on the drainage characteristics of the runway, the wind, the amount of rain that is falling and some other factors. With a precipitation like snow the runway can be made clear of it when large amounts accumulate on the surface. Therefore adjustments were made on the calculated number of landings on wet/contaminated runways based on hourly precipitation observations. These adjustments were done by using engineering judgement. Although it is realised that this approach can introduce errors in the results it is believed that the errors are small enough just to fulfil the basic objectives of the present study.

The results shown here can be used as input to the development of the probability models. However, during the development of the probability models different splits of the data could be used than presented in this report if better regression correlations can be obtained.

4.4.1 Overruns

In this section a bivariate analysis is conducted concerning overruns during takeoff and landing. The present study encompasses operations with civil aircraft with a maximum takeoff mass of 2250 kg or higher. This covers a wide range of aircraft types certified and operated under a wide range of different regulations. Also the safety equipment on these aircraft can differ significantly. In many previous flight safety studies a distinction is made between aircraft having a MTOW of less than 5670 kg and those exceeding this MTOW value. This reflects the different basis of aircraft certification which is guided by MTOW. Also most commercial passenger/cargo operations are conducted with aircraft heavier than 5670 kg MTOW. The general aviation flying activity is dominated by aircraft less than 5670 kg MTOW. These types of operations are characterised by differences in operational regulations like EU-OPS, EASA IR-OPS and FAA Part 121 that apply to most commercial flying activities and limited or no operational regulations for general aviation type of flying.

In the present analysis the data are analysed in two MTOW categories: 2250 to 5670 Kg and 5671 Kg or higher (unless there are no differences in the normal operational data with presence of a certain risk factor). In Figure 4.5 the comparison of overrun rate for different MTOW categories shows that the overrun rate is 5 times higher for aircraft in the 2250 to 5670 Kg MTOW category compared to those having an MTOW of more than 5670 kg. The difference in rates is tested to be statistically significant (RR=6.2).

Figure 4.5 Comparison of overrun rate for different MTOW categories

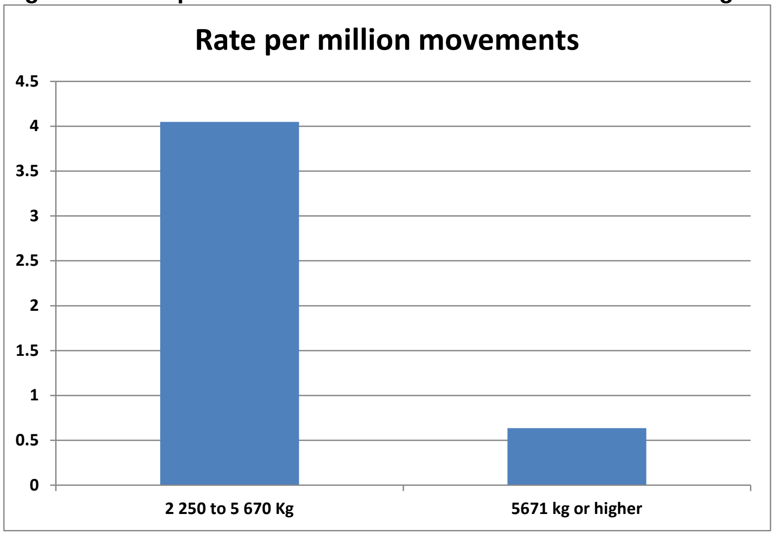


Figure 4.6 shows the overrun rate per flight phase. The rate is higher during landings than during takeoffs (RR=3.8).

Figure 4.6 Overrun rate per flight phase

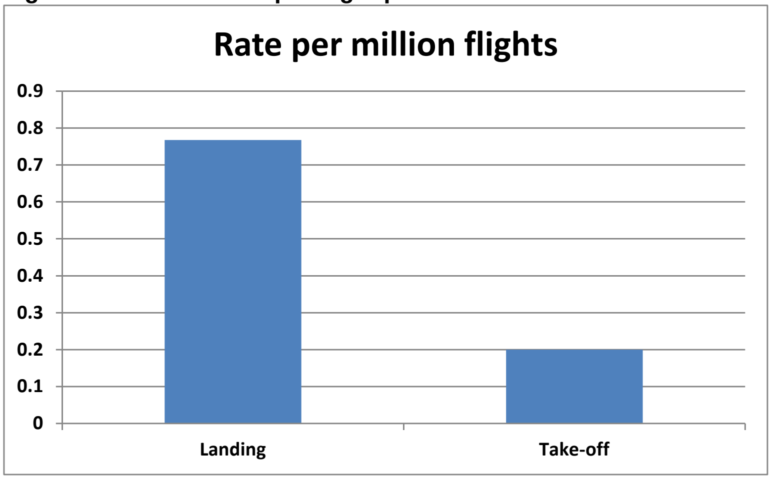


Figure 4.7 Overrun rate per light conditions

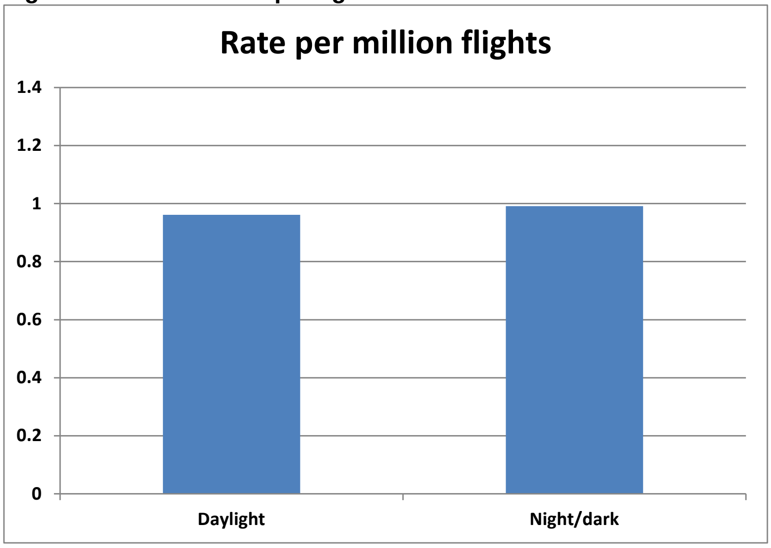


Figure 4.7 shows that light conditions have a small influence on the overrun rate (RR=0.97). The relative number of flights under the different light conditions are the same for the mass categories considered.

The influence of the general weather conditions on overrun rates is shown in Figure 4.8. As the relative number of flights conducted under VMC is different between the two MTOW groups a split is made in the comparison. For both MTOW categories the overrun rate under IMC conditions is significantly higher than under VMC conditions (RR=1.7 for 2250 to 5670 Kg MTOW category and 2.3 for the other group).

Figure 4.8 Influence general weather conditions on overrun rates

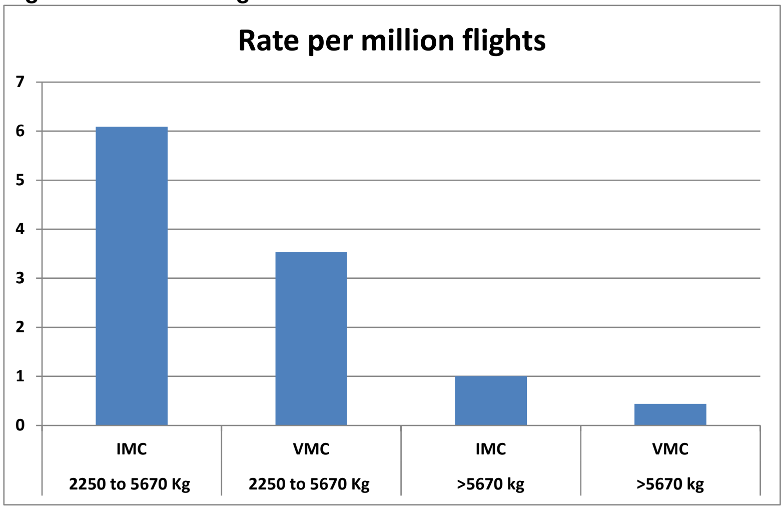


Figure 4.9 Influence approach type on landing overrun rate

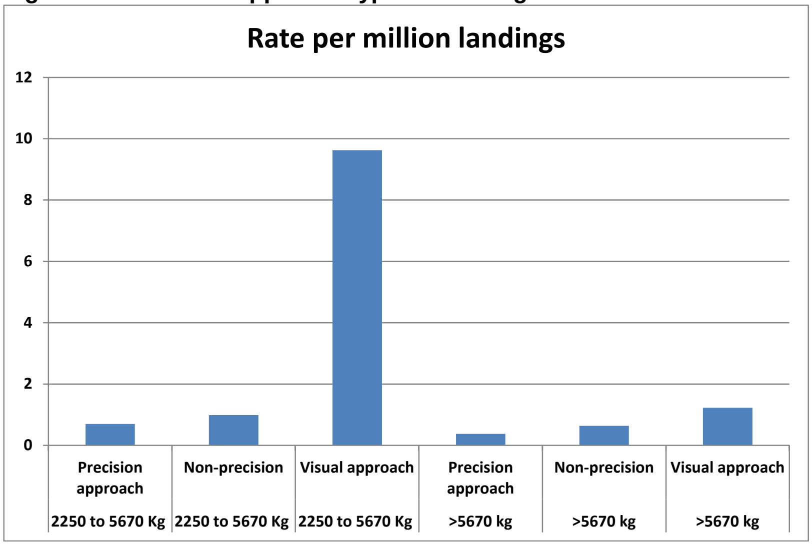


Figure 4.9 shows the influence of the approach type flown on the landing overrun rate. As in the different MTOW categories the type of approaches relatively flown are different, both categories are shown separately. Both non-precision and visual approaches are associated with a higher probability of an overrun compared to a precision approach like an ILS approach.

Figure 4.10 illustrates the impact of runway condition on the overrun rate. Compared to a dry runway the overrun rate for non-dry conditions increases (RR is 2.5 for wet runways and 10.4 for contaminated (snow, slush, ice, standing water covered) runways.

Figure 4.10 Influence of runway condition of overrun rate

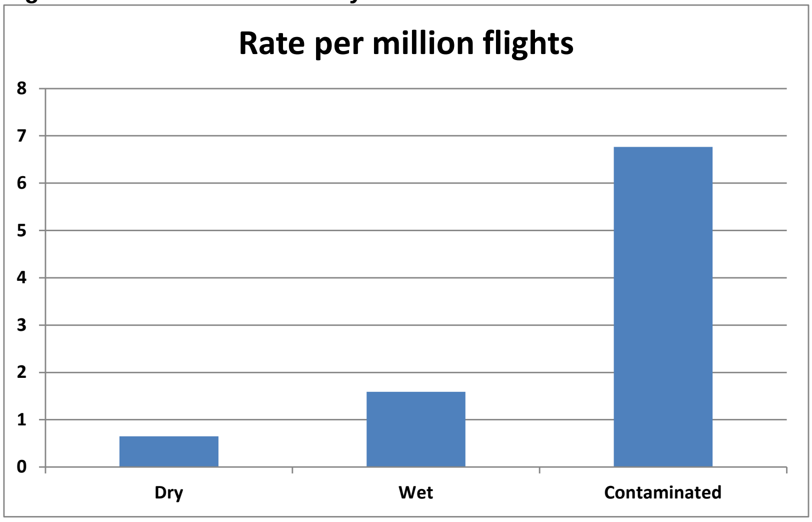


Figure 4.11 Influence visibility on overrun rate

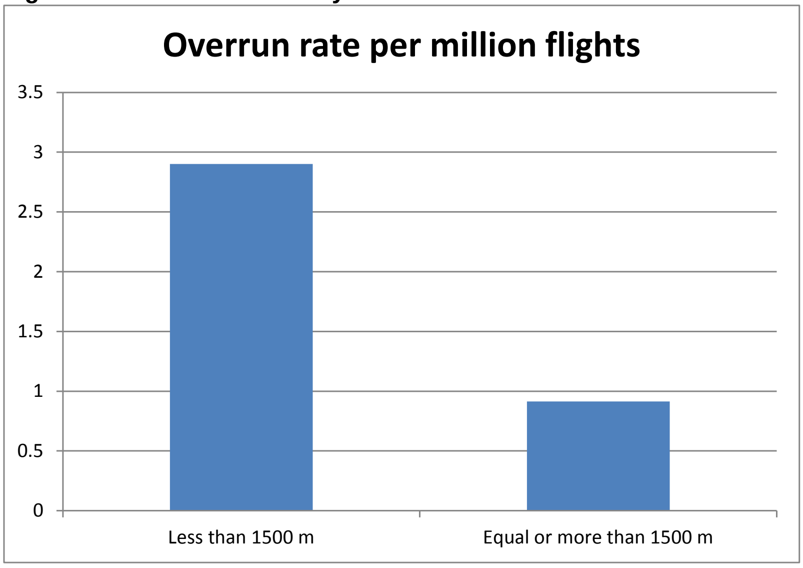


Figure 4.11 shows the influence of visibility on the overrun rate. As visibility is not a discrete value the comparison show is only for one selected value of visibility of 1500 m. During the model development other values will be analysed. The 1500 m threshold shows a significant difference in probabilities (RR of 3.2).

Figure 4.12 Influence of tailwind on overrun rate

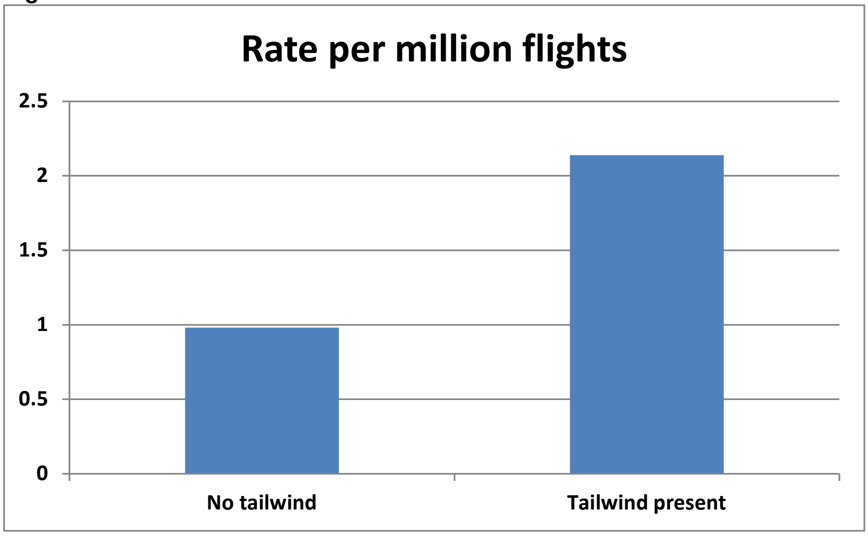


Figure 4.12 shows the influence of wind condition (head- or tailwind) on the overrun rate. As wind is not a discrete value the comparison shown is only for one selected wind condition. In the probability model development other values will be analysed e.g. different bins of tailwinds. The comparison between the presence of tailwind versus no tailwind shows a significant difference in probabilities (RR of 2.1).

Figure 4.13 Influence runway slope on overrun rate

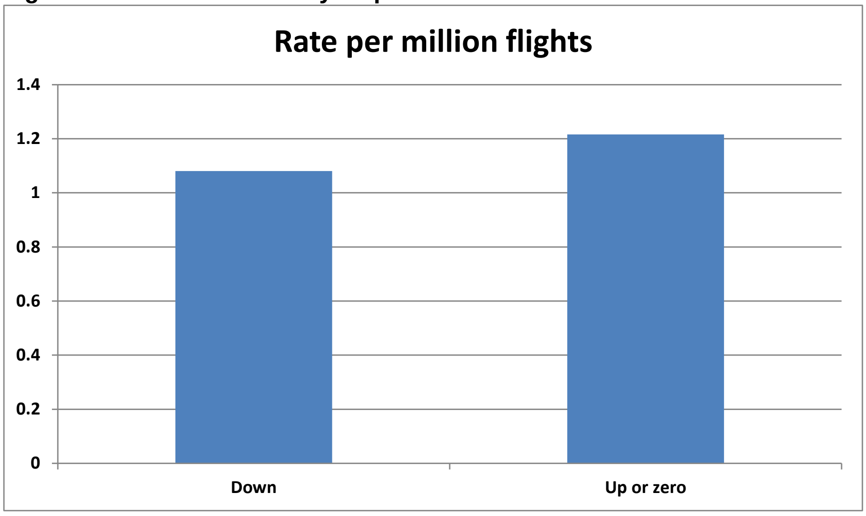


Figure 4.13 shows in the influence of the runway slope on the overrun rate. There is no significant difference in rates for overruns on a down slope runway compared to runways with no or an upslope. However when looking at a more extreme down slope situation of -1%, a significant difference in overrun rates could be identified (see Figure 4.14) in which an RR of 7.8 was found.

Figure 4.14 Influence of -1% down slope on overrun rates

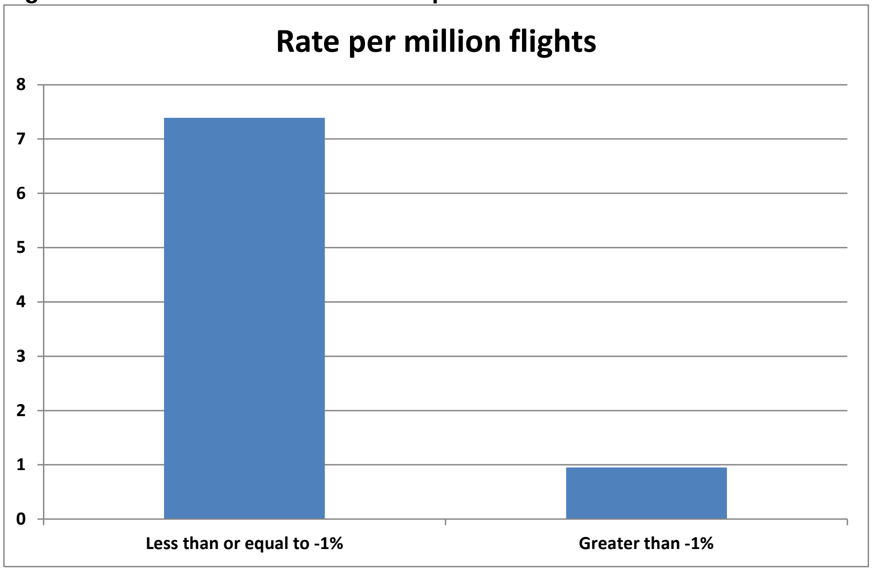


Figure 4.15 Influence of airport elevation on overrun rates

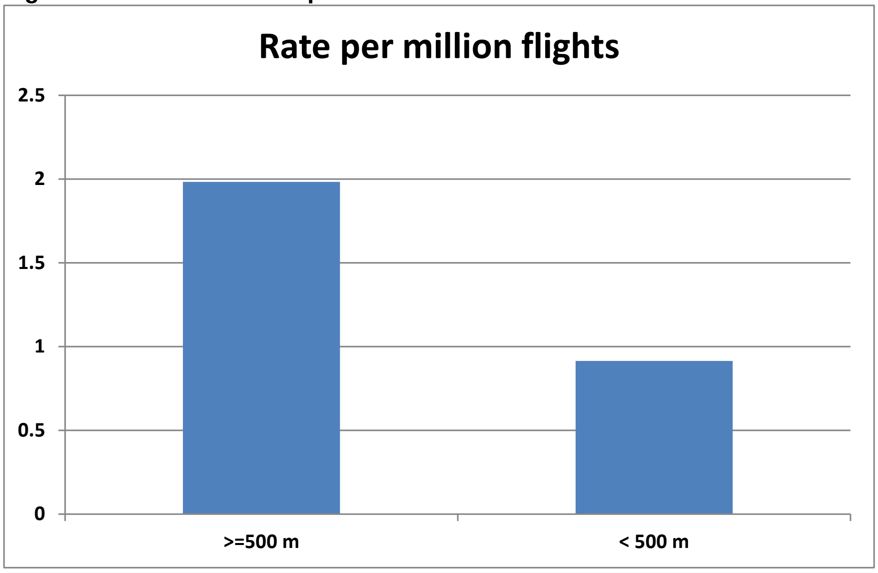


Figure 4.15 illustrates the influence of airport elevation on overrun rates. It was found that a significant difference in rates could be found at the crossing of 500 m in elevation (RR=2.1).

Figure 4.16 Influence takeoff distance margin on overrun rate

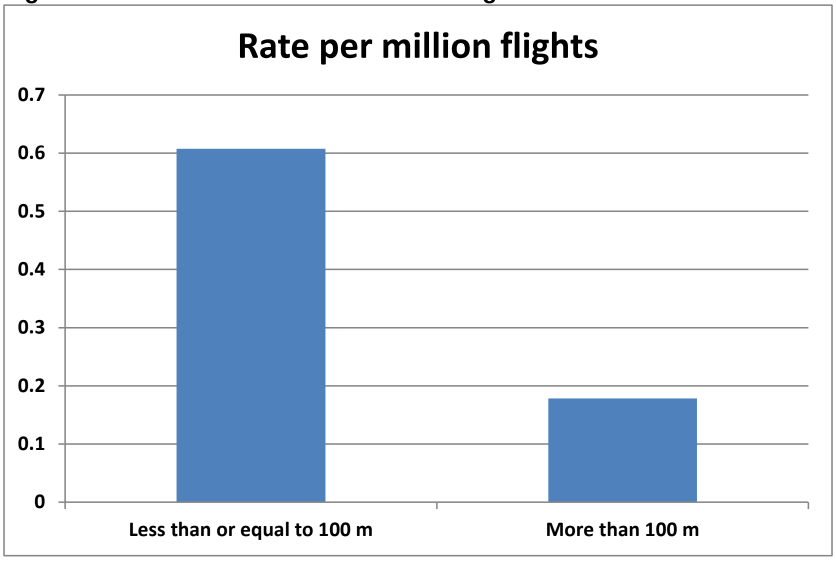


Figure 4.17 Influence landing distance margin on overrun rate

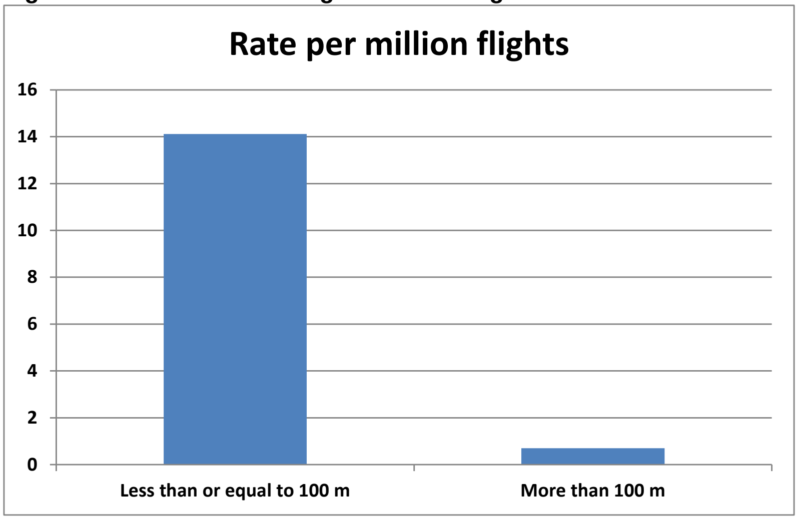


Figure 4.16 and Figure 4.17 show the influence of the takeoff and landing distance margin on the overrun rate. As significant difference was found between a margin of less than or equal to 100 m and a margin greater than 100 m (RR=3.3 for takeoff and RR= 20.0 for landing). Note that the distance margin is defined here by the difference of the runway distance available for takeoff (TORA) or landing distance available (LDA) minus the reference takeoff or landing distance for an aircraft. The reference distances are the typical takeoff or landing field lengths for a normal maximum takeoff or maximum landing mass under ISA, no wind and dry runway conditions (see Table 4.20 for standard field lengths for the most common aircraft with an MTOW of 2250 kg or greater). It is possible that this standard field length is larger than the available runway length as it is not corrected to the actual conditions during the event. The idea is that the difference between available runway length and a standard field length is used as a measure to account how critical the runway length was in an overrun. Initially the plan was to account for the actual conditions on field performance, however, it turned out that this introduced several difficulties as important details could not be taken into account (e.g. crew performance, maximum lift coefficients of the aircraft, actual braking friction etc.). It would also make the model significantly more complicated which would hamper its use by e.g. aerodrome operators.

Table 4.20 Aircraft standard field lengths

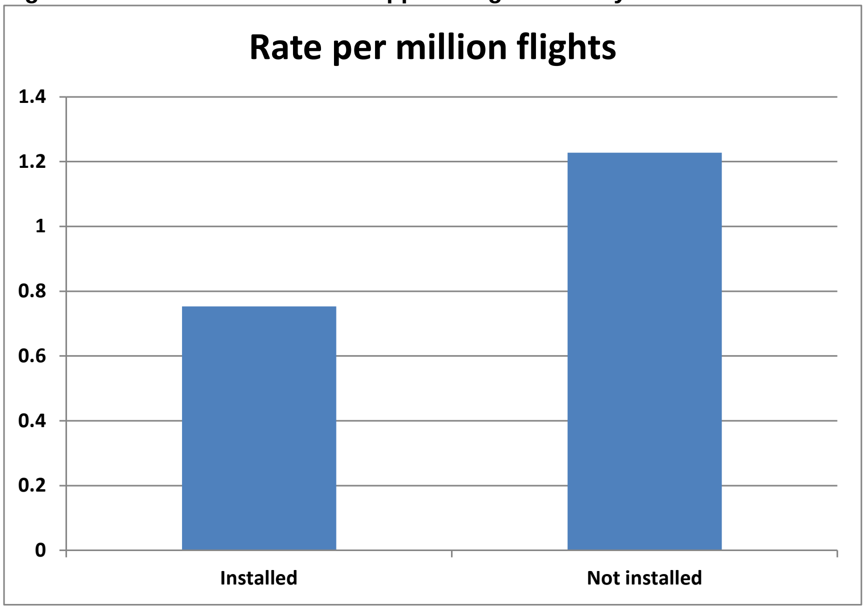
Aircraft ICAO Code	MTOW (kg)	Takeoff Distance (m)	Landing Distance (m)
A306	171671	2240	1532
A30B	171671	2240	1532
A310	149974	2290	1490
A320	73488	2190	1440
A330	229961	2300	1800
A340	274953	2765	1765
A748	21086	1000	620
AC50	3059	400	400
AC90	4649	600	700
AC95	5079	500	500
AEST	2859	550	350
ASTR	11178	1600	900
AT43	16697	1100	1000
AT72	21496	1500	1100
B190	7689	1150	825
B350	6799	1000	820
B707	86169	2650	1980
B712	54875	2100	1600
B727	95284	3000	1500
B737	66309	1800	1400
B747	396822	3300	2130
B757	115660	1900	1400
B767	186848	2900	1800
B777	247168	2900	1700
BA11	45193	2277	1450
BA46	38000	1030	1235
BE10	5349	450	650
BE20	5669	570	540
BE30	6299	570	540
BE40	7299	1200	1100
BE55	2300	450	450
BE58	2500	700	600
BE60	3069	600	400
BE99	7599	1000	900
BE9L	4580	700	380
BE9T	4966	700	380
C130	70298	1100	800
C2	24683	795	450
C208	3629	500	450
C212	7699	900	500
C303	2340	533	445
C310	2493	507	546
C340	2710	650	500
C402	2859	677	538
C404	3829	700	600

Aircraft ICAO Code	MTOW (kg)	Takeoff Distance (m)	Landing Distance (m)
C414	3059	520	700
C421	3099	600	750
C425	3899	750	650
C441	4469	550	350
C500	4919	998	570
C525	4716	939	838
C550	6849	1000	915
C560	7209	963	890
C56X	8707	1055	890
C650	14058	1600	900
C750	16190	1740	1164
CL60	21587	1600	1200
CRJ7	32995	1600	1478
D228	12500	700	450
D328	13988	1000	1200
DC10	259415	3000	1800
DC85	147375	3000	2000
DC86	158673	3000	2000
DC87	161997	3050	2000
DC9	54925	2100	1500
DH84	15647	1100	1000
DH8A	15647	900	900
DH8B	15647	1100	1000
DH8C	18639	1100	1000
DH8D	28993	1300	1100
DHC2	2300	300	300
DHC3	3600	360	260
DHC5	5669	500	300
DHC6	5600	450	570
DHC7	21317	900	1000
E110	5899	1200	1300
E120	11998	1400	1400
E135	19986	1760	1360
E145	21195	2000	1350
F100	42000	1700	1400
F27	19000	700	600
F28	29000	1700	1000
F2TH	16237	1600	1600
F50	20000	1100	1100
F70	38000	1300	1200
F900	21000	1500	700
FA10	8498	1500	1000
FA20	13158	1600	1100
FA50	17597	1400	1100
GALX	15805	1800	1050
GLEX	44493	1870	414

Aircraft ICAO Code	MTOW (kg)	Takeoff Distance (m)	Landing Distance (m)
GLF2	29615	1500	960
GLF3	31615	1800	1000
GLF4	33194	1600	1000
GLF5	41129	1570	884
H25B	12428	1700	900
H25C	14058	1900	889
IL62	164972	3300	2300
IL96	269954	2800	2000
J328	15197	1300	1200
JS31	7058	1800	1300
JS32	7359	1570	1220
JS41	10884	1500	1300
L101	195007	2400	1800
L188	51241	1300	900
LJ24	5896	1200	900
LJ25	6799	1200	900
LJ31	7029	1100	900
LJ35	8298	1300	900
LJ45	8849	1300	900
LJ55	9528	1400	1000
LJ60	10478	1600	1100
MD11	285941	3100	2100
MD80	67800	2052	1585
MD90	74487	2200	1200
MU2	4559	650	600
N262	10598	700	400
P180	5239	900	900
P68	2080	400	600
PA27	2360	300	500
PA31	2950	400	600
PAY2	4079	650	750
PAY3	5099	700	650
PAY4	5469	700	650
PC12	4499	600	550
PC7	2899	300	400
SB20	20996	1300	1300
SC7	6199	600	700
SF34	12898	1300	1100
SH33	10248	1100	1100
SH36	12298	1300	1100
SW2	5699	1200	900
SW3	5699	1300	1300
SW4	5700	1300	1200
TBM7	3000	650	500
WW24	10398	1475	750

Figure 4.18 shows the influence of a visual approach guidance system like PAPI or VASI on the undershoot rate. Absence of such a system increases the probability of an undershoot (RR=1.7).

Figure 4.18 Influence of a visual approach guidance system on overrun rate



4.4.2 Undershoots

In this section a bivariate analysis is conducted concerning landing undershoot occurrences. The present study encompasses operations with civil aircraft with a maximum takeoff mass of 2250 kg or higher. This covers a wide range of aircraft types certified and operated under a wide range of different regulations. Also the safety equipment on these aircraft can differ significantly (e.g. the installation of ground proximity warning systems and terrain awareness and warning systems mandatory on most aircraft with an MTOW of 5670 or greater). In many previous flight safety studies a distinguish is made between aircraft having a MTOW of less than 5670 kg and those exceeding this MTOW value. This reflects the different basis of aircraft certification which is guided by MTOW. Also most commercial passenger/cargo operations are conducted with aircraft heavier than 5670 kg MTOW. The general aviation flying activity is dominated by aircraft less than 5670 kg MTOW. These types of operations are characterised by differences in operational regulations like EU-OPS, EASA IR-OPS and FAA Part 121 that apply to most commercial flying activities and limited or no operational regulations for general aviation type of flying.

In the present analysis the data are analysed in two MTOW categories: 2250 to 5670 Kg and 5671 Kg or higher (unless there are no differences in the normal operational data with presence of a certain risk factor). In Figure 4.19 the comparison of undershoot rate for different MTOW categories shows that the overrun rate is 22 times higher for aircraft in the 2250 to 5670 Kg MTOW category compared to those having an MTOW of more than 5670 kg. The difference in rates is tested to be statistically significant.

Figure 4.19 Influence of MTWO category on undershoot rate

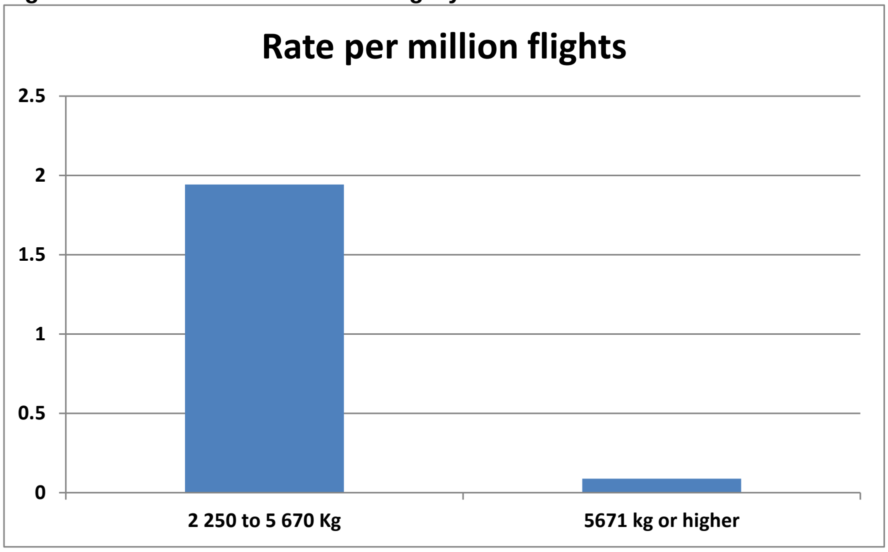
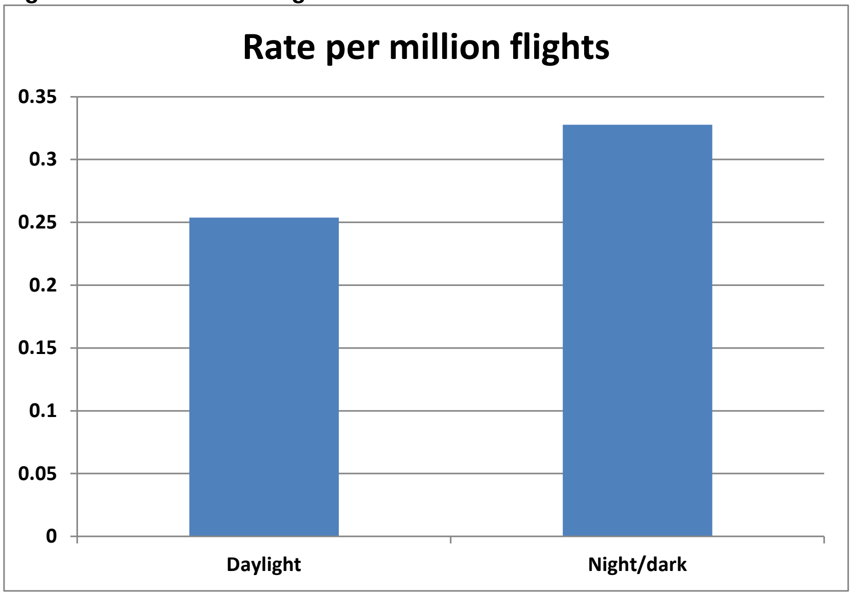


Figure 4.20 shows that light conditions have a small influence on the overrun rate (RR=1.3). The relative number of flights under the different light conditions are similar for the mass categories considered.

Figure 4.20 Influence of light conditions on undershoot rate



The influence of the general weather conditions on undershoot rates is shown in Figure 4.21. As the relative number of landings conducted under VMC is different between the two MTOW groups a split is made in the comparison. For both MTOW categories the undershoot rate under IMC conditions is significantly higher than under VMC conditions (RR=2.2 for 2250 to 5670 Kg MTOW category and 3.0 for the other group).

Figure 4.21 Influence of general weather conditions on undershoot rate

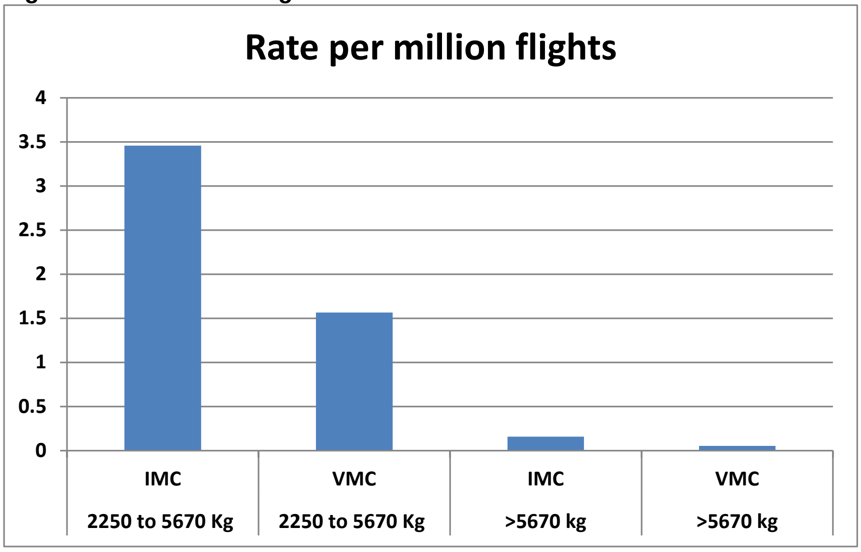


Figure 4.22 shows the influence of the approach type flown on the undershoot rate. As in the different MTOW categories the type of approaches relatively flown are different, both mass categories are shown separately. Both non-precision and visual approaches are associated with a higher probability of an undershoot compared to a precision approach like an ILS approach for the MTOW of 5670 or greater. For the mass category of 2250 to 5670 kg the visual approach are associated with a higher probability of an undershoot than during a precision or non-precision approach. However the difference between precision and non-precision approach for this mass category is not statistically significant at the 5% level.

Figure 4.22 Influence of approach type on undershoot rate

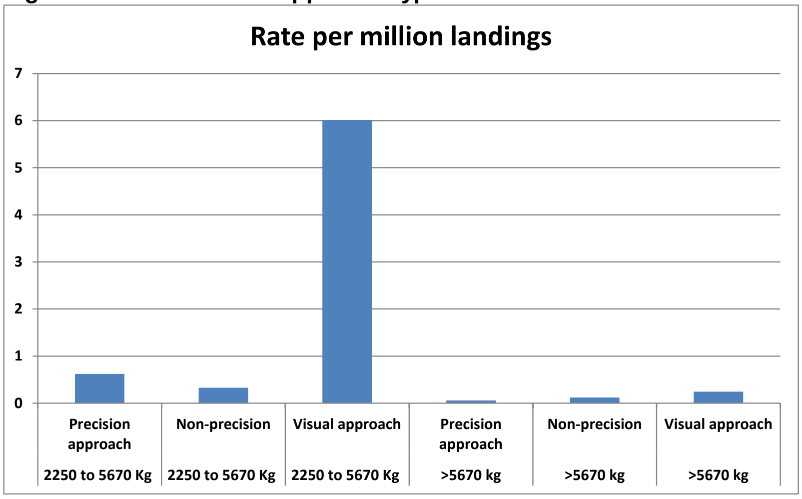


Figure 4.23 shows the influence of visibility on the overrun rate. As visibility is not a discrete value the comparison show is only for one selected value of visibility of 1500 m. During the model development other values will be analysed. The 1500 m threshold shows a significant difference in probabilities (RR of 5.1).

Figure 4.23 Influence visibility on undershoot rate

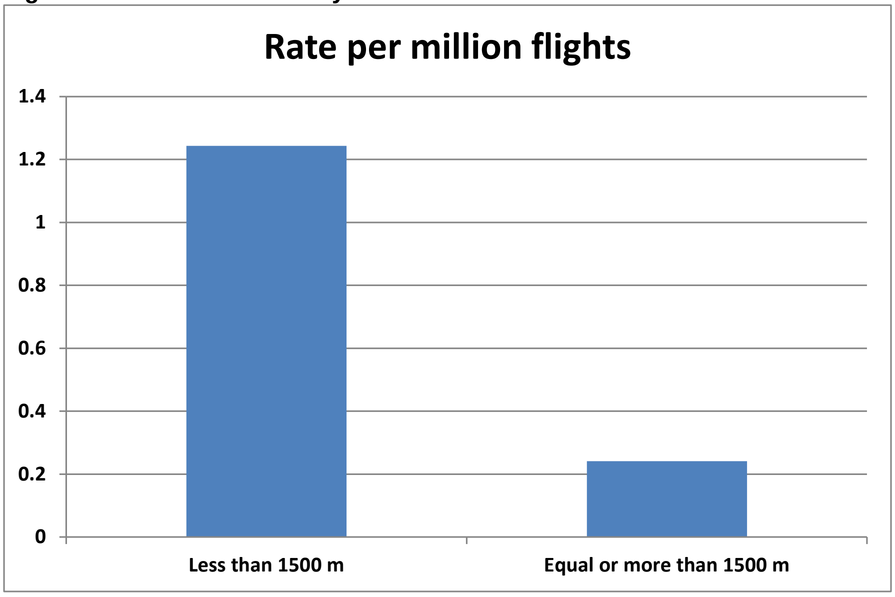


Figure 4.24 illustrates the influence of airport elevation on overrun rates. It was found that a significant difference in rates could be found at the crossing of 500 m in elevation (RR = 2.9).

Figure 4.24 Influence airport elevation on undershoot rate

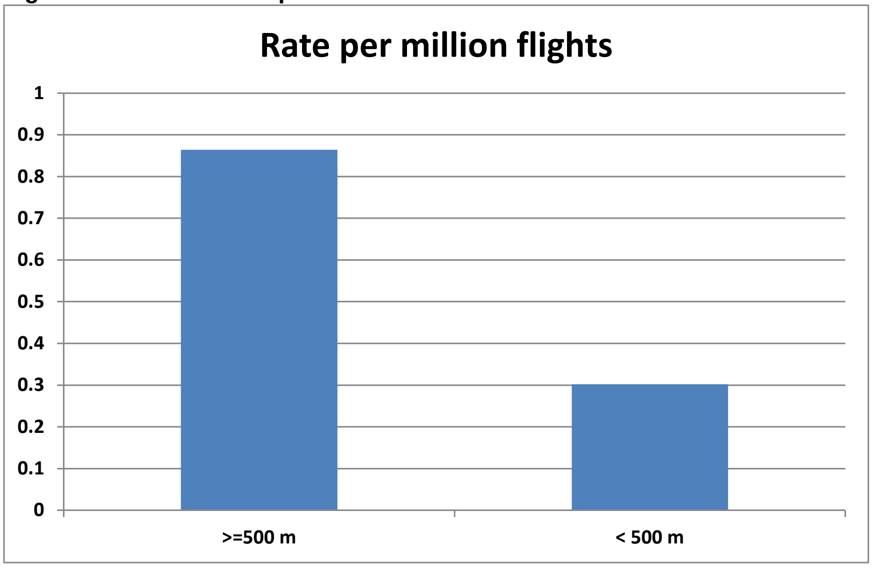
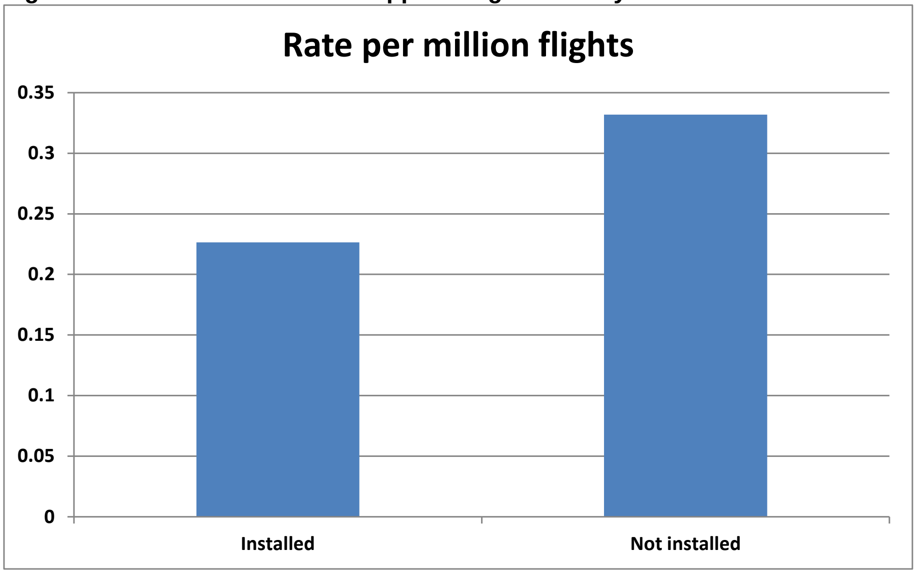


Figure 4.25 shows the influence of a visual approach guidance system like PAPI or VASI on the undershoot rate. Absence of such a system increases the probability of an undershoot (RR=1.5).

Figure 4.25 Influence of a visual approach guidance system on undershoot rate



4.5 Final remarks

The risk ratios analysed here demonstrate that associations exist between a number of takeoff/landing related factors and the risk of an overrun or undershoot. Such associations do not automatically prove causation and firstly only suggest that an increase in risk for a landing overrun accident appears when the factor is present. However in most cases can be argued that some form of causal relation (either direct or indirect) should exist. For instance increasing the airport elevation will increase the true airspeed and hence ground speed which can be a factor in overruns.

The results presented show that basically all of the analysed operational factors can influence the probability of overruns and undershoots. The risk factors are presented without any consideration of possible correlations that might exist between them. For the development of the occurrence probability models it will be assumed that the individual factors are not (strongly) correlated with each other. However this is not automatically the case for the factors analysed here. This needs to be considered when developing the probability models. Factors that are strongly correlated with each other will not be included in the model as separate factors.

Note that any comparison with the outcome of this study with results from previous safety studies should be done with great care as the data inclusion criteria are often not same. For instance the time frame, maximum takeoff mass and occurrence location countries may be different resulting in other values for the probabilities and risk ratio's.

5 Development of location probability models

5.1 Description of the occurrence data used for the location models

Location data is collected for overrun and undershoot occurrences. The location is given in a longitudinal distance from the threshold (x) and a lateral distance relative to the extended centreline of the runway (y). The origin (0,0) corresponds to the threshold. Figure 5.1 and Figure 5.2 illustrate the coordinate system for the overrun data and the undershoot data respectively. It is assumed that the distance in x and y corresponds to the nose of the aircraft in the case of overruns and the centre of the aircraft for undershoots. In some cases this is an approximation as the exact position of the nose wheel or centre of the aircraft was not reported. For those cases corrections were made as much as possible to the original data using the aircraft dimensions.

An undershoot occurrence has been defined in the present study as a landing occurrence that has occurred at no more than 500m before the threshold. Therefore, the x coordinates of the undershoot occurrences are between 0m and 500m. For the overrun occurrences the x coordinate is larger than or equal to 0m.

Figure 5.1 Coordinate system of the overrun locations

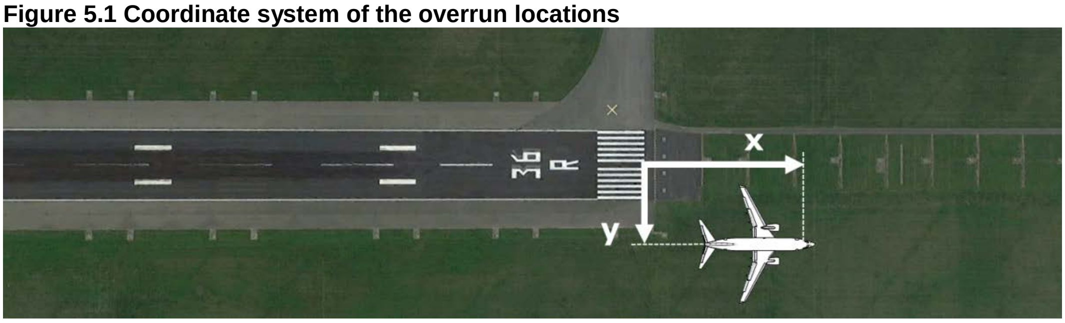
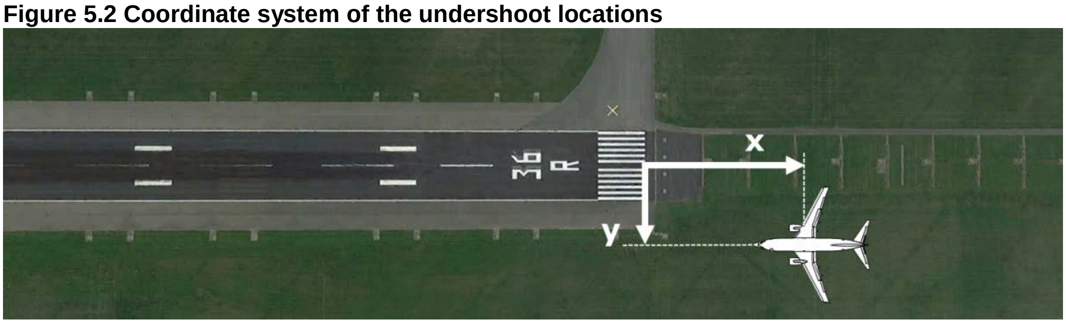


Figure 5.2 Coordinate system of the undershoot locations



Besides the type of occurrence (overrun or undershoot) and the flight phase (landing or take-off), the size of aircraft (small or large) have been provided as a relevant factor. An aircraft is classified as small in the present study if the maximum take-off mass (MTOM) is less than or equal to 5670 kg but higher than 2249 kg and large when the MTOM exceeds 5670 kg. These factors have partly been chosen based on past experience because they could have an impact on the location. Also this mass differentiation matches those of section 1 which were based on operational and certification regulations (2250-5670kg and greater than 5670 kg).

Data on occurrence locations were obtained from the NLR Air Safety database, supplemented with information from other sources/studies. Two datasets are constructed: one for overruns and one for undershoots. In order to have sufficiently large samples for case, the timeframe had to be extended compared to that of the occurrence probability model that runs from 1990-2012. For the overruns occurrences the timeframe is extended to 1980 – 2012 and for the undershoot occurrences to 1970 – 2012. The final occurrence location data sample comprised of 553 overrun occurrences and 303 undershoot occurrences. These data are shown per year in Figure 5.3. Note that no conclusion can be drawn from this figure regarding possible trends. One should be aware of certain limitations when using information on aircraft location in reports and/or accident database records. Usually no indication is given of how the distance was obtained (e.g. it may have been measured with a tape, or estimated by the investigative team). Consequently, there is a certain amount of error inherent in some of the location data collected in this study. Nevertheless, despite these limitations, the information collected is considered the best available.

Not for all data entries both coordinates (x and y) were available. For some entries, the y coordinate was missing. For the overrun data 75% of the entries was complete and for the undershoot data 73%. For the analysis of solely the longitudinal data, all data entries are used. In the other cases only the complete data entries are used. See Table 5.1 .

Table 5.1 Number of data points in the different samples

Type of occurrence	Aircraft size	Nr of Data points	Nr with y co-ordinate
Landing overrun	small	48	32
	large	372	265
Take-off overrun	small	21	17
	large	112	100
Total		**553**	**414**

Type of occurrence	Aircraft size	Nr of Data points	Nr with y co-ordinate
Landing undershoot	small	116	88
	large	187	134
Total		**303**	**222**

Figure 5.4 and Figure 5.5 provide a scatter plot of the location data samples for the overruns and the undershoots differentiated for the factors flight phase and aircraft size.

Figure 5.3 Annual number of occurrences in the location data sample

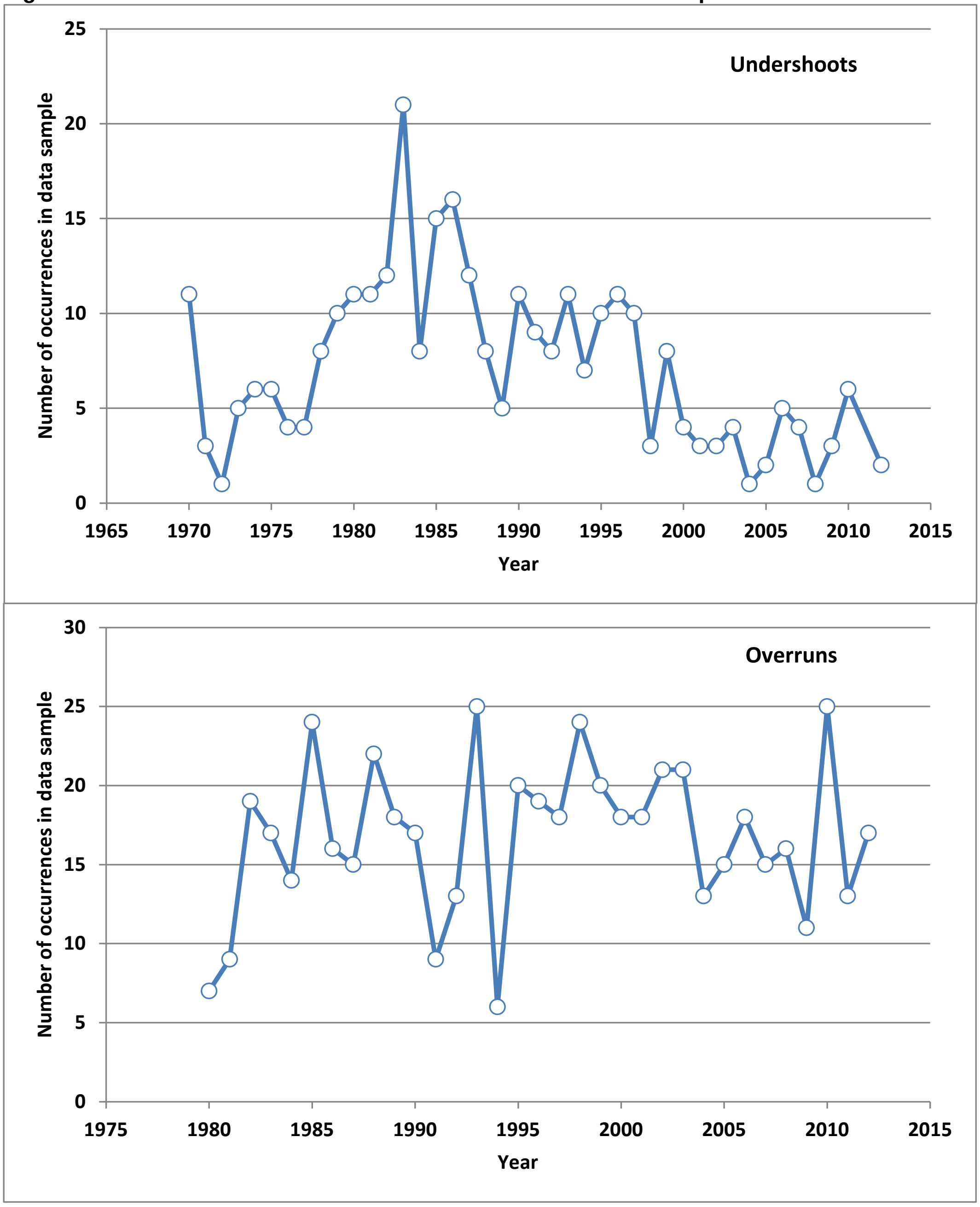
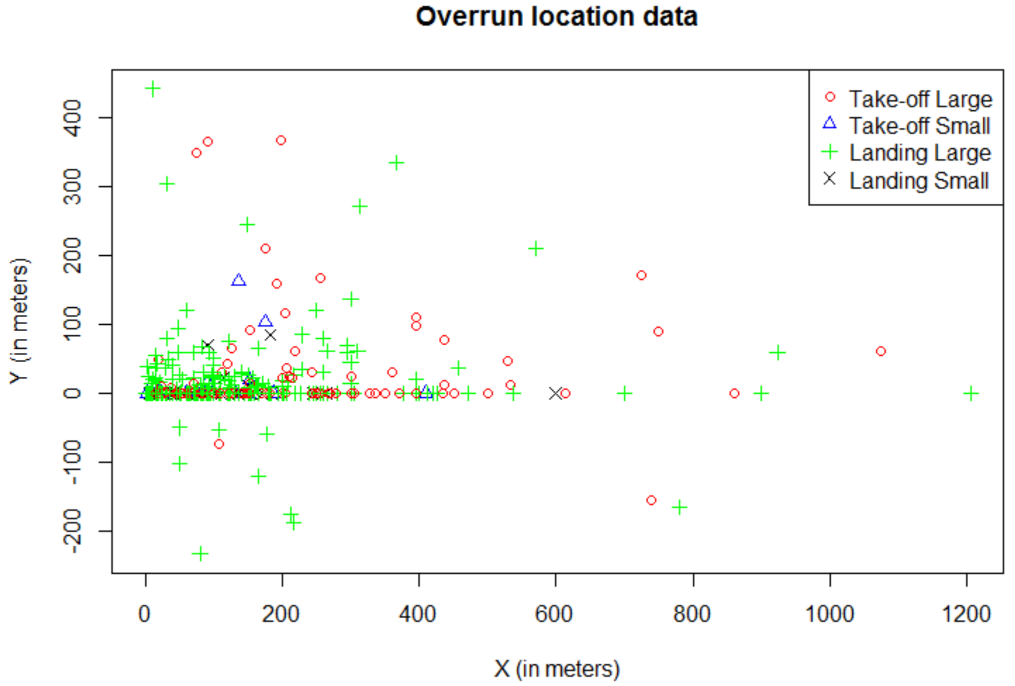
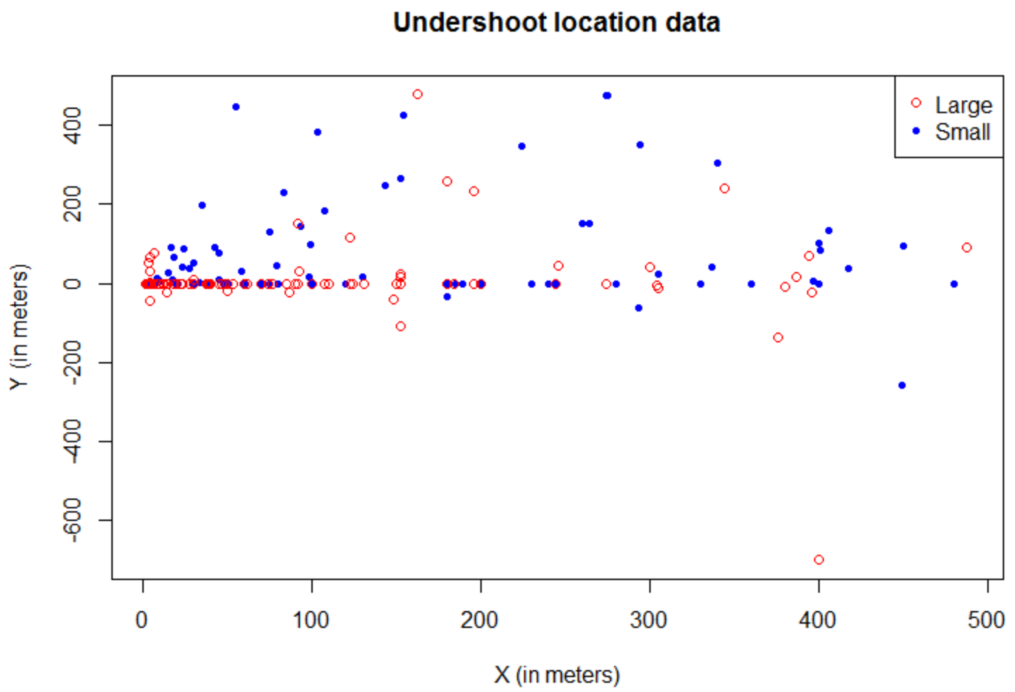


Figure 5.4 Scatter plot of the overrun accident locations



The overrun sample contains 276 entries with a y coordinate of zero (67%), 127 entries with a positive y coordinate, 11 entries with a negative y coordinate. For the undershoot data 140 entries (63%) has a zero y coordinate, 67 entries a positive y coordinate and 15 a negative y coordinate.

Figure 5.5 Scatter plot of the undershoot accident locations



5.2 Approach

5.2.1 Introduction

The location of an occurrence is given by a pair (x, y) where the x coordinate (the longitudinal distance) can take any positive value and y coordinate (the lateral distance) any value. The model for the location of a specific type of occurrence consists of a two-dimensional probability density function $f_{XY}(x, y)$. This function describes the probability that an occurrence ends at the location (x, y). The two-dimensional probability density function is established using the product rule (see for example [Ross (1998)]):

$$f_{XY}(x, y) = f_X(x) \cdot f_{Y|X}(y|X = x).$$

Here, $f_X(x)$. is the probability density function for the x-coordinate and $f_{Y|X}(y|X = x)$ is the conditional probability density function of y-coordinate given the x-coordinate. Using this form, it is made possible that the parameters of the probability density function $f_{Y|X}(y|X = x)$ depend on x. For example, the variance of the probability density function of the y-coordinate may be taken to increase with the distance x from the runway threshold.

To obtain a model for each type of occurrence first a specific type of model (a two-dimensional probability density function) has to be chosen. The form of the functions $f_X(x)$ and $f_{Y|X}(y|X = x)$ is obtained by previous experience and inspection of the data. In order to choose the correct type of model, two steps are taken. First, a non-parametric analysis is performed on issues that are observed in the data. Second, based on the results of this non-parametric analysis, the parameters of the proposed models are fitted in the parametric analysis.

5.2.2 Non-parametric analysis

Inspection of the data, as given in Section 2, leads to the following issues that need to be analysed:

1. The symmetry of the y coordinates;
2. The dependency between the x and the y coordinate;
3. Which factors are significant;
4. The amount of y coordinates close to the runway.

The symmetry of the y coordinates is analysed by first trying to obtain a good explanation from an operational point of view. If the lack of symmetry can be explained, this should be dealt with in the model.

To analyse the dependency between the x and the y coordinate, the correlation coefficient is computed. The correlation coefficient is given by:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

With $\bar{x}$ the average of the x coordinates and $\bar{y}$ the average of the y coordinates of the data sample. The correlation coefficient gives a value between -1 and 1 where 1 is total positive correlation, 0 is no correlation, and −1 is total negative correlation. It is widely used as a measure of the degree of linear dependence between two variables. When the value is close to zero it is concluded that there is little or no dependency and the two-dimensional probability density function can be written as:

$$f_{XY}(x,y) = f_X(x) \cdot f_Y(y).$$

To analyse if a factor is significant, the data sample with and without that factor are compared. The comparison is done using the Kolmogorov-Smirnov test. The Kolmogorov–Smirnov test compares a sample with a reference probability distribution (one-sample K–S test), or compares two samples (two-sample K–S test). The Kolmogorov–Smirnov statistic quantifies a distance *D* between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution, or between the empirical distribution functions of two samples. Depending on the size of the sample, a critical value is given for *D*. If *D* is below the critical value, the null hypothesis that the two distributions are equal is not rejected. If *D* is above the critical value, the null hypothesis that the two distributions are equal is rejected and it is concluded that the distributions are different. Besides the statistic, a p-value is computed. The p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. The null hypothesis is rejected when the p-value turns out to be less than a certain significance level, namely 0.05. More details on the Kolmogorov–Smirnov test can be found in any standard book on statistics, e.g. [Lawless, (1982)].

The analysis of these issues analysis, the non-parametric analysis, is performed in section 5.3.

5.2.3 Parametric analysis

After the above described non-parametric analysis, a number of distinct data samples are obtained for which probabilistic density functions are fitted. Based on our experience, often a Weibull distribution is selected as a function [Piers et al., (1993); TRB, (2008); Weijts et al., (2004)]. The survival function $R(x)$ of the Weibull distribution is given by:

$$R(x) = e^{-ax^n}.$$

This function is dependent on the parameters *a* and *n*. The Weibull distribution is often represented by scale parameter η and shape parameter β instead of a and n. The representations can be transformed into each other via the equations $n = \beta$ and $a = (1/\eta)^{\beta}$.

The survival function $R(x)$ can be obtained from the probability density function $f(x)$ by $R(x) = \int_x^{\infty} f(t)dt$ and can in this report be interpreted as the probability that the location of the occurrence is more than x.

The values of the parameters of a probability density function are estimated using the provided data samples through the maximum likelihood method (see for example [Ross, (1998)]).

Besides the Weibull distribution, a beta distribution is also used to model the undershoot occurrence, since its domain is bounded between 0 and 1. It can be applied for an arbitrary data range by scaling, i.e. in the current undershoot data case by dividing the X coordinates by 500m. The beta distribution has two parameters *a* and *b*, and its probability density function is given by:

$$f(x)=\frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}x^{a}(1-x)^{b}$$, where $\Gamma(\cdot)$ denotes the gamma function.

The datasets contain many entries with a zero y coordinate caused by e.g. an approximation of the aircraft position by the reporter when the aircraft is close to the extended centreline. In reality most aircraft will not exactly end on the extended centreline. A way to deal with this phenomenon is to consider the dataset as *left-censored*. This means that all values smaller than a threshold T are not exactly observed, but it is known that these entries have a value smaller than T, so |y| <= T. From previous experience, a typical width of a runway is considered to be a good threshold: T = 45 meters (150ft). The approach of fitting a left-censored data sample is described in more detail in [Lawless, (1982)].

The fitting of the probabilistic density functions, the parametric analysis, is performed in Section 5.4.

5.3 Non-parametric analysis results

Inspection of the data, has led to the following issues that need to be analysed:
1. The symmetry of the y coordinates;
2. The dependency between the x and the y coordinate;
3. Factors that are relevant for the location of the occurrence;
4. The amount of y coordinates close to the runway.

5.3.1 Symmetry of y coordinates

Although each of the two samples contains significantly more points with a positive y value than a negative value, there is from an operational point of view no reason why an aircraft veers more often to the left or to the right of the extended centreline. One possible explanation is that in a number of occurrences only the lateral distance to the runway is recorded and not whether it is to the left or the right of the runway. This has been a common observation in other studies e.g. [Pikaar, de Jong, and Weijts, (2000)]. There is also no physical reason to assume that the aircraft would end up more often to the left or right of the extended runway centre line. It is therefore assumed that the lateral locations are symmetrical with respect to the runway extended centreline and the absolute value of y, i.e. |y|, is used in the analysis.

5.3.2 Dependency between x and y

To assess the dependency between the longitudinal co-ordinate x and the lateral co-ordinate |y|, the correlation coefficient is computed. The correlation coefficient is a value between -1 and 1 that indicates the amount of dependency between x and |y|. The higher the absolute value of the coefficient, the stronger the dependency.

Table 5.2 The correlation coefficient of the different samples

Type of occurrences	Aircraft size	Correlation co-efficient
Landing overrun	small aircraft	0.0548
	large aircraft	0.1418
	all	0.14208
Take-off overrun	small aircraft	0.1311
	large aircraft	0.1327
	all	0.1438
All overruns		0.1546
Landing undershoot	small aircraft	0.1163
	large aircraft	0.4692
All undershoots		0.3230

The correlation coefficients between x and |y| are given in Table 5.2. The coefficients are 0.1420 for the landing overruns, 0.1438 for the take-off overruns and 0.3230 for the landing undershoots. Although these values are not zero, they are still small rather small. Only landing undershoots of large aircraft has a higher correlation coefficient, namely 0.4692.

In the [TRB, (2008)], similar results were found and in the report the following statement is made on page 32:

> *Although the correlation between x and y locations is not zero [...], the level is relatively low; it was assumed that the correlation is not important. This leads to the assumption that the transverse location distribution of accidents is fairly constant along the longitudinal locations from the threshold.*

Therefore, x and |y| can be assumed to be independent. Hence, the remainder of the analysis is performed on x and |y| separately. So, the location model can be written as:

$$f_{XY}(x,y) = f_X(x) \cdot f_Y(y)$$

5.3.3 Factor analysis

To assess whether the size of the aircraft and/or the flight phase are factors that influence the data sample, the distributions of longitudinal and lateral coordinates of the different sets are compared using the two-sample Kolmogorov–Smirnov test.

Factors related to overruns

Three factors related to overruns are investigated: the aircraft size, the flight phase and the runway length in relation to the aircraft performance.

Aircraft size

For the overrun data, the subset of small aircraft is compared to the subset of large aircraft by means of the two-sample Kolmogorov–Smirnov test. The test is performed for both the x coordinate and the |y| coordinate. The result is shown in Table 5.3.

Table 5.3 Comparison between large aircraft and small aircraft for the overrun sample

Coordinate	Kolmogorov-Smirnov statistic (D)	p-value
x	0.1547	0.1111
|y|	0.1698	0.1658

For the x coordinate and the |y| coordinate the Kolmogorov–Smirnov statistics are small and the p-values are larger than 0.05. Therefore, it is concluded that the size of the aircraft (large or small) does not influence the datasets. Therefore, no distinction between small or large aircraft is made anymore and they are combined into one data sample.

Landing and take-off

Next, the two-sample Kolmogorov–Smirnov test is applied to the subset of landing overruns compared to the subset of take-off overruns (for all aircraft), see Table 5.4.

Table 5.4 Comparison between take-off and landing for the overrun sample

Coordinate	Kolmogorov-Smirnov statistic (D)	p-value
x	0.2450	**1.084e-05**
|y|	0.0767	0.7073

For the x coordinate the Kolmogorov–Smirnov statistic is large (p-value is smaller than 0.05). Therefore, it is concluded that the flight phase (take-off or landing) influences the datasets, namely in the longitudinal direction. So, in the remainder of the analysis a distinction is made between landing overrun and take-off overrun occurrences.

Runway length and aircraft performance factors

It can be argued that the overrun distance is influence by the kinetic energy state of the aircraft when it leaves the runway. In particular the longitudinal distance could be affected as the lateral position is mainly influenced by pilot control inputs and therefore more or less random.

The energy level is determined by the mass (or size) of the aircraft and its ground speed when the aircraft exits the runway. The exit speed is often not known. This speed could be related to the margin that exists between the available runway length and the required distance during take-off or landing. For a part of the total data sample with overrun locations the runway length and a standard take-off or landing distance was known. In Figure 5.6 and Figure 5.7 the difference between the runway length and the standard take-off or landing distance is plotted against the longitudinal overrun length for small and large aircraft.

Figure 5.6 Correlation of longitudinal take-off overrun position versus takeoff distance margin

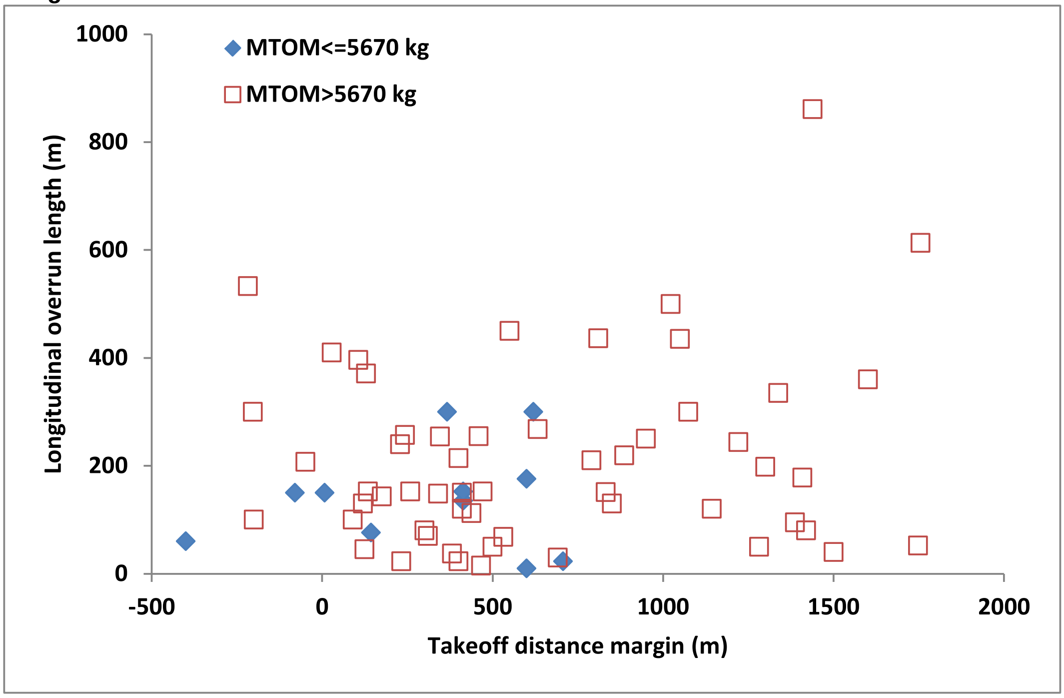
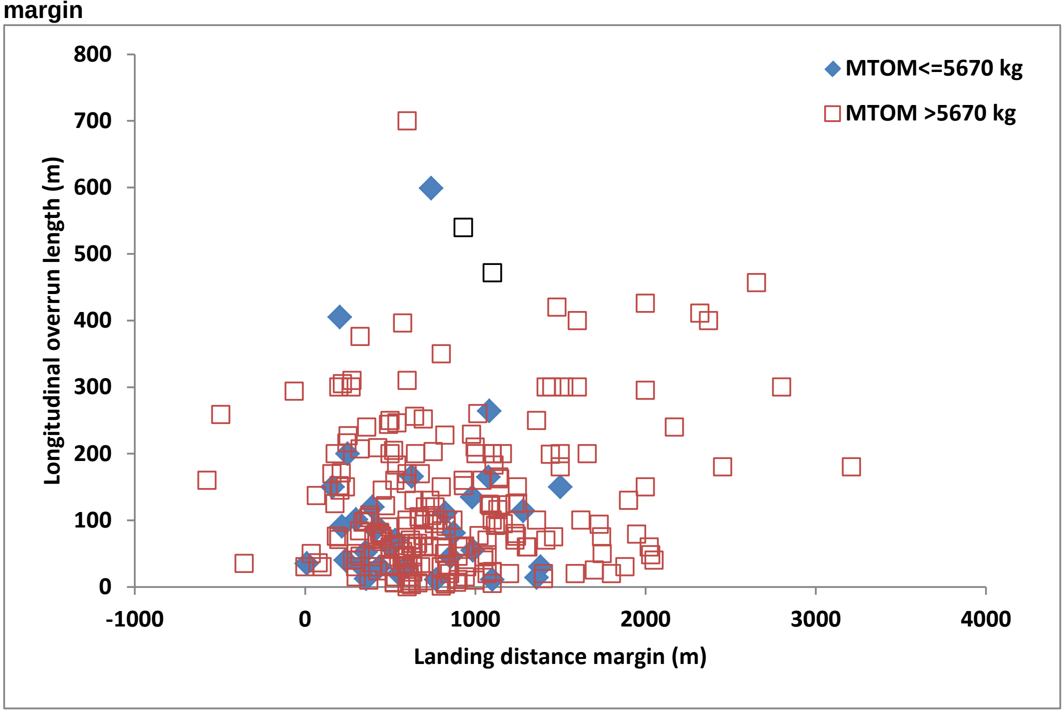


Figure 5.7 Correlation of longitudinal landing overrun position versus landing distance margin



It becomes clear from these plots that there is no clear correlation between the take-off/landing distance margins and the longitudinal overrun length. The reason for this could be that even if there is a large take-off/landing distance margin the exit speed could still be high if the pilot doesn't apply optimum braking. Indeed data on overruns shows that late or improper use of stopping devices is often a causal factor. Also when the runway is slippery the stopping forces are much less than on dry runway. In the above analysis the standard distance is for a dry runway only. However when accounting for the runway conditions by increasing the standard dry runway distances with typical penalties for the runway condition, did not improve the correlation. Apparently there are more factors that determine the longitudinal overrun position. For instance the aircraft is stopped after exiting the runway end either by or a combination of the following:

- The stopping forces on the aircraft (e.g. from tire braking forces, thrust/propeller reversers, and aerodynamic forces);
- Collision of the aircraft with an object; or
- Collapse of the landing gear (nose and/or main gear).

These factors can result in different overrun locations for the same aircraft under the same conditions and on the same runway. This could explain why it is difficult to correlated overrun distance with runway and aircraft parameters.

Approach type and runway code

It could be argued that approach type flown or runway code could influence the landing overrun location. Only for a part of the occurrences from the location data sample these elements are known. The results are shown in Figure 5.8 and Figure 5.9. Note that the absolute value of the lateral position (y) is used here (see also section 5.3.1). The data plots show there is no apparent influence of either approach type flown or runway code on the landing overrun location.

Figure 5.8 Comparison approach type and landing overrun locations

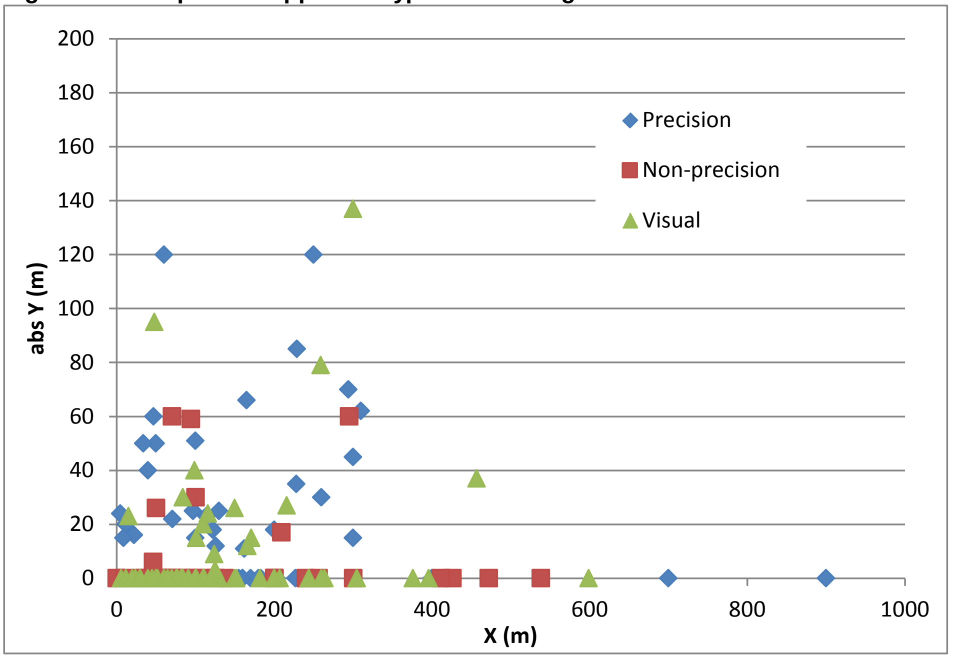
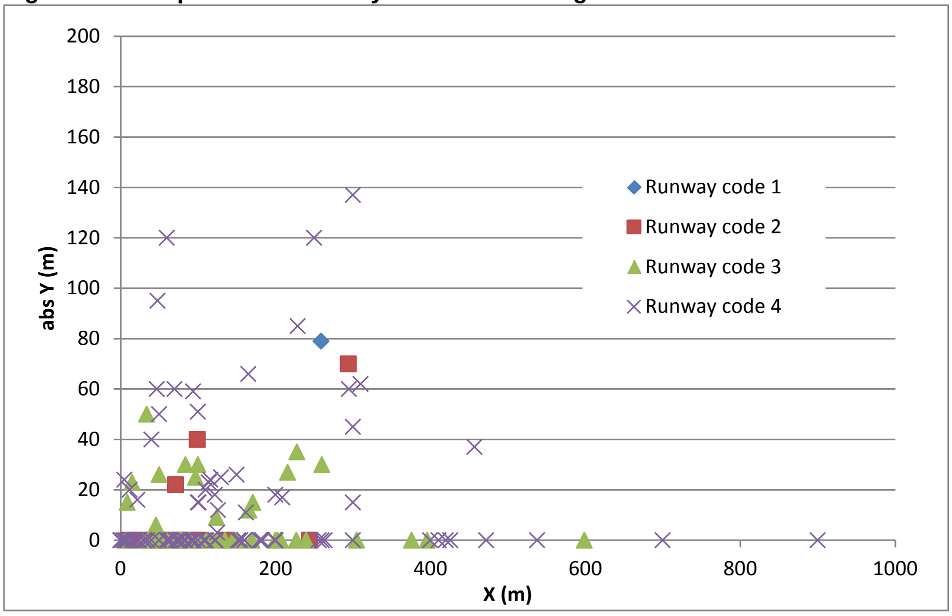


Figure 5.9 Comparison of runway code and landing overrun locations



Factors related to undershoots

For the undershoot data, the subset of small aircraft is also compared to the subset of large aircraft by means of the two-sample Kolmogorov–Smirnov test, with the test results summarized in Table 5.5.

Table 5.5 Comparison between large aircraft and small aircraft for the undershoot sample

Coordinate	Kolmogorov-Smirnov statistic (D)	p-value
x	0.1969	**0.007749**
|y|	0.318	**4.316e-05**

For both the x coordinate and the |y| coordinate the Kolmogorov–Smirnov statistics are large and therefore p-values are both small. Both are smaller than 0.05 and so the null hypothesis of equal distributions for large and small aircraft is rejected for each of the two coordinates. It is concluded, therefore, that the distribution of the location varies with the aircraft type, small or large. Thus, in the remainder of the analysis a distinction is made between undershoots by small aircraft and large aircraft.

It could be argued that the approach type or runway code could influence the location of the aircraft during an undershoot. Only for a part of the occurrences from the location data sample these elements are known. Unfortunately for the undershoots there are insufficient data to make any kind of meaningful comparison or formal statistical analysis to discriminate in these matters.

5.3.4 Number of data points close to the runway

The datasets contain many entries with a zero |y| coordinate: 67% for overruns and 63% for undershoots. This is an unrealistically high amount.

This phenomenon is handled by assuming that all values smaller than a typical runway width, which is T=45 meters (= 150ft), are not exactly observed, but it is known that these entries have a value smaller than T, so |y| <= T. This is referred to as left-censored data. In the parametric analysis, this is used for the lateral coordinates.

The amount of data entries with a |y| coordinate smaller than a typical runway width 45 meters (= 150ft), is 85% for the overruns and 79% for the undershoots.

5.3.5 Conclusion

In the remainder of the analysis, the following 4 data samples are distinguished:

- Landing overrun locations;
- Take-off overrun locations;
- Landing undershoot locations for small aircraft;
- Landing undershoot locations for large aircraft.

On these four data samples, probability density functions are fitted in the next section. For the analysis |y| is used and the |y| values are considered to be a left-censored data sample.

There was no correlation found between the overrun distance with runway and aircraft parameters such as size, approach type flown, and field performance.

5.4 Parametric analysis results

In this section probability density functions are fitted for the longitudinal distance x and lateral distance |y|. The results for each occurrence type are presented next.

5.4.1 Overrun occurrences

Table 5.6 shows the resulting parameter estimates for the two Weibull probability distribution models for the two overrun cases. Following the parameter estimation, the Kolmogorov-Smirnov test was applied to each case to check the quality of the fit of the resulting model.

The results in Table 5.6 show that the fitted Weibull distributions correspond well to the data samples. In all cases, the Kolmogorov-Smirnov statistics are small and therefore the p-values are well above 0.05. Therefore it is concluded that the data sets follow a Weibull distribution.

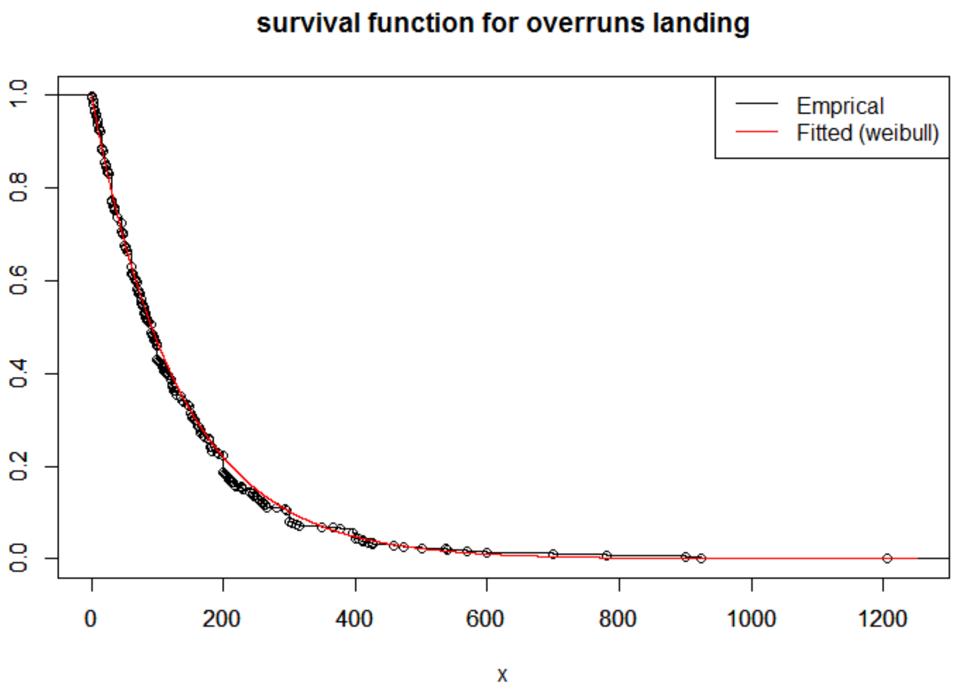
Table 5.6 Weibull distribution fitting results for the overrun samples

Data sample		Nr Samples	scale (η)	shape (β)	KS	p-value
Landing overrun	x	420	131.6715	1.0006	0.0382	0.5708
	|y|	297	10.8228	0.4802	0.0155	0.1418
Take-off overrun	x	133	224.2221	1.1268	0.0659	0.6110
	|y|	117	15.3583	0.4666	0.0261	0.1618

In Figure 5.10 a comparison is made between the empirical survival function, based on the actual data, in black and the fitted survival function of the Weibull distribution in red for landing overruns As can been seen from the graph, the fitted Weibull distribution matches the data very well which is supported by the small Kolmogorov-Smirnov statistics. The vertical blue line in the bottom graph denotes the threshold T for the left-censored data.

Figure 5.11 shows the same results but than for the take-off overrun. Also, here the fitted Weibull distribution matches the data very well which is supported by the small Kolmogorov-Smirnov statistics.

Figure 5.10 Comparison of the empirical and Weibull fitted survival functions for the x coordinate (top figure) and |y| coordinate (bottom figure) of the landing overrun sample



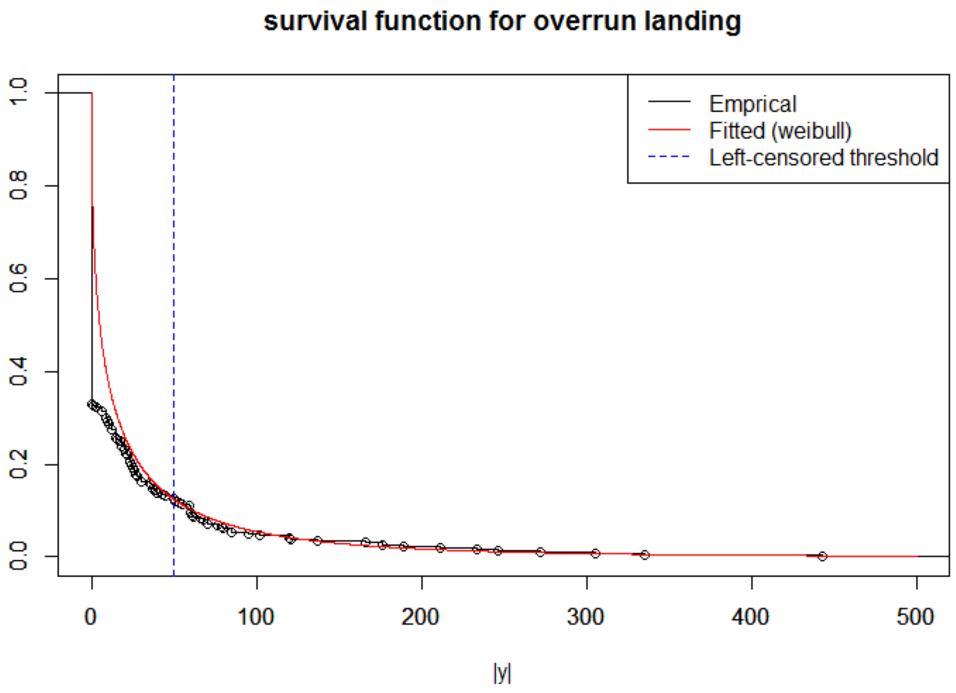
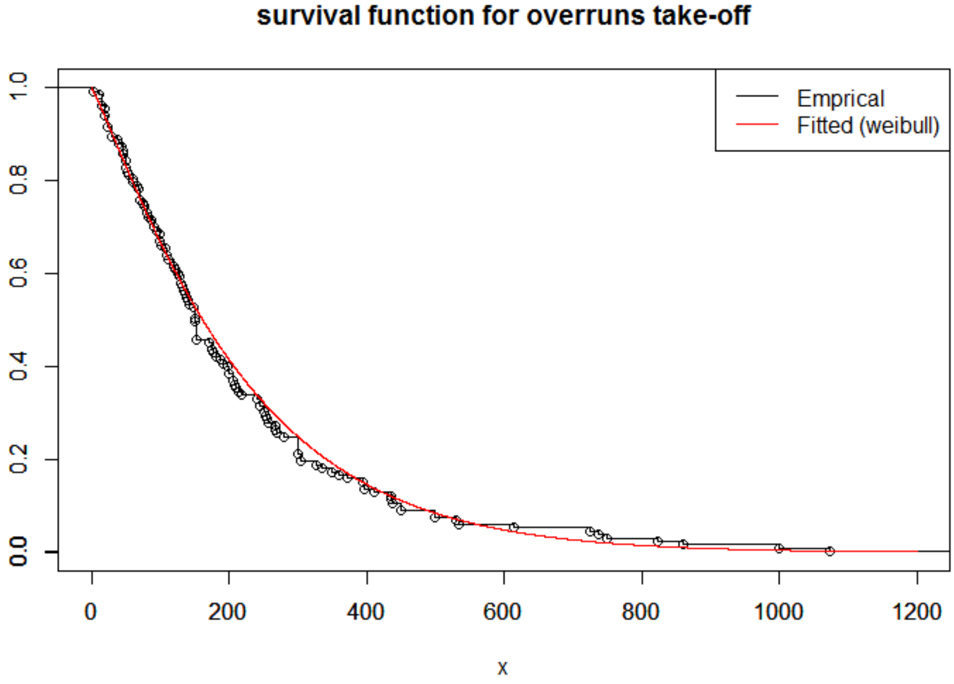
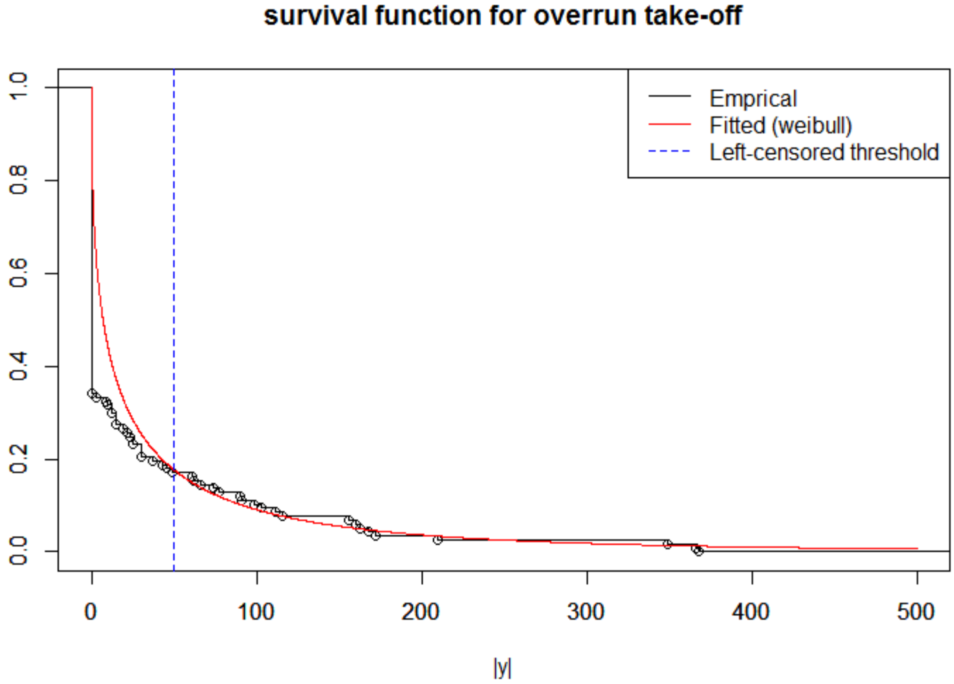


Figure 5.11 Comparison of the empirical and Weibull fitted survival functions for the x coordinate (top figure) and |y| coordinate (bottom figure) of the take-off overrun sample





5.4.2 Undershoot occurrences

Table 5.7 shows the resulting parameter estimates for the two Weibull probability distribution models for the two undershoot cases. Following the parameter estimation, the Kolmogorov-Smirnov test was applied to each case to check the quality of the fit of the resulting model.

The results in Table 5.7 show that the fitted Weibull distributions correspond well to the data samples. In all cases, the Kolmogorov-Smirnov statistics are small and therefore the p-values are well above 0.05. Therefore it is concluded that the data sets follow a Weibull distribution.

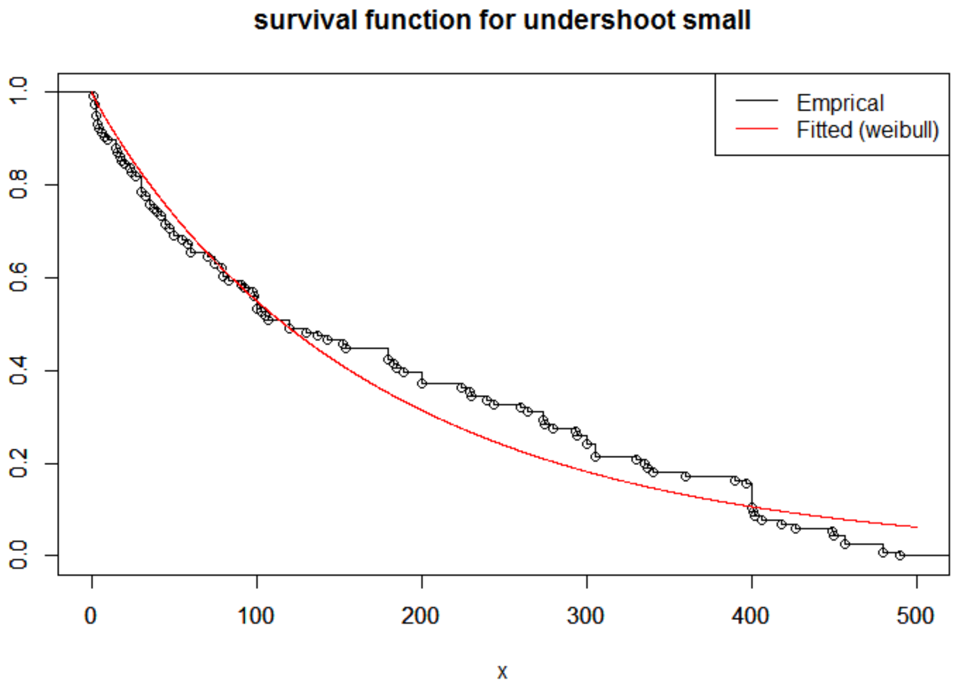
Table 5.7 Weibull distribution fitting results for the undershoot samples

Data sample		Nr Samples	scale (η)	shape (β)	KS	p-value
Landing undershoot small	x	116	171.6533	0.9546	0.1014	0.1839
	|y|	88	50.9033	0.5580	0.0427	0.2944
Landing undershoot large	x	187	109.2475	0.8030	0.0765	0.2240
	|y|	134	4.3444	0.3176	0.0158	0.0744

In Figure 5.12 a comparison is made between the empirical survival function, based on the actual data, in black and the fitted survival function of the Weibull distribution in red for the landing undershoot of small aircraft. As can been seen from the graph, the fitted Weibull distribution matches the data well which is supported by the small Kolmogorov-Smirnov statistics. The vertical blue line in the bottom graph denotes the threshold T for the left-censored data.

Figure 5.13 shows the same results but than for the landing undershoot of large aircraft. Also, here the fitted Weibull distribution matches the data well which is supported by the small Kolmogorov-Smirnov statistics.

Figure 5.12 Comparison of the empirical and Weibull fitted survival functions for the x coordinate (top figure) and |y| coordinate (bottom figure) of the undershoots of small aircraft



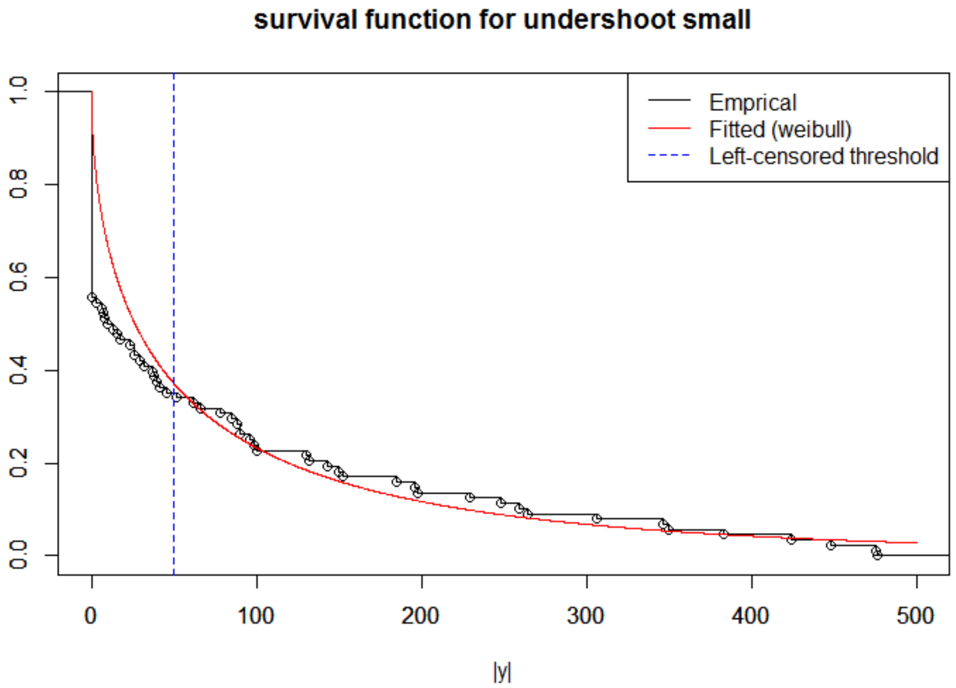
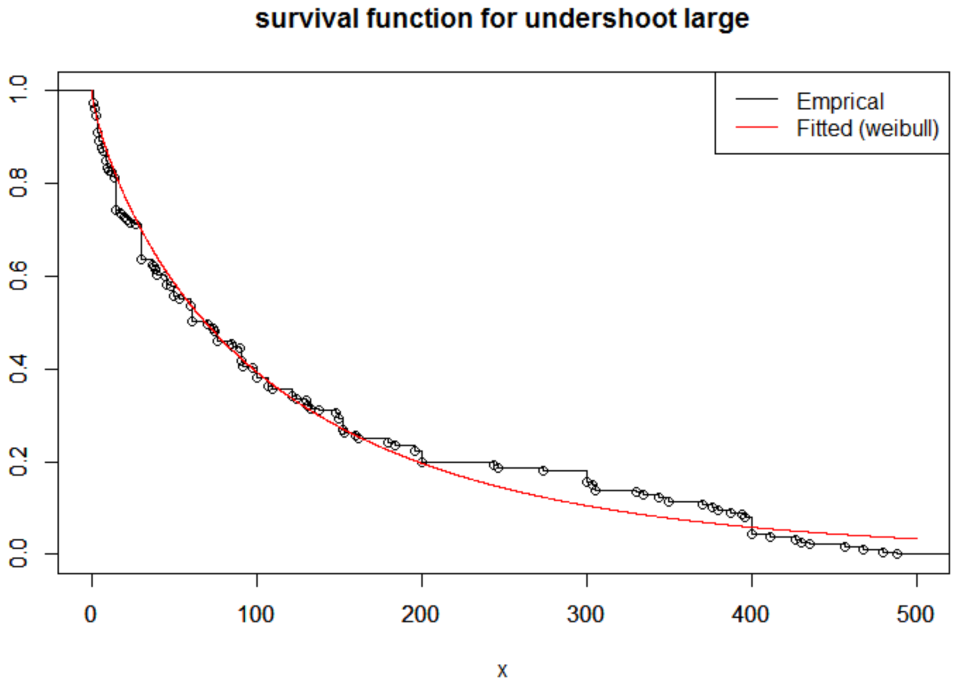
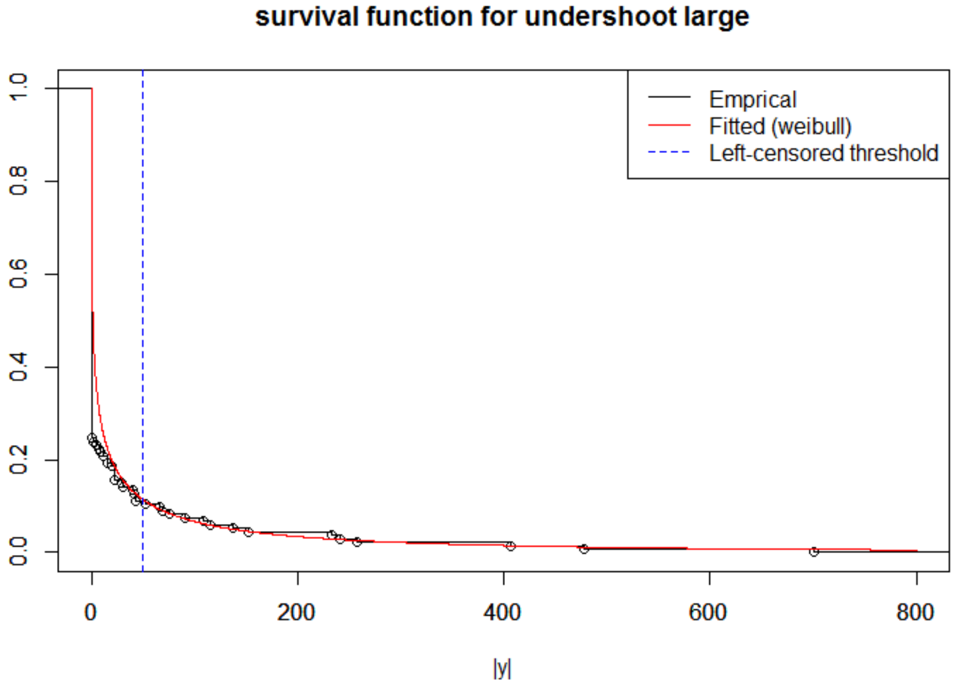


Figure 5.13 Comparison of the empirical and Weibull fitted survival functions for the x coordinate (top figure) and |y| coordinate (bottom figure) of the undershoot of large aircraft sample





An undershoot has been defined as a landing occurrence that has occurred at no more than 500m before the threshold. Therefore, the x coordinates of the undershoots are bounded between 0m and 500m. Even though the null-hypothesis of a Weibull distribution is not rejected by the Kolmogorov-Smirnov test, the Weibull distribution is not bounded by 500m. Hence, a proportion of the distribution is above 500m: for the large aircraft sample this is 3.36% and for the small aircraft sample it is 6.24%.

A beta distribution is potentially a good alternative to the Weibull distribution, since its domain is bounded between 0 and 1. It can be applied for an arbitrary data range by scaling, i.e. in the current undershoot data case by dividing the x coordinates by 500m. Table 5.8 below shows the results for the fitting of the data.

Table 5.8 Beta distribution fitting results for the undershoot samples

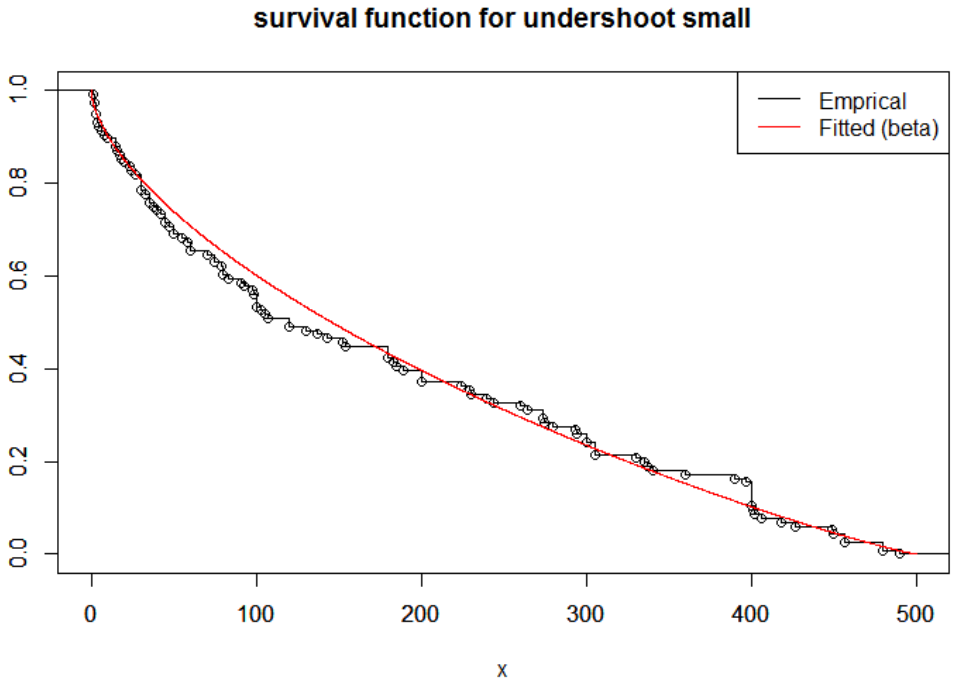
Data sample		Nr	a	b	KS	p-value
Landing undershoot small	x/500	116	0.6170	1.1218	0.0766	0.4805
Landing undershoot large	x/500	187	0.5331	1.4913	0.0948	0.0651

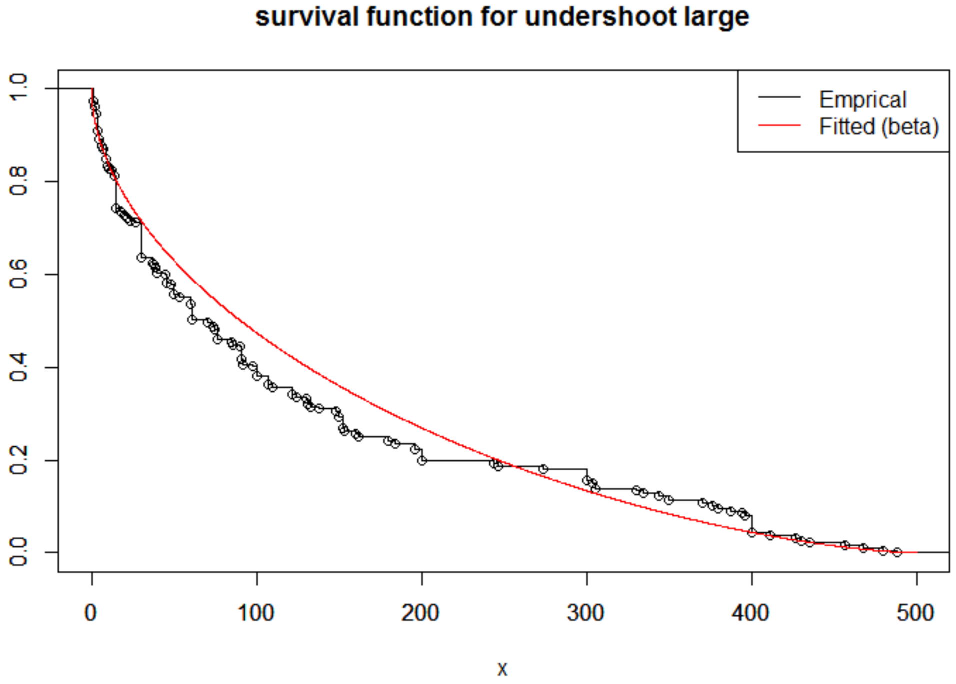
The p-values for both samples are above 0.05, so it is assumed that the data follow a beta distribution. For the large aircraft sample, the value is just above 0.05, while the fitted Weibull distribution gives a slightly higher p-value.

In Figure 5.14 a comparison is made between the empirical survival function and the fitted Weibull distribution for the x coordinate for the landing undershoot for small aircraft. When comparing these figures to top figures of Figure 5.12 and Figure 5.13, it can be seen that the beta distribution fits slightly better for the undershoots of small aircraft and slightly worse for the undershoots of large aircraft.

As the Weibull distribution is not bounded by 500m a proportion of the distribution is above this 500m. It is argued here that this gives a potential mismatch when combining the probability location models with the undershoot occurrence probability models. Therefore it is decided to use the Beta distribution for the longitudinal (x) position of undershoots instead.

Figure 5.14 Comparison of the empirical and beta fitted survival functions for the x coordinate for the undershoot of small aircraft (top figure) and for the undershoot or large aircraft (lower figure)





6 Development of overrun and undershoot occurrence probability models

Occurrence probability is one of the components of the risk assessment model for runway safety areas to be developed. A logistic regression model for occurrence probability will be worked out in this section. The model expresses the probability of an overrun or undershoot occurring as a function of a number of potentially relevant variables such as runway condition, wind speed/direction, etc. identified in sections 1 and 1. A total of six different models are developed for the following types of events:

- Runway overruns during take-off of aircraft with an MTOM larger than 5670 kg;
- Runway overruns during take-off of aircraft with an MTOM smaller than or equal to 5670 kg;
- Runway overruns during landing of aircraft with an MTOM larger than 5670 kg;
- Runway overruns during landing of aircraft with an MTOM smaller than or equal to 5670 kg;
- Runway undershoots during landing of aircraft with an MTOM larger than 5670 kg; and
- Runway undershoots during landing of aircraft with an MTOM smaller than or equal to 5670 kg.

Parameters of each model will be estimated by using accident data and normal operations data from the portion of airspace and period of time defined in sections 1 and 1.

The models and approach developed here are similar to those utilised in Transportation Research Board study [Ayres et. al., (2011)].

6.1 Background on logistic regression

The occurrence probability will be modelled by means of a logistic regression model. This means that the logarithm of the odds (logits) of an event is modelled as a linear function of a number of variables that are potentially considered to be relevant to the occurrence, or not, of an event. The odds of an event are defined as the ratio of the probabilities of an event occurring, and it not occurring. When the probability of an event occurring is denoted by $p = p(X_1, X_2, \cdots, X_n)$, then a logistic regression model is of the following form,

$$log\left(\frac{p}{1-p}\right) = a_0 + a_1X_1 + \cdots + a_nX_n \quad (1)$$

Solving of eq. (1) for the occurrence probability $p = p(X_1, X_2, \cdots, X_n)$ gives

$$p = p(X_1, X_2, \cdots, X_n) = \frac{1}{1+e^{-(a_0+a_1X_1+\cdots+a_nX_n)}} \quad (2)$$

The use of the logistic regression model dates back to the early 1960s. It is generally described for cohort studies, i.e. for studies in which a cohort of a given size, say, n, is observed over time and records are kept of cohort members either or not experiencing an event under the variables over the observation period. Though a cohort study is prospective by nature, it can equally well be used in a retrospective manner on the basis of historical data. A fairly straight-forward refinement of the retrospective cohort setting is where sampling is applied to either or both of the event and non-event movements[3]. In practice, sampling is mostly applied to the non-event flights because this may considerably reduce the amount of processing time at the cost of very little loss of accuracy. The importance of sampling is that it affects the logarithm of the odds in only a very simple way. Denote the sampling fractions of the event and non-event flights by π_1 and π_2 respectively and the event occurrence probability for the sampled flights by $p' = p'(X_1, X_2, \cdots, X_n)$. Using a prime also for the parameters of the logarithm of the odds for the sampled event movements, it can be shown that.

$$log\left(\frac{p'}{1-p'}\right) = a'_0 + a_1 X_1 + \cdots + a_n X_n \qquad (3)$$

where

$$a'_0 = log\left(\frac{\pi_1}{\pi_2}\right) + a_0 \qquad (4)$$

The above shows that the original logistic regression model of eq. (1) for the unsampled data can be obtained from the model in eq. (3) based on sampled data by substituting for a'_0 according to eq. (4) (and vice versa).

The two models in eqs. (1) and (2) are both referred to as logistic regression models whereas the model in eq. (1) is also referred to as a logit model. It is possible to extend the logistic regression model with terms describing the interaction between two (or more) of the variables.

Some alternative models are the linear regression model, the probit model, or the loglinear model. See e.g. [Ayres et al. (2011); Schlesselman, (1982)] for the advantages of the logistic regression model.

Some practical aspects

In practice, one may consider risk through various quantities, e.g. the probability of an event, the odds of an event, the logit or logarithm of the odds of an event, the relative odds of an event, or odds ratios. Two aspects of logistic regression are worth mentioning. Firstly, the logistic regression model eq. (2) allows evaluating the effect of an individual variable X_i on the probability of an event, adjusted (i.e. accounted) for the effects of the other variables. Because of the exponential relationship in eq. (2), there exists no simple relationship between the regression parameters a_i, differences ΔX_i in the variables X_i, and differences Δp in the probability of an event occurring. However, due to the linear relationship in the logit model eq. (1), it follows that a difference ΔX_i in an individual variable X_i translates linearly into a difference in the logit (or logarithm of the odds) of an event equal to $a_i \Delta X_i$ and thus in a change of $e^{a_i \Delta X_i}$ in the odds of an event, regardless of the values of the other parameters. Similarly, the relative odds or odds ratio for $X_i + \Delta X_i$ and X_i is given by $e^{a_i \Delta X_i}$. More generally, the relative odds for two movements with variables $X^* = (X_1^*, X_2^*, \cdots, X_n^*)$ and $X = (X_1, Xx_2, \cdots, X_n)$ is given by the following function $\psi(X^*, X)$ of X^* and X:

[3] Sampling in a logistic regression context is usually introduced for case-control studies, because the populations of cases and controls to sample from are known. For a conventional (prospective) cohort study, it is not known at the start which flights will develop into event and non-event flights. Determining suitable sampling fractions for the event and non-event flights is thus not possible. For a retrospective cohort study, however, it is precisely known what the event and non-event flights are, and sampling is thus quite feasible.

$$\psi(X^*, X) = e^{\sum a_i (X_i^* - X_i)} \qquad (5)$$

The other aspect worth discussing concerns the relative importance of variables. A large(r) value of a regression model parameter estimate $\hat{a}_i$ does not necessarily imply that the corresponding variable X_i is more important than the other variables, because the (variation in the) magnitude of the variable X_i also plays a part. The relative importance of variables may be compared in terms of standardized coefficients, expressed as multiples of the standard deviation of X_i, i.e. $\hat{a}_i^* = \hat{a}_i \sqrt{var(X_i)}$. A standardized coefficient $\hat{a}_i^*$ measures the change in the logit of an occurrence resulting from a change of one standard deviation in the variable X_i.

Indicator variables

The individual variables X_i, $i = 1, \cdots, n$, may be discrete or continuous and the ultimate model may contain a combination of continuous and discrete variables. An implicit assumption is that the variables have an appropriate scale of measurement. This may be a physical scale of measurement or a binary one representing for example the exposure/non exposure to a variable X_i in the form of $X_i = 1$ and $X_i = 0$ respectively. A special case is formed by categorical variables. As set out in e.g. [Hosmer and Lemesho, (2000)], a categorical variable with k "values" needs to be represented by $k - 1$ (binary) so-called indicator variables $R_1, R_2, \cdots, R_{k-1}$, say. One of the k values is taken as the reference value, represented by zero, for each of the $k - 1$ indicator variables $R_1, R_2, \cdots, R_{k-1}$, whereas the remaining values are represented by one for each of $R_1, R_2, \cdots, R_{k-1}$. This system ensures that each remaining value is compared with the reference value and is necessary to maintain the interpretation of the regression coefficients of the model in terms of odds and odds ratios. A set of indicator variables is often used to model continuous variables.

Model parameter estimation

The preferred approach to estimate the parameters of a logistic regression model is by means of the maximum likelihood estimation method [Schlesselman, (1982)]. The actual software used for the parameter estimation was the MATLAB mnrfit(X, Y) multinomial logistic regression function.

Model building

A key element of the model-building strategy concerns the (number of) variables X_i, $i = 1, \cdots, n$, to be incorporated into the logistic regression model. [Hosmer and Lemeshow, (2000)] provides some discussion of model building strategies for logistic regression modelling. In practise, the approaches can vary from purely statistical to purely operational. Rather than using either of these two extreme approaches, a (sound) combination of statistical criteria and operational insight into which variables are of importance should be used. For the current project, the potentially relevant variables have been identified under in sections 1 and 1.

A frequently used model-building approach is based on a stepwise selection of variables for inclusion into or exclusion from a model in a sequential way based solely on statistical criteria. [Hosmer and Lemeshow, (2000)] distinguishes between two main versions of the stepwise procedure, namely:

a) Forward selection with a test for backward elimination; and
b) Backward elimination followed by a test for forward selection.

A detailed algorithm for the first method of forward selection with a backward elimination test is described in [Hosmer and Lemeshow, (2000)]. [Ayres, (2011)] suggests, however, that the second method of backward elimination followed by a forward selection test is more capable of identifying relationships underlying the data. Following [Ayres, (2011)], a backward elimination method with forward selection test has been utilized in the current study. This method is generally convenient when the number of variables is moderate and one wants to consider whether one or a few variables should be dropped from an initial set of variables.

The backward elimination method may be summarized as follows. The backward method begins with successively removing each of the variables individually from the full set of n variables and performing a logistic regression for each subset of $n-1$ variables. For each of the models with $n-1$ variables, the change in two times the log likelihood is calculated with regard to the full model with n variables. Under the (null) hypothesis that the parameter pertaining to a variable removed is equal to zero, twice the change in the log likelihood has a chi-square distribution with one degree of freedom. For each of the models with $n-1$ variables, the corresponding p-values are then calculated. The lower a p-value, the less likely it is that the value of the parameter corresponding to the variable removed equals zero. Thus, the variable with the largest p-value is removed provided that this maximum p-value is larger than some "p to stay" value. If the maximum p-value is less than or equal to the "p to stay" value, then the process is ended. In logistic regression modelling, the "p to stay" value is usually taken somewhat larger than the traditional 5% level of significance of a statistical test. [Hosmer and Lemeshow, (2000)] suggests that a value of 0.20 to 0.25 might be appropriate. The latter value has been used for the logistic regression modelling application described in this report. Assuming that the process is not ended during the first backward step, it is then repeated for the remaining $n-2$ variables.

The backward elimination method also includes a forward selection process in addition to the backward elimination process. Forward selection begins once two variables have been eliminated. For each of the eliminated variables, the p-value associated with restoring the variable into the model is calculated. The variable with the lowest p-value is the candidate for restoration into the model. The criterion for this is that the pertinent p-value is less than "p to enter". Again, in logistic regression modelling, the "p to enter" value is usually taken somewhat larger than the traditional 5% level of significance in statistical testing. [Hosmer and Lemeshow, (2000)] recommends that a value in the range from 0.15 to 0.20 be used and the latter value has been adopted for the current work. Other values for "p to stay" and "p to enter" may also be trialled under the overall condition that "p to enter" < "p to stay".

In addition to the usual ending of the backward elimination method based on "p to stay" in the elimination process, the method is also ended when a variable is restored and eliminated in the next step.

6.2 Data

6.2.1 Introduction

This section presents the variables potentially considered for inclusion into the logistic regression models for the various cases of overruns during take-off, overruns during landing, and undershoots during landing. Each case is further subdivided on the basis of the aircraft MTOM being smaller than or equal to 5670 kg or greater than 5670 kg. The two categories of aircraft will be referred to as small and large respectively.

Some characteristics of the normal operations, i.e. non-occurrence movement, and occurrence movement data are also given. Each movement is characterized by a particular combination of values of the variables. These data were gathered for occurrence movements in section 1. For non-occurrence movements, such individual data were not directly available, but has been constructed by applying the occurrence probabilities of the individual variables to the total number of non-occurrence movements for each case, on the assumption of the variables being (more-or-less) independent.

6.2.2 Overruns during take-off

Table 6.1 shows in its left-most column the candidate variables that have been considered for inclusion in the logistic regression modelling for overruns during take-off, i.e. for both the occurrence and non-occurrence movements. In addition, it shows the occurrence probabilities for each variable during normal operations or non-occurrence movements, subdivided into movements of large and small aircraft. Notice that the occurrence probabilities for the two subdivisions are equal for the variables Elevation ≥ 500 m, Runway slope less than -1%, and Take-off distance margin less than or equal to 100 m.

Table 6.1 Variables to be considered for logistic regression modelling of overrun risk during take-off and their occurrence probabilities during normal operations for large and small aircraft

	Occurrence probability during normal operations (non-occurrence movements)	
Variable	MTOM >5670 kg	MTOM ≤ 5670 kg
Elevation ≥ 500 m	0.05	0.05
Dry runway	0.89	0.81
Wet runway	0.08	0.15
Contaminated runway	0.03	0.04
Tailwind between -5 and 0 kts	0.13	0.16
Tailwind < -5 kts	0.01	0.02
Headwind (≥ 0 kts)	0.86	0.82
Runway slope less than -1%	0.0026	0.0026
Take-off distance margin less than or equal to 100 m	0.05	0.05

All variables other than runway and wind conditions are binary exposure/non-exposure variables characterized by the values 1 and 0 respectively. This results in 3 (ordinary) binary variables with a total of $2^3 = 8$ states. The three possible values of runway condition require two (binary) indicator variables R_1 and R_2. A dry runway condition is taken as the reference state characterized by a value of 0 for both R_1 and R_2. The three runway conditions are then represented by the following three combinations of R_1 and R_2 states:

R_1	R_2	
0	0	Dry runway
1	0	Wet runway
0	1	Contaminated runway

Similarly, the three possible values of head or tailwind require two (binary) indicator variables S_1 and S_2. Tailwind between -5 kts and 0 kts is taken as the reference state characterized by a value of 0 for both S_1 and S_2. The three wind conditions are then represented by the following three combinations of S_1 and S_2 states:

S_1	S_2	
0	0	Tailwind between -5 kts and 0 kts
1	0	Tailwind < -5 kts
0	1	Headwind (≥ 0 kts)

Thus, each of the nine possible combinations of the three runway conditions (dry, wet, contaminated) and the three wind conditions (tailwind between -5 kts and 0 kts, tailwind < -5kts, headwind (≥ 0)), is represented by one of the three times three possible states for the pair of runway condition indicator variables and wind condition indicator variables. Each of these nine states needs to be combined with each of the 8 states of the (ordinary) binary variables Elevation, ..., Take-off distance margin less than or equal to 100m, resulting in a total of $9 \times 8 = 72$ different states. See Table 6.2 , which also shows the numbers of occurrence and non-occurrence movements which were obtained from the NLR Air Safety database for the period 1990-2012.

Table 6.2 Some characteristics pertaining to the take-off data

Characteristic	Value	
	MTOM ≥ 5670 kg	MTOM < 5670 kg
Non-occurrence movements	564,736,800	60,764,539
Occurrence movements	68	57
Total number of movements	564,736,868	60,764,596
Number of (ordinary) binary variables	3	
Number of binary states	8	
Number of poly(3)-tonomous variables	2	
Number of indicator variables	2 x 2	
Number of indicator variable states	3 x 3	
Total number of variables	7	
Total number of states	72	

The parameter estimation algorithm requires for each state the (expected) number of occurrences for the occurrence movements as well as for the non-occurrence movements. For the non-occurrence movements, the expected number of occurrences given a state is computed as the product of the number of non-occurrence movements and all the probabilities associated with each (real or indicator) variable's value represented in the state[4]. However, rather than using the actual number of non-occurrence movements, a synthetic number of n non-occurrence movements is used,

4 This process may lead to the following artefact. When the product of the probabilities is very small for a particular state, the computed expected number of non-occurrence movements may, when rounded, be equal to zero. If the occurrence data would have no occurrence movements for that same state, both the numbers of occurrences and non-occurrences for the particular state would be equal to zero, effectively meaning that there is no valid observation for that state. This particular state then needs to be removed from the full set of states.

representing sampling of the non-occurrence movements. Specific values used will be given in the Results section (section 6.3). The correction for the intercept parameter a_0 given in eq. (4) is used to account for the effect of sampling. For the occurrence movements, the number of occurrences of each state is simply counted from the data.

In order to avoid including too many variables into the logistic regression model from the start, it is useful to perform some correlation analysis on the data before starting the modelling proper. A number of statistical tests for correlation/association are listed in [Sheskin, (2003)] for various levels of measurement. Table 6.3 and Table 6.4 show the Pearson product-moment correlation coefficients for the (ordinary binary and indicator) variables to be considered for overruns during take-off. As set out in [Sheskin, (2003)], when these coefficients are computed for binary 0-1 variables, they are equivalent to the phi-coefficient (ϕ) for a 2 x 2 contingency table. It holds for such a table that $\phi^2 = \chi^2/n$, where χ^2 has a chi-square distribution with one degree of freedom. This can be used to test the null hypothesis of whether the two variables under consideration are independent. The test becomes [Gibra, (1973)].

$$\phi > \sqrt{\frac{\chi^2_{1-\alpha;1}}{n}} \qquad (6)$$

where the numerator of the quantity in the right-hand side in eq. (6) is the $1-\alpha$ quantile of a χ^2 variable with one degree of freedom, i.e. $\chi^2_{1-\alpha;1} = 3.841$. This gives critical values for ϕ of 0.238 and 0.260 for the respective sample sizes of 68 and 57 for large and small aircraft.

For large aircraft, Table 6.3 shows one value larger (in absolute value) than the pertinent critical value of 0.238, namely -0.29 for the pair of indicator variables S_1 and S_2. Since the indicator variables have been introduced explicitly for modelling purposes they will be retained.

For small aircraft, Table 6.4 also shows one value larger (in absolute value) than the pertinent critical value of 0.260, namely -0.41, again for the pair of indicator variables S_1 and S_2. Since the indicator variables have been introduced explicitly for modelling purposes they will be retained.

Table 6.3 Correlation matrix for the overrun data variables – large aircraft

	R1	R2	S1	S2	Elevation ≥ 500 m	Runway slope	Take-off distance
R1	1.00						
R2	-0.11	1.00					
S1	-0.03	-0.05	1.00				
S2	0.12	0.16	-0.29	1.00			
Elevation	-0.08	0.06	-0.03	-0.20	1.00		
Runway slope	-	-	-	-	-	1.00	
Take-off distance	0.18	-0.05	-0.05	0.07	-0.12	-	1.00

Table 6.4 Correlation matrix for the overrun data variables – small aircraft

	R1	R2	S1	S2	Elevation ≥ 500 m	Runway slope	Take-off distance
R1	1.00						
R2	-0.20	1.00					
S1	0.10	-0.10	1.00				
S2	-0.17	-0.09	-0.41	1.00			
Elevation	-0.03	-0.02	-0.09	-0.16	1.00		
Runway slope	-0.06	-0.06	-0.03	0.08	-0.05	1.00	
Take-off distance	0.21	-0.17	0.13	-0.12	-0.15	-0.05	1.00

6.2.3 Overruns during landing

Table 6.5 shows in its left-most column the candidate variables that have been considered for inclusion in the logistic regression modelling for overruns during landing for both the occurrence and non-occurrence movements. In addition, it shows the occurrence probabilities for each variable during normal operations or non-occurrence movements, subdivided into movements of large and small aircraft. Compared with overruns during take-off, there are new variables for the Type of approach, IMC conditions, Visibility less than 1500 m, Glidepath - visual system installed, and Landing distance margin rather than Take-off distance margin. The occurrence probabilities for large and small aircraft are equal for the variables Elevation ≥ 500 m, Visibility less than 1500 m, Runway slope less than -1%, and Landing distance margin less than or equal to 100 m.

Table 6.5 Variables to be considered for logistic regression modelling of overrun risk during landing and their occurrence probabilities during normal operations for large and small aircraft

	Occurrence probability during normal operations (non-occurrence movements)	
Variable	MTOM > 5670 kg	MTOM ≤ 5670 kg
Precision approach	0.75	0.44
Non-precision approach	0.12	0.11
Visual approach	0.13	0.45
Elevation ≥ 500 m	0.05	0.05
IMC conditions	0.35	0.20
Visibility less than 1500 m	0.027	0.027
Glidepath - visual system installed	0.80	0.60
Dry runway	0.89	0.81
Wet runway	0.08	0.15
Contaminated runway	0.03	0.04
Tailwind between -5 and 0 kts	0.13	0.16
Tailwind < -5 kts	0.01	0.02
Headwind (≥ 0 kts)	0.86	0.82
Runway slope less than -1%	0.0026	0.0026
Landing distance margin less than or equal to 100 m	0.05	0.05

All variables other than approach type, runway conditions, and wind conditions are binary exposure/non-exposure variables characterized by the values 1 and 0 respectively. This results in 6 (ordinary) binary variables with a total of $2^6 = 64$ states. The three possible values of approach type require two (binary) indicator variables R_1 and R_2. Precision approach is taken as the reference state characterized by a value of 0 for both R_1 and R_2. The three approach types are then represented by the following three combinations of R_1 and R_2 states:

R_1	R_2	
0	0	Precision approach
1	0	Non-precision approach
0	1	Visual approach

In the same manner as for overruns during take-off, the three possible values of runway condition and wind condition each require two (binary) indicator variables, say, S_1 and S_2, and T_1 and T_2 respectively. The different conditions are represented by the following combinations of states:

S_1	S_2	
0	0	Dry runway
1	0	Wet runway
0	1	Contaminated runway

T_1	T_2	
0	0	Tailwind between -5 kts and 0 kts
1	0	Tailwind < -5 kts
0	1	Headwind (≥ 0 kts)

Thus, each of the twenty-seven possible combinations of the three approach types (precision, non-precision, visual), the three runway conditions (dry, wet, contaminated) and the three wind conditions (tailwind between -5 kts and 0 kts, tailwind < -5kts, headwind (≥ 0)), is represented by one of the three times three times three possible states for the triples of approach type, runway condition, and wind condition indicator variables. Each of these twenty-seven states needs to be combined with each of the 64 states of the (ordinary) binary variables Elevation ≥ 500 m, ..., Landing distance margin less than or equal to 100 m, resulting in a total of $27 \times 64 = 1728$ different states. See Table 6.6, which also shows the numbers of occurrence and non-occurrence movements which were obtained from the NLR Air Safety database for the period 1990-2012.

Table 6.6 Some characteristics pertaining to the landing data

Characteristic	Value	
	MTOM > 5670 kg	MTOM ≤ 5670 kg
Non-occurrence movements	564,736,577	60,764,407
Occurrence movements	291	189
Total number of movements	564,736,868	60,764,596
Number of (ordinary) binary variables	6	
Number of binary states	64	
Number of poly(3)-tonomous variables	3	
Number of indicator variables	3 x 2	
Number of indicator variable states	3 x 3 x 3	
Total number of variables	12	
Total number of states	1728	

In the same manner as for take-off overruns, the expected number of occurrences given a state was computed for the non-occurrence movements as the product of a sampled number of n non-occurrence movements and all the probabilities associated with each (real or indicator) variable's value represented in the state. The correction for the intercept parameter a_0 given in eq. (4) is used again to account for the effect of sampling. For the occurrence movements, the number of occurrences of each state is simply counted from the data.

Table 6.7and Table 6.8show the Pearson product-moment correlation coefficients for the (ordinary binary and indicator) variables to be considered for overruns during landing. As explained in section 6.2.2, these coefficients when computed for binary 0-1 variables are equivalent to the phi-coefficient (ϕ) for a 2 x 2 contingency table which may be used to test the null hypothesis of whether the two variables under consideration are independent. The critical values for ϕ are 0.115 and 0.143 for the respective sample sizes of 291 and 189 for large and small aircraft.

Table 6.7 Correlation matrix for the overrun data variables – large aircraft

	R1	R2	S1	S2	T1	T2	Elevation ≥ 500 m	IMC conditions	Visibility less than 1500 m	Runway slope less than -1%	Landing distance margin less than or equal to 100 m	PAPI-VASi installed
R1	1.00											
R2	-0.28	1.00										
S1	0.11	-0.25	1.00									
S2	0.00	-0.20	-0.40	1.00								
T1	-0.11	0.05	0.06	-0.01	1.00							
T2	0.12	-0.08	-0.04	-0.03	-0.64	1.00						
Elevation ...	0.03	0.04	-0.16	0.15	0.04	-0.01	1.00					
IMC ...	0.11	-0.48	0.20	0.30	-0.07	0.10	-0.04	1.00				
Visibility ...	-0.05	-0.18	-0.05	0.25	-0.01	0.02	-0.07	0.22	1.00			
Runway slope	-0.06	0.08	0.03	0.04	0.02	0.03	0.23	-0.06	-0.04	1.00		
Landing distance ...	0.06	0.06	-0.03	-0.05	0.03	-0.04	-0.03	-0.10	0.06	-0.03	1.00	
PAPI-VASi installed	-0.03	-0.28	0.12	0.07	-0.07	0.06	-0.06	0.25	-0.01	-0.18	-0.18	1.00

Table 6.8 Correlation matrix for the overrun data variables – small aircraft

	R1	R2	S1	S2	T1	T2	Elevation ≥ 500 m	IMC conditions	Visibility less than 1500 m	Runway slope less than -1%	Landing distance margin less than or equal to 100 m	PAPI-VASi installed
R1	1.00											
R2	-0.66	1.00										
S1	0.27	-0.29	1.00									
S2	0.06	-0.05	-0.25	1.00								
T1	-0.07	0.04	0.02	0.05	1.00							
T2	0.02	-0.04	-0.09	0.04	-0.66	1.00						
Elevation ...	0.04	0.06	-0.22	0.16	0.06	0.04	1.00					
IMC ...	0.34	-0.58	0.23	0.17	-0.06	0.01	-0.03	1.00				
Visibility ...	-0.04	-0.22	0.07	-0.03	0.12	-0.11	-0.06	0.20	1.00			
Runway slope ...	-0.03	0.05	-0.06	-0.04	-0.05	0.08	-0.04	-0.07	-0.03	1.00		
Landing distance ...	-0.07	0.11	-0.01	-0.04	-0.04	0.03	-0.10	-0.15	-0.12	-0.04	1.00	
PAPI-VASi installed	-0.05	-0.27	-0.06	-0.02	-0.08	0.01	-0.01	0.22	0.14	-0.06	-0.14	1.00

For large aircraft, Table 6.7shows several correlation coefficients or ϕ values that exceed in absolute value the critical value of 0.115 for the overrun data of large aircraft. However, all but five of them involve indicator variables that have been introduced explicitly for modelling purposes and will be retained. The variables pertaining to the remaining five correlation coefficients are also retained in the initial modelling, but may be dropped as the modelling process set out in section 6.1 progresses.

For small aircraft, Table 6.8 also shows several correlation coefficients exceeding in absolute value the pertinent critical value of 0.143. Like in Table 6.7, the majority of them involve indicator variables and these will be retained. The remaining variables are also retained in the initial modelling, but may be dropped during the course of the modelling process described in section 6.1.

6.2.4 Undershoots during landing

Table 6.9 shows in its left-most column the candidate variables that have been considered for inclusion in the logistic regression modelling for undershoots during landing for both the occurrence and non-occurrence movements. In addition, it shows the occurrence probabilities for each variable during normal operations or non-occurrence movements, subdivided into movements of large and small aircraft. The approach-type probabilities are different for large and small aircraft and equally for IMC conditions and Glidepath – visual system installed. Like in Table 6.1 and Table 6.5, all other occurrence probabilities do not differ between large and small aircraft for normal or non-occurrence movements.

Table 6.9 Variables to be considered for logistic regression modelling of undershoot risk during landing and their occurrence probabilities during normal operations for large and small aircraft

	Occurrence probability during normal operations (non-occurrence movements)	
Variable	**MTOM > 5670 kg**	**MTOM ≤ 5670 kg**
Precision approach	0.75	0.44
Non-precision approach	0.12	0.11
Visual approach	0.13	0.45
Daylight	0.8	0.8
Elevation ≥ 500 m	0.05	0.05
IMC conditions	0.35	0.20
Visibility less than 1500 m	0.027	0.027
Glidepath - visual system installed	0.80	0.60

All variables other than approach type are binary exposure/non-exposure variables characterized by the values 1 and 0 respectively. This results in 5 (ordinary) binary variables with a total of $2^5 = 32$ states. The three possible values of approach type require two (binary) indicator variables R_1 and R_2. Precision approach is taken as the reference state characterized by a value of 0 for both R_1 and R_2 and the three approach types are then represented by the following combinations of R_1 and R_2 states:

R_1	R_2	
0	0	Precision approach
1	0	Non-precision approach
0	1	Visual approach

Each of the three possible states for the pair of approach type indicator variables needs to be combined with each of the 32 states of the (ordinary) binary variables Daylight, ..., Glidepath – visual system installed, resulting in a total of $3 \times 32 = 96$ different states. See Table 6.10, which also shows the numbers of occurrence and non-occurrence movements which were obtained from the NLR Air Safety database for the period 1990-2012.

Table 6.10 Some characteristics pertaining to the landing data

Characteristic	Value	
	MTOM > 5670 kg	MTOM ≤ 5670 kg
Non-occurrence movements	564,736,818	60,764,478
Occurrence movements	50	118
Total number of movements	564,736,868	60,764,596
Number of (ordinary) binary variables	5	
Number of binary states	32	
Number of poly(3)-tonomous variables	1	
Number of indicator variables	2	
Number of indicator variable states	3	
Total number of variables	7	
Total number of states	96	

In the same manner as for take-off and landing overruns, the expected number of occurrences given a state was computed for the non-occurrence movements as the product of a sampled number of n non-occurrence movements and all the probabilities associated with each (real or indicator) variable's value represented in the state. The correction for the intercept parameter a_0 given in eq. (4) was used again to account for the effect of sampling. For the occurrence movements, the number of occurrences of each state was simply counted from the data.

Table 6.11 and Table 6.12 show the Pearson product-moment correlation coefficients for the (ordinary binary and indicator) variables to be considered for overruns during landing. As explained before, these coefficients when computed for binary 0-1 variables are equivalent to the phi-coefficient (ϕ) for a 2 x 2 contingency table which may be used to test the null hypothesis of whether the two variables under consideration are independent. The critical values for ϕ are 0.277 and 0.180 for the respective sample sizes of 50 and 118 for large and small aircraft.

For large aircraft, Table 6.11 shows several correlation coefficients or ϕ values that exceed in absolute value the critical value of 0.277 for the overrun data of large aircraft. However, more than half of them involve indicator variables, particularly approach type R_2, which have been introduced explicitly for modelling purposes and will be retained therefore. The remaining four correlation coefficients concern the variables Visibility less than 1500 m and Glidepath - visual system installed on the one hand and Elevation ≥ 500 m, IMC conditions, and Visibility less than 1500 m on the other. These variables are also retained in the initial modelling, but may be dropped as the modelling process set out in section 6.1 progresses.

For small aircraft, Table 6.12 also shows several correlation coefficients exceeding in absolute value the pertinent critical value of 0.180. Like in Table 6.1 , more than half of them involve indicator variables and these will be retained. The remaining four correlation coefficients concern the pairs of variables IMC conditions and Elevation ≥ 500 m, Visibility less than 1500 m and IMC conditions, Glidepath - visual system installed and Daylight, and Glidepath – visual system installed and Visibility less than 1500 m. These variables are also retained in the initial modelling, but one or more of them may (have to) be dropped as the subsequent modelling process requires this.

Table 6.11 Correlation matrix for the undershoot data variables – large aircraft

	R1	R2	Daylight	Elevation ≥ 500 m	IMC conditions	Visibility less than 1500 m	Glidepath - visual system installed
R1	1.00						
R2	-0.33	1.00					
Daylight	-0.09	0.37	1.00				
Elevation ...	-0.16	-0.28	-0.18	1.00			
IMC ...	0.10	-0.48	-0.10	0.15	1.00		
Visibility ...	-0.01	-0.35	-0.04	0.34	0.44	1.00	
Glidepath ...	0.10	-0.61	-0.22	0.20	0.51	0.31	1.00

Table 6.12 Correlation matrix for the undershoot data variables – small aircraft

	R1	R2	Daylight	Elevation ≥ 500 m	IMC conditions	Visibility less than 1500 m	Glidepath-visual system installed
R1	1.00						
R2	-0.47	1.00					
Daylight	-0.06	0.29	1.00				
Elevation ...	0.02	0.07	-0.08	1.00			
IMC ...	0.31	-0.57	-0.10	-0.19	1.00		
Visibility ...	-0.06	-0.29	-0.09	-0.11	0.22	1.00	
Glidepath ...	-0.03	-0.44	-0.23	-0.11	0.17	0.20	1.00

6.3 Results

6.3.1 Introduction

This section presents the results of the application of logistic regression modelling to the cases of overruns during take-off, overruns during landing, and undershoots during landing. Each case will again be subdivided on the basis of the aircraft MTOM being smaller than or equal to 5670 kg or greater than 5670 kg, i.e. small and large aircraft.

6.3.2 *Overruns during take-off*

Take-off overruns large aircraft

The starting model for overrun occurrences during take-off of large aircraft was

$$p = p(X_1, X_2, \cdots, X_7) = \frac{1}{1+e^{-(a_0+a_1X_1+\cdots+a_{10}X_7)}} \qquad (7)$$

The parameters of this model were estimated for a sampling proportion of $\pi_2 = 1{,}600{,}000/564{,}736{,}800 = 2.8331782 \times 10^{-3}$ of the non-occurrence or normal operation movements. The artefact mentioned in footnote 2 in section 6.2.2 played a part for 10 of the total number of 72 states, leaving 62 states with valid observations. The occurrence data were not sampled. Using eq. (4) with $a_0' = -10.3097$ and $\log(\pi_2) = -5.8664$ gave $a_0 = -16.1761$. Table 6.13 shows all the parameter estimates together with their standard errors. The extremely large standard error for the “Runway slope less than -1%” variable is due to this variable not being present in any of the overrun occurrence data. This may be compared with the small aircraft case for which this variable was present in the pertinent overrun data once.

Table 6.13 Parameter estimates for the logistic regression model eq. (7) for overrun occurrence probability for large aircraft during take-off

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-10.3097	0.3449	-29.8939	0.0000
X_0 intercept	a_0	-16.1761			
R_1 runway condition	a_1	0.0297	0.4675	0.0635	0.9494
R_2 runway condition	a_2	1.5982	0.3601	4.4384	0.0000
S_1 wind condition	a_3	0.3675	1.0541	0.3487	0.7273
S_2 wind condition	a_4	-0.0261	0.3583	-0.0730	0.9418
Elevation ≥ 500 m	a_5	0.4107	0.4646	0.8838	0.3768
Runway slope less than -1%	a_6	-17.6969	10036	-0.0018	0.9986
Take-off distance margin less than or equal to 100 m	a_7	1.2992	0.3293	3.9449	0.0001

The Table 6.13 column headed “t” gives Wald’s test statistic, which is defined as the ratio of $\hat{a}_i$ and its standard error. The Wald statistics for the individual variables X_i/parameters a_i have a standard normal distribution under the null hypothesis of the true value of a_i being zero. The corresponding p- values are shown in the last column of Table 6.13. Small p-values indicate that the null hypothesis of the true parameter value being zero is relatively unlikely. Put differently, the smaller a p-value, the more important the pertinent variable X_i/parameters a_i.

The backward elimination method normally begins with removing each variable individually from the full logistic regression model and estimating the parameters of each of the seven models with six variables/parameters. However, given the extreme value of the standard error for the “Runway slope less than -1%” coefficient a_6, the corresponding variable is dropped from the model without further consideration. On the other hand, it is wanted to keep the runway condition and wind condition indicator variables within the model. This leaves two variables for potential removal from the model (in addition to the permanent removal of Runway slope less than -1%), namely: Elevation ≥ 500 m and Take-off distance margin ≤ 100 m.

Table 6.14 shows the results of the first backward elimination step for the full logistic regression model. The (relatively) large values of the change in deviance result in correspondingly small p-values. Clearly, the p-values in Table 6.14 are smaller than the p-value for removal of a model variable. Hence, the two variables potentially considered for removal from the full model will be retained. On the other hand, the Runway slope less than -1% variable is still to be removed.

Table 6.14 Results of first backward elimination step for overruns during take-off of large aircraft

Full model without variable (and without runway slope variable)	Change in deviance	p- value based on χ^2 distribution with two degrees of freedom
Elevation ≥ 500 m	10.2770	5.87E-03
Take-off distance margin ≤ 100 m	7.6912	2.14E-02

Table 6.15 shows the results for the logistic regression model of eq. (7) without the Runway less than -1% variable. This is marked in the table by a zero value in bold for the a_6 parameter. It can be seen that the parameter estimates for the reduced model are marginally different from those for the full model. The same is true for the standard errors, Wald's test statistic, and the p-values. These results confirm that the Runway slope less than -1% variable does not contribute to the model.

Table 6.15 Parameter estimates for the logistic regression model eq. (7) for overrun occurrence probability for large aircraft during take-off without the Runway slope less than -1% variable

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-10.3123	0.3449	-29.9016	0.0000
X_0 intercept	a_0	-16.1786			
R_1 runway condition	a_1	0.0296	0.4675	0.0634	0.9495
R_2 runway condition	a_2	1.5983	0.3601	4.4387	0.0000
S_1 wind condition	a_3	0.3678	1.0541	0.3489	0.7271
S_2 wind condition	a_4	-0.0262	0.3583	-0.0731	0.9417
Elevation ≥ 500 m	a_5	0.4107	0.4646	0.8840	0.3767
Runway slope less than -1%	a_6	**0**	-	-	-
Take-off distance margin less than or equal to 100 m	a_7	1.2993	0.3293	3.9451	0.0001

Take-off overruns small aircraft

The logistic regression model in eq. (7) was also used for overrun occurrence risk of small aircraft during take-off. There are three differences compared to the large aircraft case. Firstly, the runway condition and wind condition probabilities for non-occurrence take-off movements of small aircraft differ from those of large aircraft (cf. Table 6.1). The second difference concerns the number of non-occurrence movements, which is approximately a factor of ten smaller for small aircraft compared to the large aircraft case (cf. Table 6.2). Finally, the number of occurrence movements is approximately 10 movements smaller, i.e. 57 as opposed to 68 (Table 6.2).

The parameters of the model were estimated for a sampling proportion of $\pi_2 = 1{,}600{,}000/60{,}764{,}539 = 2.6331147 \times 10^{-2}$ of the non-occurrence or normal operation movements. The artefact mentioned in footnote 2 in section 6.2.2 played a part for 8 of the total number of 72 states, leaving 64 states with valid observations. The occurrence data were not sampled. Using eq. (3.4) with $a_0' = -10.4449$ and $\log(\pi_2) = -3.6370$ gave $a_0 = -14.0819$. Table 6.16 shows all the parameter estimates together with their standard errors. The most striking difference between the current small-aircraft case (Table 6.16) and the large-aircraft case (Table 6.15) concerns the standard error of the "Runway slope less than -1%" parameter estimate, which now has a more realistic value of approximately 1.0.

Table 6.16 Parameter estimates for the logistic regression model eq. (7) for overrun occurrence probability for small aircraft during take-off

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-10.4449	0.3246	-32.1815	0.0000
X_0 intercept	a_0	-14.0819			
R_1 runway condition	a_1	0.3513	0.3554	0.9885	0.3229
R_2 runway condition	a_2	1.5687	0.3707	4.2312	0.0000
S_1 wind condition	a_3	0.7807	0.6514	1.1985	0.2307
S_2 wind condition	a_4	-0.2708	0.3379	-0.8016	0.4228
Elevation ≥ 500 m	a_5	0.9792	0.4036	2.4264	0.0153
Runway slope less than -1%	a_6	1.9339	1.0091	1.9164	0.0553
Take-off distance margin less than or equal to 100 m	a_7	1.1329	0.3814	2.9708	0.0030

The backward elimination method has also been applied for the small-aircraft case. As for the large-aircraft case, it is wanted to keep the runway condition and wind condition indicator variables within the model. This leaves three variables for potential removal from the model, namely: Elevation ≥ 500 m, Runway slope < -1%, and Take-off distance margin ≤ 100 m.

Table 6.17 shows the results of the first backward elimination step for the full logistic regression model. The table shows large changes in the deviance for the variables Elevation ≥ 500 m and Take-off distance margin ≤ 100 m with correspondingly (very) small p-values based on a χ^2 distribution with one degree of freedom (a single variable only was removed per run). The remaining Runway slope < -1% variable has a (moderately) low p-value. Since all three p-values are less than the p-value for removal specified at the end of section 6.1, all of the variables listed in Table 6.17 are retained within the full model given by eq. (7) with parameter values given in Table 6.16.

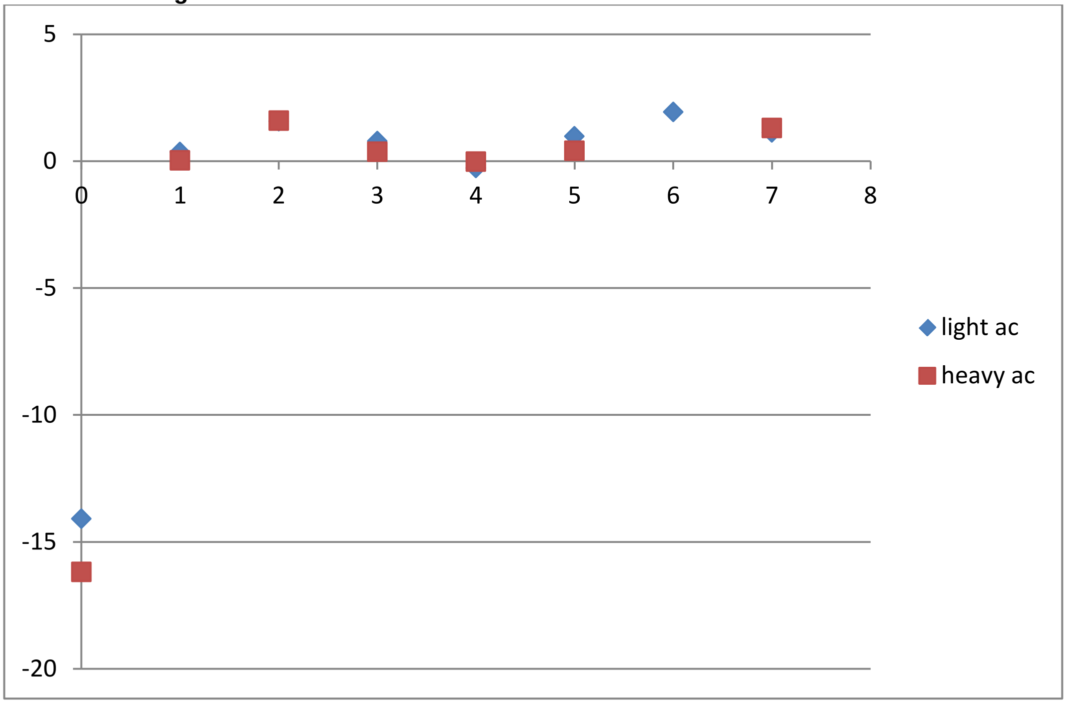
Table 6.17 Results of first backward elimination step for overruns during take-off of small aircraft

Full model without variable	Change in deviance	p- value based on χ^2 distribution with one degree of freedom
Elevation ≥ 500 m	20.2528	0.0000
Runway slope < -1%	3.4828	0.0620
Take-off distance margin ≤ 100 m	13.4452	2.46E-04

Comparison of large and small aircraft models

Figure 6.1 shows a comparison of the logistic regression model parameter estimates for small and large aircraft for take-off overruns. The numbers along the horizontal axis refer to the subscripts of the various parameters/variables, e.g. the number 4 refers to parameter a_4, etc. Apart from the "Runway slope less than -1%" parameter a_6, which is not included in the model for the large aircraft case, and the intercept parameter a_0, the estimates for the two cases appear to be nearly the same.

Figure 6.1 Logistic regression model parameter estimates for large and small aircraft overruns during take-off



6.3.3 *Overruns during landing*

Landing overruns large aircraft

The starting model for overrun occurrences during landing of large aircraft was

$$p = p(X_1, X_2, \cdots, X_{12}) = \frac{1}{1+e^{-(a_0+a_1X_1+\cdots+ a_{13}X_{12})}} \quad (8)$$

The parameters of this model were estimated for a sampling proportion of $\pi_2 = 16{,}000{,}000/564{,}736{,}577 = 2.8331793 \times 10^{-2}$ of the non-occurrence or normal operation movements, resulting in $\log(\pi_2) = -3.5638$. The artefact mentioned in footnote 2 in section 6.2.2 played a part for 604 of the total number of 1728 states, leaving 1124 states with valid observations. The occurrence data were not sampled. Table 6.18 shows all the parameter estimates together with their standard errors, Wald's test statistic t, and the corresponding p-values. Small p-values indicate that the null hypothesis of the true parameter value being zero is relatively unlikely. Put differently, the smaller a p-value, the more important the pertinent variable X_i/parameter a_i. One p-value is fairly large, namely for the Landing distance margin less than or equal to 100 m variable, whereas the remaining p-values are small to very small, indicating generally that the pertinent variables are important. The fairly large p-value of 0.4955 suggests that the Landing distance margin less than or equal to 100 m variable is the least important.

Table 6.18 Parameter estimates for the logistic regression model eq. (8) for overrun occurrence probability for large aircraft during landing

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-11.9366	0.2085	-57.2547	0.0000
X_0 intercept	a_0	-15.5004			
R_1 approach type	a_1	0.5336	0.1720	3.1014	0.0019
R_2 approach type	a_2	1.1924	0.1321	9.0264	0.0000
S_1 runway condition	a_3	2.0366	0.1401	14.5343	0.0000
S_2 runway condition	a_4	2.9468	0.1432	20.5735	0.0000
T_1 wind condition	a_5	2.5239	0.2184	11.5546	0.0000
T_2 wind condition	a_6	-0.3187	0.1676	-1.9015	0.0572
Elevation ≥ 500 m	a_7	0.6692	0.2021	3.3107	0.0009
IMC conditions	a_8	1.0883	0.1205	9.0317	1.69E-19
Visibility less than 1500 m	a_9	1.4280	0.1929	7.4023	1.34E-13
Glidepath – visual system installed	a_{10}	-0.8002	0.1224	-6.5393	6.18E-11
Runway slope less than -1%	a_{11}	1.9539	0.4515	4.3275	1.51E-05
Landing distance margin less than or equal to 100 m	a_{12}	0.1716	0.2500	0.6864	0.4925

The backward elimination method was subsequently applied. Normally, this involves removing each variable individually from the full logistic regression model and estimating the parameters of each of the twelve models with eleven variables. However, in a similar manner as for the overruns during take-off, it was wanted to keep some variables in the landing-overrun model, namely the approach type, runway condition and wind condition indicator variables. This left six variables for potential removal from the model, namely: Elevation ≥ 500 m, IMC conditions, Visibility < 1500 m, Glidepath-visual system installed, Runway slope < -1%, and Take-off distance margin ≤ 100 m.

Table 6.19 shows the results of the first backward elimination step for the full logistic regression model. The large values of the change in deviance result in correspondingly small p–values. Clearly, the p-values in Table 6.19 are smaller than the p-value for removal of a model variable. Hence, the six variables potentially considered for removal from the full model will be retained.

Table 6.19 Results of first backward elimination step for overruns during landing of large aircraft

Full model without variable (and without runway slope variable)	Change in deviance	p- value based on χ^2 distribution with two degrees of freedom
Elevation ≥ 500 m	185.8250	2.59E-42
IMC conditions	326.3722	5.93E-73
Visibility < 1500 m	153.6518	2.76E-35
Glidepath-visual system installed	266.4600	6.71E-60
Runway slope < -1%	79.9006	3.94E-19
Take-off distance margin ≤ 100 m	127.9404	1.16E-29

Landing overruns small aircraft

The logistic regression model in eq. (8) was also used for overrun occurrence risk of small aircraft during landing. There are three differences compared to the large aircraft case. Firstly, the approach type, runway condition, and wind condition probabilities for non-occurrence take-off movements of small aircraft differ from those of large aircraft (cf. Table 6.5). The second difference concerns the number of non-occurrence movements, which is approximately a factor of ten smaller for small aircraft compared to the large aircraft case (cf. Table 6.6). Finally, the number of occurrence movements is approximately 100 movements smaller, i.e. 189 as opposed to 291 (Table 6.6).

The parameters of this model were estimated for a sampling proportion of $\pi_2 = 1{,}600{,}000/60{,}764{,}407 = 2.6331204 \times 10^{-1}$ of the non-occurrence or normal operation movements, resulting in $\log(\pi_2) = -1.3344$. The artefact mentioned in footnote 2 in section 6.2.2 played again a part and resulted in 1226 valid observations. The occurrence data were not sampled.

Table 6.20 shows all the parameter estimates together with their standard errors, Wald's test statistics and p-values. All but one p-values are small to very very small, the exception being indicator variable T_2 wind condition, 0.1758, representing headwind (≥ 0 kts).

Table 6.20 Parameter estimates for the logistic regression model eq. (8) for overrun occurrence probability for small aircraft during landing

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-12.8333	0.2987	-42.9611	0
X_0 intercept	a_0	-14.1677			
R_1 approach type	a_1	1.3326	0.3289	4.0514	5.09E-05
R_2 approach type	a_2	2.0570	0.2433	8.4534	2.83E-17
S_1 runway condition	a_3	0.8397	0.1725	4.8672	1.13E-06
S_2 runway condition	a_4	1.6583	0.2084	7.9574	1.76E-15
T_1 wind condition	a_5	2.2575	0.2435	9.2699	1.86E-20
T_2 wind condition	a_6	-0.2726	0.2013	-1.3539	0.1758
Elevation ≥ 500 m	a_7	0.9700	0.2225	4.3590	1.31E-05
IMC conditions	a_8	0.5469	0.1585	3.4501	0.0006
Visibility less than 1500 m	a_9	1.2720	0.2543	5.0021	5.67E-07
Glidepath – visual system installed	a_{10}	-1.6280	0.1735	-9.3824	6.45E-21
Runway slope less than -1%	a_{11}	1.4471	0.7111	2.0351	0.0418
Landing distance margin less than or equal to 100 m	a_{12}	1.0655	0.2147	4.9619	6.98E-07

The backward elimination method has also been applied for the small-aircraft case. As for the large-aircraft case, it was wanted to keep the approach type, runway condition and wind condition indicator variables within the model. This left six variables for potential removal from the model, namely: Elevation ≥ 500 m, IMC conditions, Visibility < 1500 m, Glidepath-visual system installed, Runway slope < -1%, and Landing distance margin ≤ 100 m.

Table 6.21 shows the results of the first backward elimination step for the full logistic regression model. The table shows very large changes in the deviance for all variables, perhaps with the exception of the Runway slope < -1% variable. Since all p-values are well below the p-value for removal specified at the end of section 6.1, all of the variables listed in Table 6.21 are retained within the full model given by eq. (8) with parameter values given in Table 6.20.

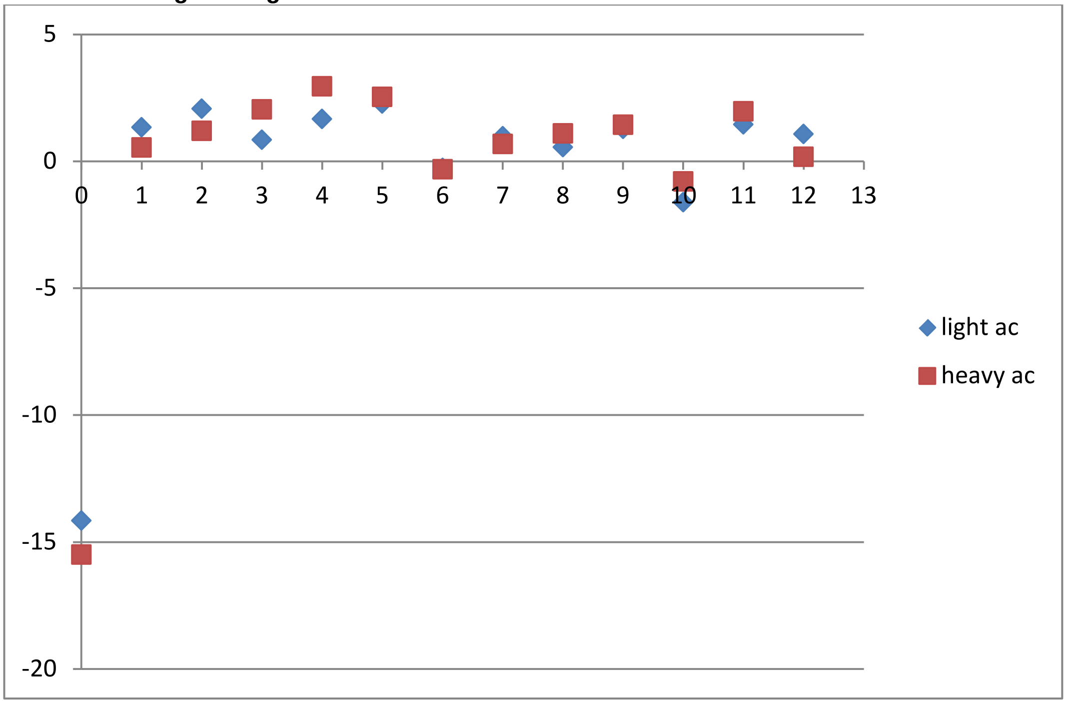
Table 6.21 Results of first backward elimination step for overruns during landing of small aircraft

Full model without variable	Change in deviance	p- value based on χ^2 distribution with one degree of freedom
Elevation ≥ 500 m	105.0382	1.20E-24
IMC conditions	241.3610	1.99E-54
Visibility < 1500 m	112.3080	3.06E-26
Glidepath-visual system installed	176.4350	2.91E-40
Runway slope < -1%	13.8124	2.02E-04
Take-off distance margin ≤ 100 m	80.8460	2.44E-19

Comparison of large and small aircraft models

Figure 6.2 shows a comparison of the logistic regression model parameter estimates for small and large aircraft for landing overruns. The numbers along the horizontal axis refer to the subscripts of the various parameters/variables, e.g. the number 7 refers to parameter a_7, etc. The estimates for the two cases are seen to show a fairly strong similarity.

Figure 6.2 Logistic regression model parameter estimates for large and small aircraft overruns during landing



6.3.4 *Undershoots during landing*

Landing undershoots large aircraft

The starting model for undershoot occurrences during landing of large aircraft was

$$p = p(X_1, X_2, \cdots, X_7) = \frac{1}{1+e^{-(a_0+a_1X_1+a_1X_1+\cdots+\ a_7X_7)}} \qquad (9)$$

The parameters of this model were estimated for a sampling proportion of $\pi_2 = 25{,}600{,}000/564{,}736{,}818 = 4.533085\ \times 10^{-2}$ of the non-occurrence or normal operation movements. The artefact mentioned in footnote 2 in section 6.2.2 did not play a part for the number of non-occurrence movements used. The occurrence data were not sampled. Using eq. (4) with $a_0' = -14.1017$ and $\log(\pi_2) = -3.0938$ gave $a_0 = -17.1955$. Table 6.22 shows all the parameter estimates together with their standard errors, Wald's test statistic t, and the corresponding p-values. One p-value is moderately small, 0.1607, for the Daylight variable, and another one is large, 0.7238, for the Glidepath – visual system installed variable. The remaining p-values are small to very small, indicating generally that the pertinent variables are important.

Table 6.22 Parameter estimates for the logistic regression model eq. (9) for undershoot occurrence probability for large aircraft during landing

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-14.1017	0.4575	-30.8226	0.0000
X_0 intercept	a_0	-17.1955			
R_1 approach type	a_1	0.7340	0.4083	1.7979	0.0722
R_2 approach type	a_2	1.4649	0.3118	4.6980	2.63E-06
Daylight	a_3	-0.4418	0.3150	-1.4027	0.1607
Elevation ≥ 500 m	a_4	0.9520	0.4352	2.1874	0.0287
IMC conditions	a_5	1.1944	0.2946	4.0539	5.04E-05
Visibility less than 1500 m	a_6	2.5386	0.3224	7.8736	3.45E-15
Glidepath - visual system installed	a_7	-0.1206	0.3414	-0.3533	0.7238

The backward elimination method has again been applied to the large-aircraft case. For the undershoot occurrences, it was wanted to keep the approach type indicator variables within the model. This left five variables for potential removal from the model, namely: Daylight, Elevation ≥ 500 m, IMC conditions, Visibility < 1500 m, and Glidepath-visual system installed.

Table 6.23 shows the results of the first backward elimination step for the full logistic regression model. The table shows large changes in the deviance for all the variables eliminated one-by-one with correspondingly very small p-values based on a χ^2 distribution with one degree of freedom (a single variable only was removed per run). All of the variables listed in Table 6.23, therefore, are retained within the full model given by eq. (9) with parameter values given in Table 6.22.

Table 6.23 Results of first backward elimination step for undershoots during landing of large aircraft

Full model without variable	Change in deviance	p- value based on χ^2 distribution with one degree of freedom
Daylight	38.4082	5.74E-10
Elevation ≥ 500 m	31.0674	2.49E-08
IMC conditions	52.7248	3.84E-13
Visibility < 1500 m	45.5134	1.52E-11
Glidepath-visual system installed	66.1376	4.21E-16

Landing undershoots small aircraft

The logistic regression model in eq. (9) was also used for undershoot occurrence risk of small aircraft during landing. The variables for non-occurrence landing movements of small aircraft differ with those of large-aircraft with regard to the occurrence probabilities of the three types of approaches, the IMC conditions, and the Glidepath – visual system installed variable (cf. Table 6.9). Also, the number of non-occurrence movements during landing is again a factor of approximately ten smaller for small aircraft compared to the large aircraft case. Finally, the number of occurrence movements is more than twice as large as for large aircraft in approximately a tenth of the number of landing movements.

The parameters of the model were estimated for a sampling proportion of $\pi_2 = 25{,}600{,}000/60{,}764{,}478 = 4.2129877 \times 10^{-1}$ of the non-occurrence or normal operation movements. The artefact mentioned in footnote 2 in section 6.2.2 did not play a part for the number of non-occurrence movements used. The occurrence data were not sampled. Using eq. (4) with $a_0' = -13.2011$ and $\log(\pi_2) = -0.8644$ gave $a_0 = -14.0655$. Table 6.24 shows all the parameter estimates together with their standard errors, Wald's test statistic t, and the corresponding p-values. The p-values for the R_1 approach type indicator variable and for the Daylight variable of the logistic regression model for small aircraft are fairly large, 0.4677 and 0.4345 respectively, (cf. values of 0.0722 and 0.1607 for large aircraft) suggesting that these two variables are less important for the model. The remaining variables have small to very small p-values.

Table 6.24 Parameter estimates for the logistic regression model eq. (9) for undershoot occurrence probability for small aircraft during landing

Variable	Parameter	Estimate $\hat{a}_i$	Standard error of $\hat{a}_i$	t	p
X_0' intercept	a_0'	-13.2011	0.3153	-41.8650	0.0000
X_0 intercept	a_0	-14.0655			
R_1 approach type	a_1	0.3448	0.4749	0.7262	0.4677
R_2 approach type	a_2	1.6982	0.2633	6.4486	1.13E-10
Daylight	a_3	-0.1713	0.2191	-0.7815	0.4345
Elevation ≥ 500 m	a_4	1.0921	0.2689	4.0613	0.0000
IMC conditions	a_5	0.7932	0.1923	4.1256	3.70E-05
Visibility less than 1500 m	a_6	0.9635	0.3662	2.6312	0.0085
Glidepath, visual system installed	a_7	-0.8535	0.1888	-4.5217	6.14E-06

The backward elimination method was also applied to the small-aircraft case. Like for the large- aircraft case, it was wanted to keep the approach type indicator variables within the model for the undershoot occurrences. Hence, this left again the same five variables for potential removal from the model, namely: Daylight, Elevation ≥ 500 m, IMC conditions, Visibility < 1500 m, and Glidepath-visual system installed.

Table 6.25 shows the results of the first backward elimination step for the full logistic regression model. With the exception of the Visibility < 1500 m variable, the table shows even larger changes in the deviance for the variables eliminated one-by-one than Table 6.23 for large aircraft, with correspondingly very small p-values based on a χ^2 distribution with one degree of freedom. All of the variables listed in Table 6.25, therefore, are retained within the full model given by eq. (9) with parameter values given in Table 6.22.

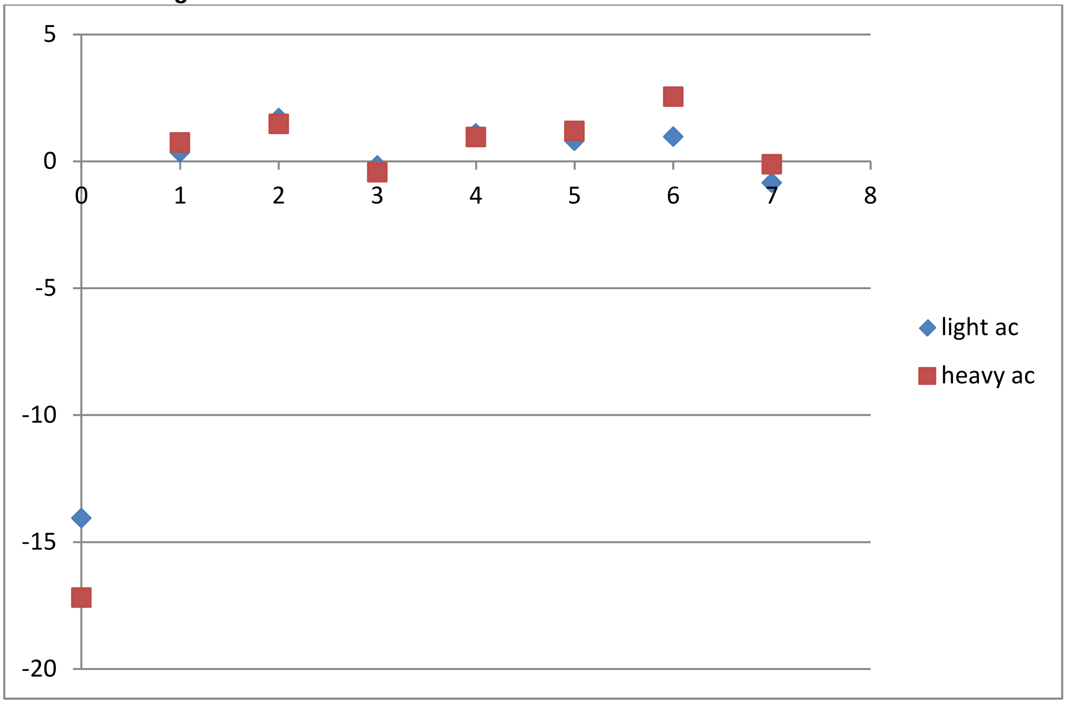
Table 6.25 Results of first backward elimination step for undershoots during landing of large aircraft

Full model without variable	Change in deviance	p- value based on χ^2 distribution with one degree of freedom
Daylight	54.1649	1.84E-13
Elevation ≥ 500 m	37.9314	7.33E-10
IMC conditions	116.5726	3.56E-27
Visibility < 1500 m	41.1294	1.42E-10
Glidepath-visual system installed	86.3474	1.51E-20

Comparison of large and small aircraft models

Figure 6.3 shows a comparison of the logistic regression model parameter estimates for small and large aircraft for landing undershoots. The numbers along the horizontal axis refer to the subscripts of the various parameters/variables, e.g. the number 3 refers to parameter a_3, etc. The parameter estimates differ very little between small aircraft and large aircraft, except for the intercept parameter a_0 and the Visibility less than 1500 m parameter a_6.

Figure 6.3 Logistic regression model parameter estimates for large and small aircraft overruns during take-off



6.4 Final remarks on occurrence probability models

Occurrence and normal operations data have been used to develop logistic regression models for overrun occurrence probability during take-off and landing as well as for undershoot occurrence probability during landing. Separate models have been developed for aircraft with an MTOM larger than or smaller than 5670 kg.

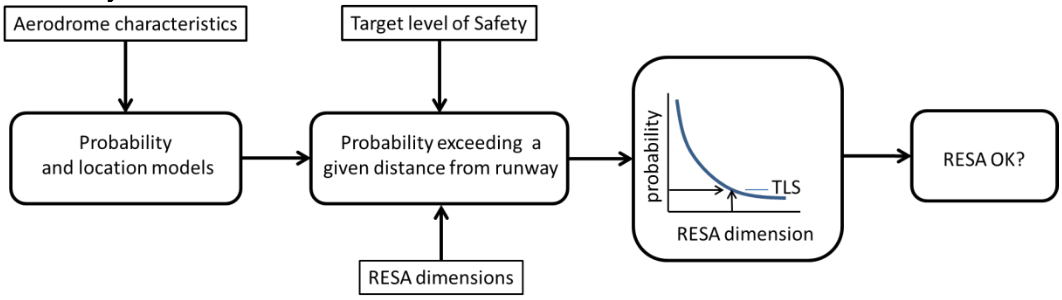
Backward stepwise logistic regression was performed where the full models were based on the variables identified for the various cases in section 1. The method worked well for overruns during take-off and landing, and for undershoots during landing. The full models were retained because the first backward elimination step showed that removal of any of the individual variables was not supported by the hypothesis that the corresponding model parameters were equal to zero.

7 Application of the models

7.1 Introduction

This section describes a procedure to evaluate a RESA using the models and the approach developed in this study. With the models for calculating the overrun/undershoot probability and the location probability it is possible to calculate the overall probability of overruns or undershoots involving locations exceeding a given distance from the runway end. This probability can then be compared to a selected target level of safety. The original RESA/strip dimensions were determined by ICAO using this method. The method allows the user to analyse an existing RESA, or a proposed new RESA, and/or new declared-distances and compare the probability of exceedance of the RESA with a defined TLS value. The method is illustrated in Figure 7.1.

Figure 7.1 Schematic overview of the proposed method for safety assessment of runway and safety areas



7.2 Calculation of probability for ending outside the RESA

The probability of ending outside the RESA can be calculated using the models developed in sections 5 and 6. There are basically 2 scenarios that need to be considered for this assessment. First scenario is that an aircraft overruns or undershoots the runway and stays within the lateral boundaries (Yr) of the RESA but does end up beyond its longitudinal boundary (Xr including the strip length)[5]. The second scenario is that the aircraft ends up beyond the lateral boundaries (Yr) of the RESA but stays within the longitudinal boundary (Xr including the strip length). These scenarios are illustrated in Figure 7.2 for an overrun case. However, the same principle also applies to undershoots.

Figure 7.2 Illustration of the two scenarios considered in the RESA safety assessment

5 By definition Xr includes the length of strip. The strip is always taken into account in all previous assessments of the RESA dimensions. That means that an aircraft could end up in strip but this was still considered by e.g. ICAO when assessing RESA dimensions.

The total probability that an aircraft ends outside the RESA is given as:

$$P = \text{Prob}\{\text{takeoff/landing overrun or undershoot}\} \times \text{Prob}\{x > Xr\} \times (1 - \text{Prob}\{|y| > Yr\}) + \text{Prob}\{\text{takeoff/landing overrun or undershoot}\} \times \text{Prob}\{|y| > Yr\}$$

This equation assumes that the aircraft can also end up in runway strip. Such of way to assess the RESA sizes was also adopted in other studies e.g. [ICAO, (1974), ICAO, (2011), Eddowes et. al, (2001)].This equation also implies that a simple and rectangular-shaped RESA is evaluated. The analysis of other shapes is possible but requires a modification of the equation. The RESA is then divided into several sub-sections for which the probability that an aircraft will not end up in each segment is calculated. The sum of all probabilities of each segment is then equal to the total probability that an aircraft ends outside the RESA.

The probability P is calculated for each occurrence type and aircraft category separately. The total probability is then the weighted sum of the individual calculated probabilities. The probabilities are weighted using the traffic for each event type (e.g. the number of landings with small aircraft, takeoffs with large aircraft etc.). This weighing of probabilities is done to spread the risk according to the traffic distribution. This avoids that one scenario dominates the overall probability which does not reflect the actual use of the runway. Finally the weighted probability can be compared to a target level of safety.

The equation for calculating the probability of an overrun or undershoot occurrence is given by:

$$p = \frac{1}{1 + e^{-(a_0 + a_1 X_1 + \cdots + a_n X_n)}} = \frac{1}{1 + e^{-(C)}}$$

The coefficient C depends on the occurrence scenario and external variables. For each scenario considered in this study the computation of coefficient C is given in Table 7.1. For a given takeoff or landing coefficient C can be determined considering the external factors present during the takeoff/landing. A number of baseline conditions are assumed such as a precision approach for landing overruns and undershoots, a tailwind between -5 and 0 knots and a dry runway for the takeoff and landing overruns. Some of the variables cannot exist simultaneously. For instance a runway is dry, wet, or contaminated. If for instance a runway in the takeoff overrun scenario is wet, the parameter associated with contaminated runway should be set to zero. The same applies to approach type and wind conditions.

In Table 7.2 an overview is given of the location probability models for the different scenarios. The Beta cumulative distribution function used to model landing undershoots cannot be expressed analytically. Therefore only the parameters for this distribution are shown in Table 7.2. The equation for the probability density function for Beta can be solved numerically using incomplete Beta functions or using a Beta cumulative distribution function, which is available in software tools like MS Excel. The user should note that differences can exist in these software tools in the way the variables a and b are defined in the Beta distribution. The probability density function for Beta is defined here by:

$$f(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\left(\frac{x}{500}\right)^a (1-\frac{x}{500})^b$$

The value ‘500’ comes from the definition for an undershoot used in this study (touchdown between 0 and 500 metres from the threshold) and indicates the upper boundary of the distribution.

Table 7.1 Overview of the computation coefficient C

Scenario	Coefficient C
Takeoff overrun (small aircraft)	–14.0819 + 0.3513 (wet runway) + 1.5687 (contaminated runway) + 0.7807 (tailwind < -5 knots) – 0.2708 (Headwind ≥ 0 kts) + 0.9792 (Elevation ≥ 500 m) +1.9339 (Runway slope less than -1%) + 1.1329 (Take-off distance margin ≤ 100 m).
Takeoff overrun (large aircraft)	–16.1786 + 0.0296 (wet runway) + 1.5983 (contaminated runway) + 0.3678 (tailwind < -5 knots) – 0.0262 (Headwind ≥ 0 kts) + 0.4107 (Elevation ≥ 500 m) + 1.2993 (Take-off distance margin ≤ 100 m).
Landing overrun (small aircraft)	–14.1677 + 1.3326 (Non Precision Approach) + 2.057 (Visual approach) + 0.8397 (Wet runway) + 1.6583 (Contaminated runway) + 2.2575 (Tailwind < -5 knots) – 0.2726 (Headwind ≥ 0 kts) +0.9700 (Elevation ≥ 500 m) + 0.5469 (IMC conditions) + 1.2720 (Visibility < 1500 m) – 1.628 (Glidepath – visual system installed) + 1.4471 (Runway slope < -1%) + 1.0655 (Landing distance margin ≤ 100 m).
Landing overrun (large aircraft)	–15.5004 + 0.5336 (Non Precision Approach) + 1.1924 (Visual approach) + 2.0366 (Wet runway) + 2.9468 (Contaminated runway) + 2.5239 (Tailwind < -5 knots) – 0.3187 (Headwind ≥ 0 kts) + 0.6692 (Elevation ≥ 500 m) + 1.0883 (IMC conditions) + 1.4280 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 1.9539 (Runway slope < -1%) + 0.1716 (Landing distance margin ≤ 100 m).
Landing undershoot (small aircraft)	–14.0655 + 0.3448 (Non precision approach) + 1.6982 (Visual approach) – 0.1713 (Daylight) + 1.0921 (Elevation ≥ 500 m) + 0.7932 (IMC conditions) + 0.9635 (Visibility < 1500 m) – 0.8535 (Glidepath – visual system installed).
Landing undershoot (large aircraft)	–17.1955 + 0.734 (Non precision approach) + 1.4649 (Visual approach) – 0.4418 (Daylight) + 0.952 (Elevation ≥ 500 m) + 1.1944 (IMC conditions) + 2.5386 (Visibility < 1500 m) – 0.1206 (Glidepath – visual system installed).

Table 7.2 Overview of the location probability models

Scenario	Longitudinal cumulative probability distribution	Lateral cumulative probability distribution
Takeoff overrun (small and large aircraft)	$e^{-0.0022450x^{1.1268}}$	$e^{-0.279545\|y\|^{0.4666}}$
Landing overrun (small and large aircraft)	$e^{-0.007572x^{1.10006}}$	$e^{-0.318647\|y\|^{0.4802}}$
Landing undershoot small aircraft	a= 0.6170 and b=1.1218, see footnote	$e^{-0.111593\|y\|^{0.558}}$
Landing undershoot large aircraft	a= 0.5331 and b=1.4913, see footnote	$e^{-0.627182\|y\|^{0.3176}}$

*Coefficients of the Beta cumulative distribution function.

For calculating the probability of an event occurring (e.g. a landing overrun), a representative traffic sample for the runway that is being assessed needs to be available. The best way to obtain such data is to collect historical traffic data of the runway end, e.g. takeoffs and landing per runway end. These data can be collected e.g. through the Air Traffic Control organisation at the aerodrome. If a new aerodrome is being assessed such data can be generated by analysing the traffic scenarios developed for the new aerodrome. This would include number of takeoffs and landing by aircraft type. Weather data for this approach should be based on historical climate data for the location. In the end the traffic data sample should contain the parameters that are used in the probability models (see Table 7.1). There are several ways to achieve this. For instance weather data can be retrieved from the airport weather station or METAR records. Most challenging will be to identify the type of approach flown. This information is normally not available from e.g. radar data, ADS-B, or other reports. The aerodrome operator should apply a pragmatic approach in obtaining this type of information for an individual flight. For instance under certain weather conditions, visual approaches will not be flown. Also non-precision approaches will not be flown when e.g. visibility drops below certain values. The aerodrome operator can also contact the major airlines at the aerodrome that can assist in determining the most likely approach type flown for certain landings. There is no formal guideline on how large the traffic data sample should be. However, the sample should cover all seasons and normal traffic variations. A sample comprising of selected months of operations, that characterise the whole year can suffice only when different seasons, environmental conditions, and seasonal variations of traffic are represented correctly in these months. Otherwise a whole year of data should be used. If however, the weather conditions are exceptional or the runway usage was not normal, the user should consider other years for defining a representative traffic sample. Great care should be taken when defining the traffic sample for aerodromes whose traffic mix volume changes dramatically throughout the year. Such short peaks could have a significant influence on the representativeness of the traffic sample. This can be an issue when only certain months of operations form a complete year are selected for the traffic sample. Finally as guideline traffic samples smaller than say 800-1000 takeoff/landings per runway end and per mass category should not be used to estimate occurrence probabilities to avoid a large influence of outliers. This number references to the total number of takeoffs or landings per mass category. For example if the traffic sample encompasses 2500 landing on one runway end of which 2000 are with large aircraft and 500 with small aircraft, it is not recommended to calculate the landing undershoot probability for small aircraft based on 500 landings.

If a traffic sample with the parameters from the model is available, the probability of an event occurring (e.g. takeoff overrun) can be calculated for each individual flight in the sample. The average of the probabilities of each individual flight is then the estimated probability for that particular event (e.g. takeoff overrun probability for large aircraft) to be used for the assessment.

The modelling approach on its own should be enough to allow a safety analyst to perform a risk analysis for RESAs. However less experienced users may need some expert help to make correct use of the models. Experts with knowledge of risk modelling and flight operations could be of help in that case.

7.3 Target level of safety

A target level of safety describes an event with a probability of occurrence and consequences acceptable to the society. It is normally the role of the regulatory authorities to translate the society expectations of safety into a quantitative target level of safety. Target levels of safety are normally defined by a regulatory body that wants to achieve a certain safety level. Very few target levels of safety are published that are related to RESAs. For instance ICAO [ICAO, (1974)] used a target level of safety of 6.6×10^{-7} per flight. This was based on statistical data on veeroff occurrences. It was decided that this could also be used as a TLS for undershoots and overruns when analysing the dimensions of strips and RESAs. A slightly lower target level of safety value of 1×10^{-7} was use as example by [Ayres, M. Jr. et al, (2011)], which was not based on any historical data. The same value was set by Asford for landing overrun rates [Asford, (1977)]. Based on the data provided by the CAA UK in discussing RESA dimensions, a target level of safety for overruns of 5.5×10^{-7} per movement can be derived [CAA UK, (1997)]. This value is slightly lower than the original ICAO TLS. In a study conducted for the Norwegian CAA, Eddowes et.al. propose a target level of safety of 1×10^{-7} in assessing RESA dimensions [Eddowes et. al., (2001)]. A level of 1×10^{-8} was also proposed in this study by Eddowes et. al. as a desirable target. A recent study of the ICAO ADREP data on runway overruns suggests that the recommended distance of 240 m would capture approximately 83 per cent of overruns. This ICAO study did not take the probability of an overrun into account and therefore did not provide the level of safety which ICAO tried to achieve with the recommend length of 240 metres. Analysis of the data analysed in the present study suggest an overrun probability of 0.48×10^{-6} per takeoff or landing for the ICAO study. This would suggest a target level of safety of 0.8×10^{-7} ($=0.17 \times 0.48 \times 10^{-6}$), which is close to some of the previous mentioned targets.

The consequences of an overrun or undershoot are not considered in the present study (see section 1.2). In some studies the consequences of the event are also considered in the target level of safety following the classical risk matrix method [Ayres, M. Jr. et al, (2011)]. The TLS value originally defined by ICAO did not consider the consequences of the undershoot or overrun. Basically all consequences when leaving the RESA with a probability of equal or less than the defined TLS, are possible (e.g. no damage to the aircraft to a fatal accidents or major damage to the aircraft) according to this approach of ICAO. This also applies to the later analysis done by ICAO. The TLS value of 5.5×10^{-7} of the CAA UK covers serious incidents. These are non-fatal occurrences with only minor or no damage to the aircraft and or minor or no injuries to the passengers. The same applies to the TLS values provided by Eddowes et. al. [Eddowes et. al., (2001)].

Most of the TLS values discussed above are typically targeted against large aircraft (e.g. MTOM in excess of 5670 kg) operating on instrument runways. Small aircraft operating on non-instrument runways are not considered in deriving any of these TLS values.

In summary a target level of safety for RESA dimensions of 1×10^{-7} seems very reasonable as starting point considering the above discussion for large aircraft on instrument runways. For small aircraft on non-instrument runways it is unclear what a feasible TLS could be. It can be expected that this TLS will be higher than for large aircraft operating on instrument runways due to the lower safety performance of small aircraft on non-instrument runways. In the end the actual target values should be defined by the regulator (EASA).

A major drawback of the target level of safety concept in the case of RESAs is that it could be that an aerodrome that meets the recommended RESA dimensions cannot meet the specified TLS. This can happen if the probability of e.g. an overrun and/or undershoot is very high due to the presence of high risk operations (e.g. relative high number of landings on contaminated runways). In such a case a regulator simply has to accept this as it is impractical to demand larger RESA dimensions beyond the recommended standards.

7.4 Simple illustrative examples of RESA risk assessment method

To demonstrate the models some simple example are presented in this section.

Example one

A runway is used for landings with both small and large aircraft. The runway has no slope, the airport elevation is 0 m, and visual glide slope path indicator is installed. The traffic sample is shown in Table 7.3. What is the landing overrun rate based on this traffic sample? The landing overrun probability for each landing is given by:

$$p = \frac{1}{1 + e^{-(C)}}$$

The coefficient C can be computed for each flight using the equations given in Table 7.1. For example for landing number 5 the coefficient C is computed as follows:

C= –15.5004 + 0 (Non Precision Approach) + 0 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) –0.3187 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 1.0883 (IMC conditions) + 1.4280 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0.1716 (Landing distance margin ≤ 100 m) = –15.5004 – 0.3187 – 0.8002 + 1.0883 + 0.1716 = **–13.9314**

The probability of landing overrun during landing number 5 is then:

$$p = \frac{1}{1 + e^{-(-13.9314)}} = 8.91 \times 10^{-7}$$

For each landing in the traffic sample the overrun probability is computed. The results are shown in Table 7.4. Finally the landing overrun probability is the average of the overrun probabilities of landings 1 to 10 ($1.88x10^{-6}$). As there is no difference in the location distribution of landing overruns for small and large aircraft (see Table 7.2), the landing overrun probabilities of both small and large aircraft from the traffic sample can be taken together to compute the average landing overrun probability. Note that in this example only a limited traffic sample is used. It is advised to use a larger sample during actual application of the models. As guideline traffic samples smaller than 800-1000 flights should not be used to estimate occurrence probabilities.

Table 7.3 Example traffic sample

Landing	Aircraft mass category	Approach type	Runway condition	Headwind/ tailwind (knots)	IMC/ VMC	Visibility (m)	Landing distance margin (m)
1	Large	Precision	Dry	6	VMC	5000	800
2	Large	Precision	Dry	10	VMC	10000	700
3	Large	Visual	Wet	-4	VMC	9000	650
4	Large	Precision	Snow covered	1	IMC	500	900
5	Large	Precision	Dry	3	IMC	1200	50
6	Small	Precision	Dry	-2	VMC	7500	1800
7	Small	Visual	Dry	-7	VMC	8000	1500
8	Small	Visual	Dry	2	VMC	10000	1500
9	Small	Non-precision	Wet	5	IMC	1800	1200
10	Small	Visual	Dry	12	VMC	8000	1000

Table 7.4 Example calculation of landing probabilities per landing from the traffic sample

Landing	Calculation of C	C	Probability
1	–15.5004 + 0 (Non Precision Approach) +) (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) –0.3187 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-16.6193	6.06E-08
2	–15.5004 + 0 (Non Precision Approach) + 0 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) –0.3187 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-16.6193	6.06E-08
3	–15.5004 + 0 (Non Precision Approach) + 1.1924 (Visual approach) + 2.0366 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) -0 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-13.0716	2.10E-06

Landing	Calculation of C	C	Probability
4	–15.5004 + 0 (Non Precision Approach) + 0 (Visual approach) + 0 (Wet runway) + 2.9468 (Contaminated runway) + 0 (Tailwind < -5 knots) –0.3187 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 1.0883 (IMC conditions) + 1.428 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-11.1562	1.43E-05
5	–15.5004 + 0 (Non Precision Approach) + 0 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) –0.3187 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 1.0883 (IMC conditions) + 1.4280 (Visibility < 1500 m) – 0.8002 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0.1716 (Landing distance margin ≤ 100 m).	-13.9314	8.91E-07
6	–16.4703 + 0 (Non Precision Approach) + 0 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) – 0 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 1.628 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-18.0983	1.38E-08
7	–16.4703 + 0 (Non Precision Approach) + 2.057 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 2.2575 (Tailwind < -5 knots) – 0 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 1.628 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-13.7838	1.03E-06
8	–16.4703 + 0 (Non Precision Approach) + 2.057 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) – 0.2726 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 1.628 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-16.3139	8.22E-08
9	–16.4703 + 1.3326 (Non Precision Approach) + 0 (Visual approach) + 0.8397 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) – 0.2726 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0.5469 (IMC conditions) + 0 (Visibility < 1500 m) – 1.628 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-15.6517	1.59E-07
10	–16.4703 + 0 (Non Precision Approach) + 2.057 (Visual approach) + 0 (Wet runway) + 0 (Contaminated runway) + 0 (Tailwind < -5 knots) – 0.2726 (Headwind ≥ 0 kts) + 0 (Elevation ≥ 500 m) + 0 (IMC conditions) + 0 (Visibility < 1500 m) – 1.628 (Glidepath – visual system installed) + 0 (Runway slope < -1%) + 0 (Landing distance margin ≤ 100 m).	-16.3139	8.22E-08

Example Two

Runway 25 is solely used for takeoffs with large aircraft. The runway has a strip of 60 meters and the RESA is 200 metres long and 60 metres wide. The strip measures 60 metres from the end of the runway. The runway has an aerodrome reference code 3 so the recommended RESA length should be 240 m. The runway width is 45 meters so the RESA width should be 90 metres. Runway 07 is not used for landings so undershoots are not considered in the analysis. The takeoff overrun probability is calculated to be $1.6\text{x}10^{-7}$. What is the probability that the aircraft ends up outside the non-conformal RESA?

The total probability that an aircraft ends outside the RESA (including the runway strip) is given as:

$$\text{P}=\text{Prob}\{\text{takeoff}\}\times\text{Prob}\{\text{x}>\text{Xr}\}\times(1 - \text{Prob}\{|y| > \text{Yr}\}) + \text{Prob}\{\text{takeofft}\}\times \text{Prob}\{|y| > \text{Yr}\}$$

Xr in this example equals to the length of the strip plus the length of the RESA: 60+200= 260 metres and Yr equals to 30 metres. Using the appropriate formulas gives:

$$P=1.6\text{x}10^{-7}\times e^{-0.0022450\times 260^{1.1268}}\times(1 - e^{-0.279545\times|30|^{0.4666}}) +$$
$$+\ 1.6\text{x}10^{-7}\times\ e^{-0.279545\times|30|^{0.4666}}$$

$$P=1.6\text{x}10^{-7}\times 0.31\times(1 - 0.26) + 1.6\text{x}10^{-7}\times 0.26= 7.8\times 10^{-8}$$

If as target level of safety the original ICAO value of 6.6x10^{-7} per flight is used, it can be concluded that the RESA of this runway provides a level of safety that is better than the target level of safety used here. The non-conformal RESA could therefore be acceptable in this example.

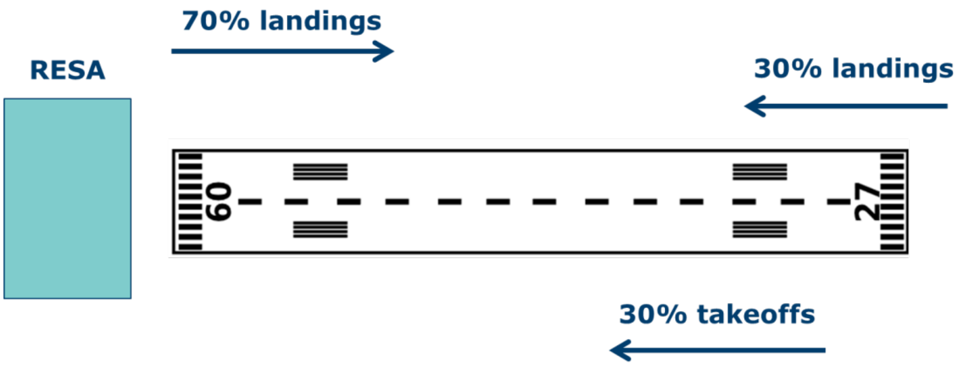
7.5 Example applications of RESA risk assessment method to actual aerodromes

In this section three examples are discussed that demonstrate the use of the RESA assessment method developed in this study. The examples represent real cases of aerodromes in Europe. The names of these aerodromes have been de-identified and the identifications of the involved runways have been changed. It is explicitly mentioned that this concerns a demonstration and not a validation. The validation has been carried out as part of the regression analysis in section 5 and 6. As such, adding extra examples does not affect the validity of the models developed.

7.5.1 Example aerodrome A

Aerodrome A has a single runway with a length of 1450 metres and 45 meters wide. The traffic on this runway is mainly characterised by commercial passenger flights with large twin turboprop aircraft (40-50 seats), some business jets and small single and twin turbo prop aircraft. The RESA for runway 27 is 70 meters long and 90 meters wide and is located 60 metres from the end of the runway. The RESA for runway 09 is 240 metres long and 90 metres wide. There is no space available to increase the length of the RESA for runway 27. About 70% of landings are conducted on runway 09 and 30% on runway 27. Furthermore about 30% of all takeoffs are conducted from runway 27. The total number of movements of aircraft with an MTOM of 2250 kg or higher is about 13,000 annually. The situation for the runway is summarised in Figure 7.3. Runway 09 has an ILS and a PAPI. The airport elevation is close to sea level. The runway has no up or down slope.

Figure 7.3 Overview of the runway at aerodrome A



For the safety assessment of the RESA both undershoots, and takeoff/landing overruns have to be considered. Traffic data with the relevant parameters for the probability models are available for four years of operation. Based on these data the probabilities for the different events are computed by taking the average of the computed probabilities for each individual flight (see section 7.2 for an explanation of this approach). The results are shown in Table 7.5 for the different events. These probabilities have not yet been weighted according to the traffic distribution of each event.

Table 7.5 Non-weighted probabilities for the different events for aerodrome A

Event	Probability
Landing undershoot (small)	1.27E-06
Landing undershoot (large)	1.14E-07
Takeoff overrun (small)	7.04E-07
Takeoff overrun (large)	9.69E-08
Landing overrun (small)	5.06E-07
Landing overrun (large)	1.35E-06

The probabilities for the different events are multiplied with the relative share of the event in the traffic using the distribution for one year of traffic to avoid that one scenario dominates the overall probability which does not reflect the actual use of the runway[6]. The results are shown in Table 7.6.

Table 7.6 Weighted probabilities for the different events for aerodrome A

Event	Probability	Typical one year traffic (takeoffs or landings)	Relative traffic (%)	Weighted probability
Landing undershoot (small)	1.27E-06	1960	23	2.92E-07
Landing undershoot (large)	1.14E-07	2590	31	3.53E-08
Takeoff overrun (small)	7.04E-07	800	9	6.34E-08
Takeoff overrun (large)	9.69E-08	1200	14	1.36E-08
Landing overrun (small)	5.06E-07	840	10	5.06E-08
Landing overrun (large)	1.35E-06	1110	13	1.76E-07

The probability that an aircraft ends outside the RESA for an event is given as (see section 7.2):

$$P=\text{Prob}\{\text{takeoff/landing overrun or undershoot}\}\times\text{Prob}\{x>Xr\}\times(1-\text{Prob}\{|y|>Yr\})+\text{Prob}\{\text{takeoff/landing overrun or undershoot}\}\times\text{Prob}\{|y|>Yr\}$$

Xr in this case is equal to 130 metres (70 RESA+ 60 strip length) and Yr is equal to 45 metres. For each event the probability that an aircraft ends outside the RESA is computed using the weighted probabilities from Table 7.6 and the probabilities location formulae from Table 7.2. The results are shown in Table 7.7. The total probability that an aircraft ends outside the RESA is simply the sum of the individual probabilities and equals to $3.81\text{x}10^{-7}$.

6 The probabilities are estimated for each event type using the 4 years of data. The traffic distribution over the 4 year period has no influence on this. However, when calculating the overall average rate one should take the traffic distribution that matches the current and future operation. In this case the most recent year was representative for traffic distribution in the coming years.

Table 7.7 Computation of probability that an aircraft ends outside the RESA aerodrome A

Event	Weighted probability (from Table 7.6)	Prob{x>Xr}	Prob{│y│>Yr}	Probability that an aircraft ends outside the RESA
Landing undershoot (small)	2.92E-07	0.53	0.39	2.09E-07
Landing undershoot (large)	3.53E-08	0.40	0.12	1.68E-08
Takeoff overrun (small)	6.34E-08	0.58	0.19	4.20E-08
Takeoff overrun (large)	1.36E-08	0.58	0.19	8.98E-09
Landing overrun (small)	5.06E-08	0.37	0.14	2.32E-08
Landing overrun (large)	1.76E-07	0.37	0.14	8.06E-08
			Sum	**3.81E-07**

Next the total probability that an aircraft ends outside the RESA should be compared to a target level of safety. Several TLS values are discussed in section 7.3. A comparison with several TLS values is shown Table 7.8. If the TLS of $1.0x10^{-7}$ is taken here in this example, the RESA needs to be enlarged. As indicated earlier in this example there is no space to increase the size of the RESA. The alternatives are to install an arresting system or to reduce the available runway length. Reducing the runway length is the cheapest solution however this could hamper the operations at the aerodrome (e.g. reduction in maximum landing or takeoff weight). The largest aircraft that can operate the aerodrome is an ATR72. With ISA, no wind conditions this aircraft has a runway distance margin of 125 meters during takeoff and around 500 meters during landing on dry runways[7]. The takeoff is the most critical condition however this still provides some margin. Another possibility is to redirect some of the landings with small aircraft as the landing undershoot probability is by far the largest contributor to the probability that an aircraft ends outside the RESA.

Table 7.8 Comparison total probability that an aircraft ends outside the RESA with different target levels of safety for aerodrome A

Source	TLS	Total probability that an aircraft ends outside the RESA (see Table 7.7)
[ICAO, (1974)]	6.6E-07	3.81E-07
[CAA UK, (1997)]	4.0E-07	3.81E-07
[Eddowes et. al., (2001), and Ayres, M. Jr. et al, (2011)]	1.0E-07	3.81E-07

[7] Obtained from the ATR72 flight manual.

7.5.2 Example aerodrome B

This example concerns a large international aerodrome that wants to shift one of it is runways as it is crossing another runway which causes operational restrictions. The runway 27 now has a RESA of 240 metres in length and 150 metres wide which is located 60 metres from the runway end. Shifting of the runway while maintaining the same runway length, causes a problem with RESA dimensions. Land restrictions limit the RESA length to 80 metres with a strip length of 60 metres. RESA width is not affected. The runway length cannot be reduced as it causes too many operational restrictions to the largest aircraft that operate at the aerodrome (B747-400, A380). The runway has a length of 3500 metres and is 45 meters wide. The runway has no significant slope. Runway 27 is only used for takeoffs by large aircraft (MTOM>5670 kg). The airport elevation is close to sea level.

Installation of an Engineered Material Arresting System (EMAS) is not a feasible option in this case as this system would require a length of 180 meters to effectively stop a B747-400[8] whereas only 140 meters is available. The question now is what is the probability that an aircraft ends outside the RESA when it is only 80 meters in length and does this falls below a defined TLS?

Data on departing aircraft were available for a period of 5 years and encompassed more than 166,000 takeoffs with large aircraft. Using these data the average takeoff overrun rate was computed to be 9.36×10^{-8} by using the equation from Table 7.1 for takeoff overrun probability for large aircraft for each individual takeoff. As only takeoffs with large aircraft are conducted on the runway, no weighing of the traffic is needed in this case. It can be noticed immediately that the estimated overrun probability is already below most of the TLS values for a RESA reviewed in section 7.3. This is an interesting case as it shows that for this example, having a RESA does not provide a meaningful additional level of safety as the probability of a takeoff overrun is already extremely low. For the sake of completeness the probability that an aircraft ends outside the RESA of 80 metres in length is computed. This probability is equal to 5.71×10^{-8} and is well below the known TLS values. Current regulations do not differentiate in takeoff and landings when defining RESAs. If a runway is solely used for takeoffs with large aircraft it is not unlikely that the calculated overrun probabilities will be very low as in this example case. However, it will be difficult for e.g. the general public or pilot unions to accept a runway without any RESA if there is space to have one (even if it is smaller than required by regulations). In this example the aerodrome was actually considering placing a RESA of 80 meters or an EMAS system with a length of 80 metres just because of these reasons.

7.5.3 Example aerodrome C

In this example an aerodrome with a non-instrument runway is considered. This aerodrome has a non-instrument runway with a length of 950 metres, a width of 30 metres, and a slope of 1.1%. Takeoffs and landings are primarily conducted in one direction (into the downslope direction) due to the wind conditions at this aerodrome and account for more than 99% of all traffic. The traffic is composed of small single piston-engine aircraft and single engine turbo-prop aircraft. The single engine turbo-prop aircraft conduct about 1500 takeoffs and landings each year. The runway currently has no RESAs and only has a strip of 60 meters at both runway ends. A RESA of 30 metres in length and a width of twice that of the runway at both runway ends are explored for this aerodrome. The traffic sample contains data on 3000 takeoffs and 3000 landings

[8] Results from an assessment done by ZODIAC Aerospace the supplier of EMAS.

covering a period 5 years. These data are used to compute the takeoff and landing overrun probabilities and the landing undershoot probability.

The non-weighted overrun probabilities are shown in Table 7.9. Both the takeoff and landing traffic is equally distributed over the runway. The weighted overrun probabilities are shown in Table 7.10. Finally the computation of the probability that an aircraft ends outside the RESA is shown in Table 7.11 using the following equation:

$$P = \text{Prob}\{\text{takeoff/landing overrun or undershoot}\} \times \text{Prob}\{x > Xr\} \times (1 - \text{Prob}\{|y| > Yr\}) + \text{Prob}\{\text{takeoff/landing overrun or undershoot}\} \times \text{Prob}\{|y| > Yr\}$$

Table 7.9 Non-weighted probabilities for the different events for aerodrome C

Event	Probability
Takeoff overrun (small)	4.53E-06
Landing overrun (small)	2.46E-06

Table 7.10 Weighted probabilities for the different events for aerodrome C

Event	Probability	Typical one year traffic (takeoffs or landings)	Relative traffic (%)	Weighted probability
Takeoff overrun (small)	4.53E-06	750	50	2.27E-06
Landing overrun (small)	2.46E-06	750	50	1.23E-06

Table 7.11 Computation of probability that an aircraft ends outside the RESA aerodrome C (overruns)

Event	Weighted probability (from Table 7.10)	Prob{x>Xr}	Prob{│y│>Yr}	Probability that an aircraft ends outside the RESA
Takeoff overrun (small)	2.27E-06	0.70	0.25	1.76E-06
Landing overrun (small)	1.23E-06	0.50	0.20	7.41E-07
			Sum	**2.5E-06**

For the other runway end only landing undershoots need to be considered in this example. The undershoot probability is calculated to be equal to 3.62×10^{-6}. As only landing undershoots are considered no weighing of this probability is needed. The computation of the probability that an aircraft ends outside the RESA during a landing undershoot is shown in Table 7.12.

Table 7.12 Computation of probability that an aircraft ends outside the RESA aerodrome C (undershoots)

Event	Undershoot probability	Prob{x >Xr}	Prob{│y│>Yr}	Probability that an aircraft ends outside the RESA
Landing undershoot (small)	3.62E-06	0.63	0.48	2.92E-06

Next the total probability that an aircraft ends outside the RESA should be compared to a target level of safety. Several TLS values are discussed in section 7.3. However these targets all concern larger aircraft (e.g. MTOM in excess of 5670 kg) on instrument runways. As illustrated later in section **8.4** the probability that an aircraft ends outside a RESA of 30 meters for non-instrument runway is much higher than the TLS set for the instrument runways. For non-instrument runways with code 1 or 2 the TLS should be higher than for the instrument runways basically because these runways are mainly used by aircraft that are certified under less strict regulations than large aircraft that land e.g. with the aid of instrument landing systems. Furthermore these aircraft are often operated by crews which are often less experienced and trained than crews from larger aircraft. In the end higher accident probabilities can be expected and therefore a different TLS for RESAs should be used for non-instrument runways than for instrument runways. The actual TLS for such runways is a decision to be made by the regulator (EASA).

8 Preliminary Regulatory Impact Assessment and application of the risk model to aerodromes

8.1 Introduction

In order to assess whether further rulemaking regarding RESAs could be necessary, a Preliminary Regulatory Impact Assessment is executed. This pre-RIA should answer the following question: Is rulemaking necessary or should the issue better be addressed by other means? In the next sections basically follow the steps of the EASA pre-RIA template[9] and contains the following elements:

- Analysis of the issue;
- Review of regulation;
- Safety risk assessment;
- Baseline assessment;
- Objectives, options, preliminary impacts and recommended action; and
- Complexity and controversy.

8.2 Analysis of the issue

A significant part of all accidents and serious incidents occur during takeoff and landing (70-80%). Many of these events involve a runway overrun or undershoot of the runway. An undershoot can be seen as a condition that occurs during an approach to landing that results in an inadvertent landing or contact with the ground short of the runway, normally due to misjudgement of distance, speed, and/or altitude on final approach. An overrun is the continuation of an aircraft movement beyond the end of the runway; i.e., overrunning the intended landing or takeoff area. The normal protection for an aircraft and its occupants to these type of events is provided by a so-called runway end safety area (RESA). This is an area symmetrical about the extended runway centre line and adjacent to the end of the strip. It is primarily intended to reduce the risk of damage to an aircraft undershooting or overrunning the runway. Its main purpose is however to reduce the risk for overruns rather than undershoots as overruns occur much more frequent than undershoots. Several safety studies as well as recent overrun accidents in Europe and other parts of the world show that the risks associated with overruns continues to be significant [Van Es, (2010)], especially in those cases where a RESA did not meet the ICAO requirements for RESA dimensions. A number of recent fatal overrun accidents has re-emphasised the importance of a properly designed RESA to mitigate the consequences of such accidents. An NPA on Runway Excursions has been published by EASA. This should prevent part of the accidents/incidents in the scope of this study.

For a variety of reasons, a significant part of the aerodromes in Europe that fall within the scope of the Basic Regulation do not (fully) comply with the RESA requirements. This situation is not limited to aerodromes located in EASA countries but is seen throughout the world. Most of these airports do not have sufficient land to accommodate the

[9] http://easa.europa.eu/system/files/dfu/rulemaking-docs-procedures-and-work-instructions-TE-RMP-00037-002-Pre-RIA.pdf.

recommended RESAs or are faced with very expensive land acquisition for which safety benefit may only be marginal. Reducing the declared distances for takeoff and landing could also be unfeasible for these aerodromes from a business case perspective as this could hamper operators to operate their aircraft cost-effectively[10]. Many aerodromes were constructed before requirements for RESAs were introduced (by e.g. ICAO or EASA). EASA therefore states that for applicable runways where the RESA does not extend to the recommended distance, as part of their Safety Management System, aerodromes operators should assess the risk and implement appropriate and suitable mitigation measures as necessary.

8.3 Regulation on runway end safety areas

This section provides an overview of the most common regulation, standards and recommended practices related to RESA dimensions.

8.3.1 ICAO

In 1974 the ICAO secretariat presented a review of runway strips dimensions in which the need to develop specifications for overruns and undershoots areas was considered [ICAO, (1974)]. In this review the term RESA was not used. Instead it was called an “overrun area” or “undershoot area”. Strips were considered to have a similar function as RESAs have nowadays. Occurrence data of overruns and undershoots were used by ICAO to define the dimensions of the strips and overrun/undershoot areas. The historical data covered the period 1950-1970. From these data probabilities of the different occurrences were estimated and location distributions of the occurrences relative to the threshold were determined. The combination of occurrence probability and location of the overrun or undershoot were then related to an agreed target level of safety of 6.6×10^{-7}. The consequence of overruns/undershoots ending beyond the TLS were not considered. In the original ICAO study the need to extend the strip ahead of the threshold by at least 90 metres was also mentioned. Later ANNEX 14 was extended to have a specifically defined overrun area called runway end safety area. It was stated that the RESA shall extend from the end of a runway strip to a distance of at least 90 m and the width shall be at least twice that of the associated runway. This applied to runways for which the code number is 3 or 4; and to instrument runways for which the code number is 1 or 2. A proposal for amending these RESA length requirements was discussed in the First Meeting of the Airport Design Study Group (ADSG), in April 1995. The group stated that the RESA should extend beyond the end of the strip, where practicable, to a distance of 240 m where the code number was 3 or 4 and to 120 m where the code number was 1 or 2. The ICAO study group of 1995 developed two requirements, one with the status of a Standard RESA of 90 m, and the other with that of a Recommended Practice to reflect these conclusions. The 1999 revision of Annex 14 incorporated a recommended practice of a RESA length of 240 m or 120 m beyond the edge of the runway strip for code 3 and 4 runways and code 1 or 2 instrument runways respectively. More recently ICAO updated the material in Annex 14 related to RESA dimensions. Recognising the importance of the provision of RESA, ICAO with the assistance of the Aerodromes Panel, made an amendment to Annex 14, Volume I, to strengthen the requirement for RESAs. The latest version of ICAO Annex 14 (published July 2013) recommends that a runway end safety

[10] E.g. a reduced takeoff and landing distance could negatively affect the payload that operators can take on a flight or hamper the use of reduced thrust takeoffs or reduced flap landings.

area should, as far as practicable, extend from the end of a runway strip to a distance of at least:

- 240 m where the code number is 3 or 4;
- 120 m where the code number is 1 or 2 and the runway is an instrument one; and
- 30 m where the code number is 1 or 2 and the runway is a non-instrument one.

If an arresting system is installed, the above length may be reduced, based on the design specification of the system, subject to acceptance by the State. The RESA length specifications are partly backed up by historical data with aircraft overruns (undershoots were not taken into account). A study of the ICAO ADREP data on runway overruns suggested that the standard distance of 90 m for the length of a RESA would capture approximately 61% of overruns, with 83% being contained within the recommended distance of 240 m [Wang (2013), ICAO (2011)]. In the recent amendment of ICAO Annex 14 there is a new requirement for the provision of a RESA for code 1 or 2 non-instrument runways (though as a recommended practice). This arises from overrun data from studies carried out in some states that the risk from overruns is also present for non-instrument runways. The 30 m length for non-instrument runways with code number 1 or 2, is based on the professional judgment of the ICAO Aerodrome Design Working Group (under the Aerodromes Panel). The Aerodrome Design Working Group agreed to propose a recommended practice that such runways have a 30 m RESA beyond the edge of the runway strip [ICAO-ADWG, (2009)].

8.3.2 FAA

The FAA has defined runway end safety area dimensions (called runway safety areas by the FAA) in FAA AC 150/5300-13, Airport Design. These dimensions are related to the aircraft approach category, aircraft design group, runway type and approach minima. The runway end safety dimensions for the different combinations of these variables are listed in Table 8.1 through Table 8.5. For instance a runway safety area of 305 metres beyond each runway end is defined by the FAA on runways that are used by aircraft with approach speeds of 121 knots or more. This 305 metres is equivalent to the ICAO recommended 240 m plus 60 m strip length for code number 3 or 4 runways and is based on the fact that 90% of overruns analysed by the FAA came to rest within 1000' (305m) beyond runway end [David, (1990)]. At US federally obligated airports and at airports certificated under 14 Code of Federal regulations (CFR) part 139, the runway safety area shall conform to the standards contained in FAA AC 150/5300-13 Airport Design (see Table 8.1 through Table 8.5), to the extent practicable. In cases where it is not practicable to improve a safety area to meet FAA standards, alternatives should be considered, like for instance a relocation of the runway; reduction in runway length; or the use of Engineered Materials Arresting Systems (EMAS).

Table 8.1 Runway end dimensions for aircraft approach category A & B visual runways and runways with not lower than 3/4-statute mile (1,200 m) approach visibility minimums (FAA)

Aircraft design group	I	I	II	III	IV
Runway Safety Area Width (m)	36	36	45	90	150
Runway Safety Area Length beyond runway end (m)	72	72	90	180	300

Table 8.2 Runway end dimensions for aircraft approach category A & B runways with lower than 3/4-statute mile (1,200 m) approach visibility minimums (FAA)

Aircraft design group	I	I	II	III	IV
Runway Safety Area Width (m)	90	90	90	120	150
Runway Safety Area Length beyond runway end (m)	180	180	180	240	300

Table 8.3 Runway end dimensions for aircraft approach categories C & D (FAA)

Aircraft design group	I	II	III	IV	V	VI
Runway Safety Area Width (m)	150	150	150	150	150	150
Runway Safety Area Length beyond runway end (m)	300	300	300	300	300	300

Table 8.4 Aircraft approach category (FAA)

Category A: Speed 90 knots or less.
Category B: Between 91 and 120 knots.
Category C: Between 121 and 140 knots.
Category D: Between 141 knots and 165 knots.

Table 8.5 Aircraft Design Group (FAA)

Group	Wing Span
I	up to but not including 15 m
II	15 m up to but not including 24 m
III	24 m up to but not including 36 m
IV	36 m up to but not including 52 m
V	52 m up to but not including 65 m
VI	65 m up to but not including 80 m

8.3.3 EASA

EASA has recently published Certification Specifications (CS) and Guidance Material (GM) for Aerodromes Design CS-ADR-DSN that also considers runway end safety areas. EASA CS ADR-DSN.C.210 Runway End Safety Areas, states that a runway end safety area should be provided at each end of a runway strip where:

- the runway code number is 3 or 4; and
- the runway code number is 1 or 2 and the runway is an instrument one.

EASA CS ADR-DSN.C.215 specifies the dimensions of runway end safety areas as follows:

- Length of RESA:
  - A runway end safety area should extend from the end of a runway strip to a distance of at least 90 m and, as far as practicable, extend to a distance of:
    - 240 m where the code number is 3 or 4; and
    - 120 m where the code number is 1 or 2 and the runway is an instrument one.
- Width of RESA:
  - The width of a runway end safety area should be at least twice that of the associated runway and, wherever practicable, be equal to that of the graded portion of the associated runway strip.

The length of the runway end safety area may be reduced where an arresting system is installed, based on the design specifications of the system.

These EASA specifications follow the ICAO Annex 14 material on RESAs except that where the code number is 1 or 2 and the runway is a non-instrument one, no RESA is specified by EASA.

8.3.4 Discussion

Many countries in the world try to follow the ICAO standards for RESA dimensions (e.g. 90 metres RESA length). A number of them have adopted the recommend RESA dimensions (e.g. 240 m and 120 m). Very rarely countries specify a shorter or longer RESA length[11]. The 30 meters RESA for code 1, 2 non-instrument runways is a new recommended practice by ICAO. Not many countries in world have such requirements for code 1, 2 non-instrument runways. An example is the USA (see Table 8.1). Note that in general the FAA requirements for a RESA are only slightly different from the ICAO values (including strip length).

Tool

Regulatory changes are required in order to ensure legal certainty and equal implementation across the EASA Member States. EASA guidance material contained in GM1 ADR-DSN.C.215 on the dimensions of runway end safety areas, states that for applicable runways where the RESA does not extend to the recommended distance, aerodromes should assess the risk and implement appropriate and suitable mitigation measures as necessary. EASA mentions several mitigation measures in the guidance material. However, EASA does not provide any tools in the guidance material to conduct a quantitative risk assessment. The need of such tools has been recognised by EASA and other regulatory bodies like FAA and Transport Canada.

Cat 1-2

EASA follows the standards and recommended practices provided by ICAO Annex 14, except that no RESA dimensions are (yet) specified for those cases where the code number is 1 or 2 and the runway is a non-instrument one. A new rulemaking task will address the remaining SARPs contained in ICAO State Letter 20 that EASA has not taken into account, including non-instrument runways 1 and 2. Note that a non-instrument runway located at an aerodrome which has at least one instrument runway which meets the criteria set in the basic regulation 216/2008 also has to be certified as part of the aerodrome.

8.4 Safety risk assessment

Scope of the safety risk assessment

a) Type of accidents: overruns

Undershoots are not taken into account here. The main reason for this approach is that the undershoot rate for large aircraft is very low compared to the overrun rates of these aircraft. This was not the case when ICAO originally developed the RESA requirements in the early 1970s. Due to the introduction of PAPIs, the increase in precision approaches, the use of TAWS and GPWS, better flight crew training etc. the undershoot rate has improvement significantly (at least a factor 15 improvement) since ICAO did their first analysis. The overrun rate only improved by a factor of around 2 during the same period.

[11] A rare example of this practice is for instance the Netherlands which has introduced a so-called extended RESA. This adds 600 metres to the recommended length of 240 metres for code 3 and 4. Another example is Japan which has specified a RESA of just 40 metres. Another example is Russia that does not specify the need for RESAs at all.

b) Partial safety risk assessment based on frequency of events

Risk is a combination of frequency and severity of event, however the scope of the study is only limited to the frequency of the event (from the Terms of Reference of the contract). Therefore the safety risk assessment is only related to the frequency of the events.

RESA – 240 m

As discussed in section 7.3 the ICAO RESA length of 240 metres would capture approximately 83 per cent of overruns taken into account a strip length of 60 metres. Therefore, it is recognised and accepted that some overruns will exceed the 240 m recommended RESA distance.

It is estimated that the probability that an aircraft will not stay within 240 metres during an overrun is $0.8x10^{-7}$, based on the analysis presented in section 7.3. The consequences to the aircraft in such an overrun case typically depend on the speed of the aircraft and the surrounds (e.g. obstacles). However, one can assume that this normally results in minor injuries to the occupants and /or minor equipment damage when looking at data of actual overruns (minor incident). As follows from the calculated probability of $0.8x10^{-7}$, it is judged that it is very unlikely that this occurs (improbable)[12]. In terms of the pre-RIA risk matrix this would be a low level of frequency.

RESA – 120 m

The same reasoning can be applied to the 120 m RESA where the code number is 1 or 2 and the runway is an instrument one.

RESA – 90 m

The standard RESA of 90 metres will contain approximately 61 per cent of the overruns (see section 7.2) taken into account a strip length of 60 metres. It is then estimated that the probability that an aircraft will not stay within 90 metres RESA is $1.7x10^{-7}$, based on the analysis presented in section 7.2. As the aircraft speed when leaving the 90 metres RESA will be higher than for the 240 or 120 metres RESA one can assume that this results in injury to the occupants and /or major equipment damage (instead of minor damage, hence hazardous). As follows from the calculated probability of $1.7x10^{-7}$ it is very unlikely that this occurs (improbable). In terms of the pre-RIA risk matrix the 90 metres RESA would be a medium level of frequency.

RESA for aerodrome code number 1 or 2

EASA has not specified dimensions for a RESA where the code number is 1 or 2 and the runway is a non-instrument. Detailed data on overruns (and undershoots) for where the code number is 1 or 2 and the runway is a non-instrument one are very limited. With the data analysed and collected in the present study it is possible to make a rough estimate of the risk levels in absence of a RESA and strip with length of 30 metres. The strip of 30 metres will contain approximately 20 per cent of the overruns. It is estimated with these data that the probability that an aircraft will not stay within 30 metres RESA is approximately $3x10^{-6}$ assuming that only small aircraft will operate on these type of runways (remote). With the relative small area that protects the aircraft during an overrun the speed when exiting the strip will be relatively high. One can then assume that an overrun results in serious injuries to the occupants and /or major equipment damage

[12] It is not possible to make a good judgement of the qualitative probability for overruns for different RESA dimensions. The pre-RIA template from EASA does not provide a quantitative scale for the risk matrix. Therefore an interpretation of the qualitative scale was made using existing risk matrices (e.g. EASA CS AMC 25.1309). Different interpretations are possible as there is no common agreement on this matter.

(hazardous). In terms of the pre-RIA risk matrix, absence of a RESA for non-instrument runways with code number is 1 or 2 would be medium/high level of frequency.

8.5 Baseline assessment: Environmental, social, economic, and harmonisation risks

8.5.1 Environmental risks

The environmental risks (noise and emissions) are all judged to be of no significance as no risks could be identified in terms of gaseous emissions or noise.

8.5.2 Social risks

No social risks or issues, e.g. in terms of limiting free movement of persons, health issues, licencing issues etc. could be identified. The social risks are judged as of no significance.

8.5.3 Economic risks

Economic risks and proportionality issues (e.g. where current rules induce a high cost to industry or distort competition are identified.

Cost to comply with current regulations

There could be potentially excessive costs for authorities, industry, or licence holders. Lack of tools to perform the safety risk assessments prevent the stakeholders to use the flexibility of the regulation. There are aerodromes in EASA countries that do not have sufficient land to accommodate the Certification Specification for the RESAs or are faced with very expensive land acquisition. A 2009 study by the Agency involving a sample of large and medium sized aerodromes across Europe shows that 34 out of 51 aerodromes do not fully meet the ICAO recommendations and 7 do not meet the ICAO standards regarding RESA dimensions [Schorcht and Schmidt, (2010)]. Reducing the declared distances for takeoff and landing could also be unfeasible for these aerodromes from a business case perspective as this could hamper aircraft operators to run a cost-effective operation.

Level playing field

Imposing the RESAs dimensions as specified by EASA to these aerodromes would also introduce an uneven playing field amongst the aerodromes. Aerodromes could be faced with significant investment costs without getting the same level of safety achieved from the RESAs compared to other aerodromes. An aerodrome could be forced to invest significantly in order to meet even the minimum RESA dimensions as examples have shown. In one recent case an aerodrome in an EASA member state, required a RESA that would cross a road next to the aerodrome. As a solution a tunnel is now planned upon the RESA of 90x90 metres would be placed at a total cost of 58 million Euro's (EMAS was not possible to be implemented). These costs were taken by the local government and not by the aerodrome in this example. The total annual revenue of this aerodrome is around 75 million Euro's. Normally such an aerodrome would not be able to make such high investments. Taking into account the above mentioned facts, the overall economic risks are judged to be of a high significance.

8.5.4 Regulatory coordination and harmonisation risks

No regulatory coordination or harmonisation risks could be identified, except for non-instrument Cat 1-2 runways. EASA tends to follow ICAO regarding RESA specifications. FAA has slightly different RESA dimensions however in general these are comparable to ICAO.

8.6 Objectives, options, preliminary impacts and recommended action

8.6.1 Objectives

The general objectives are connected to the objectives laid down in article 2 of Regulation (EC) No. 216/2008, the Basic Regulation. Article 2.1 provides the general and overall objective of EASA. The principal objective is to establish and maintain a high uniform level of civil aviation safety in Europe. In Article 2.2 the additional objectives of EASA are described. Important objectives for this study are:

- To promote cost-efficiency in the regulatory and certification process and to avoid duplication at national and European level (2.2.c);
- To provide a level playing field for all actors in the internal aviation market (2.2.f).

The specific objective for the options of the rule making proposal is to support business evolution at aerodromes and for aircraft operators while ensuring a high level of safety and a consistent approach among the different organisations and Member States.

8.6.2 Options

In order to achieve this objective, the options shown in Table 8.6 were identified. These options are non-exhaustive, preliminary and indicative and, thus, do not prejudge future rulemaking activities which may contain different options.

Table 8.6 Options

Option	Description
0	No rulemaking (baseline option; issues remain as outlined in sections 8.5 and 8.5.3).
1	Provision of additional guidance material in GM1 ADR-DSN.C.215 for the risk assessment of non-compliant RESAs.
2	Rulemaking for a RESA for non-instrument runways with code number 1 or 2.
3	Provision of additional guidance material in GM1 ADR-DSN.C.215 for the risk assessment of non-compliant RESAs. Rulemaking for a RESA for non-instrument runways with code number 1 or 2.

8.6.3 Preliminary impacts and recommended action

The baseline option (Option 0) would not address the issue and the related concerns in the area of economic and of safety risks. It could also create an uneven playing field between actors of the aviation market as discussed in section 8.5.3.

The impact of both option 1 and 2 is compared to the baseline option 0 in Table 8.7. Also the combination of Option 1 & 2, called Option 3 is shown.

Option 1 will have a positive economic impact: EASA mentions several mitigation measures in the guidance material. However, EASA does not provide any tools in the guidance material to conduct a quantitative risk assessment. The need of such tools has been recognised by EASA and other regulatory bodies like FAA and Transport Canada. The present study provides the development of such tools for EASA.

If the aerodrome demonstrates that it has a better safety level that required by the target level of safety, one could argue that safety improves. However the aerodrome has taken no mitigating measures to actually achieve this. It just has the means to demonstrate it.

Option 2 will have positive impact on safety as well as on regulatory coordination and harmonisation. It could however have a negative impact on the economics as some aerodromes with non-instrument runways are required to construct a RESA.

Table 8.7 Impact of options compared to option 0 (Baseline)

	Option 1 Provision of additional guidance material in GM1 ADR-DSN.C.215 for the risk assessment of non-compliant RESAs	**Option 2** Rulemaking for a RESA for non-instrument runways with code number 1 or 2	**Option 3** Both Option 1 and 2
Safety impact	+/0	+	+
Economic impact	+	-	0
Environmental impact	0	0	0
Social impact	0	0	0
Impact on regulatory coordination and harmonisation	0	+	+

The present study provides the development of such tools for EASA. Not all overruns and undershoots will end in a RESA nor is it always feasible to define RESAs that will capture all of them. It is recognised and accepted by ICAO that some overruns (and undershoots) would exceed the recommended RESA distance. Essential to these developments (besides having representative models) is therefore the definition of a target level of safety.

Currently EASA has no RESA specifications for non-instrument runways with code number 1 or 2. The risk assessment presented in section 8.4 indicated that the safety risk associated with this condition was rated as being a medium/high significant. The RESA specified in ICAO Annex 14 of 30 m for non-instrument runways with code number is 1 or 2, was based on the professional judgment of the ICAO Aerodrome Design Working Group (under the Aerodromes Panel). No formal data analysis has been applied by ICAO to derive this distance. The 30 m RESA length was recommended with only overruns in mind and is considered a starting point by ICAO. Undershoots were not considered by ICAO. The 30 metres RESA length used by ICAO seems a good option to consider for non-instrument runways with code number 1 or 2 as this matches with the RESA lengths used by FAA.

The combination of Option 1 & 2, Option 3, is most likely to achieve the objectives stated at the beginning of this section. It is therefore estimated that the Option 3 is the preferred option.

8.7 Complexity and controversy

The proposed rulemaking action is not considered complex for the following reasons: it does not affect several CSs; it does not propose a new rulemaking concept; and it does not deal with a new subject that needs research. The choice of the target level of safety when assessing RESA dimensions can have a significant economic impact. Setting very high safety standards (e.g. low TLS) could result in high economic penalties for both aerodrome and aircraft operators. This will vary amongst the different EASA member states as costs for e.g. labour costs vary amongst the member states.

9 Conclusions and recommendations

9.1 Conclusions

For a variety of reasons, a significant part of the aerodromes falling within the scope of the Basic Regulation do not (fully) comply with the runway end safety requirements. Many aerodromes were constructed before requirements for RESAs were introduced. Airports often do not have sufficient land to accommodate RESAs. In the context of the application of the safety management system requirement and irrespectively of the level of compliance with the relevant RESA related specifications, aerodrome operators should be able to assess the overrun or undershoot safety risks associated with their aerodromes, and undertake appropriate mitigation actions within their competence (e.g. determination of new declared distances, extension of existing RESA, etc.). The standards for runway end safety areas are depended only on the runway code and the availability of instrument procedures. However, there are numerous factors that may lead to aircraft overruns and undershoots not directly related to runway code or instrument procedures. Factors like tailwind conditions, non-dry runways, runway down slope, visibility conditions, and visual landing aids for instance have an impact on the overrun and undershoot risk of each operation. In the end take-off and landing operations are carried out under varying levels of safety which can vary among different aerodromes having the same runway and RESA dimensions. Therefore tools should be available for assessing the risk associated with the application of non-standard RESA sizes that account for varying safety levels.

This study provides a comprehensive risk-based assessment procedure that accounts for several aerodrome related risk factors associated with aircraft overruns and undershoots. A probabilistic method is developed in this study that integrates the probability of an overrun or undershoot occurrence with the probability where the aircraft ends or hits the surface near the runway end. The model development used representative historical data on overruns and undershoots with aircraft with a MTOM of 2250 kg or higher combined with normal exposure data. The models account for the specific meteorological and operation conditions that characterise the operations. These factors are related to an increase in the probability of an overrun or undershoot occurrence as determined by a logistic regression technique used for this study. The overall output of the models is an estimation of the probability that an aircraft does not end up in the RESA. The user of the models can evaluate alternatives (e.g. reduced runway length, different RESA sizes, changes in runway usage, installation of landing aids etc.) that are most effective to obtain an acceptable level of risk.

The safety assessment method developed in this study calls for a target level of safety. Several target level of safety values that have been used for sizing RESAs in the past, are reviewed in this study. Based on these values a target level of safety for RESA dimensions of 1×10^{-7} seems very reasonable as starting point for large aircraft operations on instrument runways. For small aircraft operations on non-instrument runways it is unclear what a feasible target level of safety could be. It can be expected that this TLS will be higher than for large aircraft operating on instrument runways due to the lower safety performance of small aircraft on non-instrument runways. In the end the actual target level of safety values should be defined by the regulator (EASA).

The method is successfully demonstrated by applying it to a number of example aerodromes using actual operational data of these aerodromes. The results of the current study can be used by a broad range of civil aviation organizations for risk assessment and cost-benefit studies of different RESAs dimensions.

The modelling approach on its own should be enough to allow a safety analyst to perform a risk analysis for RESAs. However less experienced users may need some expert help to make correct use of the models. Experts with knowledge of risk modelling and flight operations could be of help in that case.

In order to assess whether further rulemaking regarding RESAs could be necessary, a Preliminary Regulatory Impact Assessment is executed. The pre-RIA showed that there could be potentially excessive costs for authorities, industry, or licence holders when an aerodrome cannot comply with the recommended RESAs for instrument runways. EASA currently does not provide any tools in the guidance material to conduct a quantitative risk assessment of existing RESAs. The need of such tools has been recognised by EASA and other regulatory bodies like FAA and Transport Canada. The present study provides the development of such tools for EASA. Not all overruns and undershoots will end in a RESA nor is it always feasible to define RESAs that will capture all of them. It is recognised and accepted by ICAO that some overruns (and undershoots) would exceed the recommended RESA distance. Currently EASA has no RESA specifications for non-instrument runways with code number 1 or 2 as opposed to ICAO. The pre-RIA showed that the safety risk associated with this condition was rated as being a medium/high significant. To resolve this it is recommended that EASA would formulate RESA requirements for non-instrument runways with code number 1 or 2.

9.2 Recommendations

It is recommended that EASA supports the development of user-friendly software that incorporates the models developed in this study. This will help the less experienced users to perform a risk analysis for RESAs and also make it much easier to analyses alternative solutions.

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