Final Report on the Risk Analysis in Support of Aerodrome Design Rules

A report produced for the Norwegian Civil Aviation Authority

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Executive Summary

The Luftfartstilsynet, the Norwegian Civil Aviation Authority, commissioned AEA Technology to carry out a risk analysis study in support of the development of aerodrome design rules, intended to define the Norwegian requirements for the physical design of aerodromes that can provide for adequately safe traffic handling. Current requirements in Norway are based primarily on those set out in Annex 14 of the International Civil Aviation Organization (ICAO). Taking account in particular of the special topographic conditions surrounding Norwegian aerodromes, it is anticipated that there may be some scope for improving the effectiveness of that basic framework as applied specifically in Norway. In addition, there may be a more widespread interest in the general refinement and optimisation of aerodrome design requirements.

The risk analysis has been undertaken with particular reference to the following aspects of aerodrome design:

- length and reference codes of runways and taxiways;
- runway and taxiway strips;
- runway end safety areas;
- separation distances between runways and taxiways;
- definition of obstacle limitation surfaces.

Against this background, the intention has been to develop a more “objective-based” or “risk-based” system of design requirements that will enable a certain “target level of safety” (TLS) to be met. Essentially, the project objective has been to relate the residual risk associated with relevant operational hazards to the design features that provide protection against those hazards. This should allow definition of the dimensional requirements to achieve a desired TLS, according to the nature of operations at an aerodrome. (It should be noted that the dimensional requirements defined within the project are based on physical safeguarding only and do not account for technical safeguarding[1]; allowance for technical safeguarding may lead to increased restrictions in certain physical design rules, particularly in relation to obstacle limitation surfaces.) The rationale behind the adoption of this “risk-based” approach is simply that provision of safety involves sacrifices in terms of the cost and effort required to provide it and the foregoing of the use of land for other purposes. It is important to ensure that this effort and these sacrifices are properly directed so as to maximise the safety benefit derived from them.

The approach adopted has relied, to a large extent, on the development of empirical risk models based on operating experience and the insights gained from it. In adopting this approach, it is recognised that such models have their limitations, arising in part from the fact that the resources that can be made available in conducting such a study are not unlimited and from the wide range of issues addressed. Notwithstanding these limitations, we believe that the “risk-based” approach offers real benefits and these could be enhanced by further and more detailed analysis to address the limitations of the work undertaken to date.

[1] Technical safeguarding relates to the protection of communication, navigational and surveillance (CNS) system signals from either physical or electromagnetic interference/obstruction.

The process for risk assessment undertaken during the study has comprised the following elements:

- Development of quantitative risk standards or “target levels of safety” (TLS) against which to evaluate the level of safety provided by the design features of interest;
- Functional Hazard Analysis (FHA) to identify hazards to operations and the relationship between aerodrome features and the mitigation they provide against those identified hazards;
- Development of quantitative risk models, typically allowing the characterisation of risk in terms of the likelihood of occurrence of certain hazard scenarios, the location of an aircraft during such an event in relation to the intended path and the safety margin provided by the relevant aerodrome design feature, and the severity of the incident consequences.

This risk assessment process was underpinned by an initial review of standards and practices of aerodromes in Norway.

The basic TLS against which to evaluate residual risk levels associated with the various aerodrome design features has been established primarily by reference to historical incident rates. On this basis we identify a fatal (total hull loss) accident rate for airport related accidents of approximately 0.2 per million movements (2×10^{-7} per movement) as the primary residual risk benchmark for “first world” operations. A number of distinct hazard scenarios contribute to this total rate and therefore, if this total risk “budget” is apportioned between different hazards, the TLS for any single hazard will be correspondingly lower than this overall rate. On this basis, we propose the use of a basic “benchmark” TLS of 10^{-7} per movement, recognising that we would wish to improve upon this where possible, such that a TLS of 10^{-8} per movement might be preferred where practicable. Risks below 10^{-9} per movement may generally be regarded as small and of minimal regulatory concern.

Having proposed these basic quantitative standards we identify the need for caution when employing them and the need to give particular consideration to the circumstances in which they are to be applied. In the current context we note that overrun and controlled flight into terrain (CFIT) accidents on approach and landing are major contributors to the overall total hull loss rate of 2×10^{-7} per movement. We note further that historical accident rates vary significantly according to the nature of operations, with some types of operation exhibiting a risk that is somewhat higher than the recent historic average and others exhibiting a risk that is correspondingly lower. It may therefore not be realistic to expect that the TLS of 10^{-7} per movement based on the average accident can be generally achievable, even when apportioned between a number of hazard scenarios. We conclude that some flexibility is required when considering the use of a TLS as a safety management tool. In addition, we note that operational practices and procedural measures as well as aerodrome design features contribute to airport safety. In some situations, safety improvements might be more effectively achieved through directing attention to such measures rather than increasing the safety margins provided by aerodrome design.

The severity of incident consequences is a further consideration in the setting of safety targets. Certain aspects of aerodrome design may protect against incidents that are unlikely to result directly in catastrophic consequences, such as low speed aircraft wingtip collisions during taxiing operations. The acceptable level of frequency with which such incidents occur will obviously be higher than for catastrophic events, and hence a higher TLS will be appropriate.

The risk analysis undertaken during the study was based primarily on review of operational experience, in particular accident and incident data, taking account of the findings of a Functional Hazard Analysis undertaken in the initial stages of the study. (A Functional Hazard Analysis is a formal and systematic process for the identification of hazards associated with an activity. The purpose of the FHA in the context of this Aerodrome Design Rules study was to determine relevant hazards to aircraft associated with aerodrome operations (*e.g.* approach, landing, taxiing, take-off roll, and associated fault sequences) and the physical design of aerodromes.)

A series of quantitative risk models was developed that describe a number of distinct hazard scenarios and these models enable the safety margins provided by the various aerodrome design features of interest to be evaluated. Two distinct operational scenarios have been considered:

- deviation of aircraft about the intended path, as encountered during normal operations;
- specific fault sequences, outside normal operations, that may lead to deviation of an aircraft from its intended path and that are sufficiently foreseeable to warrant some level of risk mitigation.

The risk models have been developed primarily by reference to empirical data derived from measurements during operation or from historical incident/accident analysis. For example, the risk model in respect of the approach surface was based on the likelihood of deviation of an aircraft vertically from the intended glide slope and laterally from the extended runway centreline during approach and landing, as determined from operational measurement and from consideration of instrument landing system performance. In the case of overrun and undershoot risk, the models were derived from historical accident data on the frequency of occurrence of these events and the probability of touchdown or overrun a given distance from the runway.

The risk models developed and the aerodrome design features to which they relate are as follows:

- take-off and landing overrun risk models, in relation to the provision of runway end strip and runway end safety area (RESA);
- landing undershoot risk model, in relation to the provision of runway end strip and runway end safety area (RESA);
- lateral veer-off model, for take-off and landing operations, in relation to the width of the runway strip (in particular the graded area of the strip);
- taxiway deviation model, in relation to the taxiway strip width and the separation distances between a runway and a parallel taxiway, between parallel taxiways and between an object and a taxiway;
- approach and landing deviation model, in relation to the approach and landing surfaces;
- missed approach/balked landing deviation model, in relation to the runway strip width, the inner and outer transitional surfaces and the balked landing surface.

The specific requirements under Annex 14 are defined according to three different criteria relating to the nature of aircraft utilising an aerodrome and the nature of the associated operations:

- the reference code number of the aircraft that the aerodrome is intended to serve, as defined in accordance with the runway length requirements of the aircraft;
- the reference code letter of the aircraft that the aerodrome is intended to serve, as defined according to the width requirements of the aircraft, characterised in terms of wingspan and outer gear wheel span;
- whether the runway is used for take-off or approach operations and, in the case of approach operations, whether these are visual, non-precision instrument or precision instrument operations (either Cat I, II or III).

Using the risk models, two distinct aspects of the requirements defined within Annex 14 have been assessed, as follows:

- the dependence of design requirements on the three key criteria of reference code number, reference code letter and category of operation (instrument/non-instrument, take-off/landing) and whether the relationships under Annex 14 provide the most appropriate basis for provision of safety to a given level;
- the physical dimensions that are required in order for a given type of operation to meet a given TLS and whether the Annex 14 requirements provide safety to the desired level or are unnecessarily onerous, given the level of safety that they provide.

In general, the Annex 14 design features can be seen to represent a rational set of measures for the provision of safety. However, the risk analysis indicates that the precise requirements do not always provide for consistent levels of safety, according to aerodrome code and designation. Particular points to note are as follows:

- Incident rates for some hazard scenarios (overrun, undershoot and lateral veer-off) at visual and non-precision instrument runways are often found to be higher than those at precision instrument runways whereas Annex 14 often defines more stringent design rule requirements in the case of precision instrument runways: these differences would not be justified from a risk-based perspective.
- For a number of design requirements (for example runway strip width and RESA length) that are defined according to reference code number (aeroplane field length requirement), the risk models indicate little or no dependence of the level of risk on aeroplane characteristics: again the differences in Annex 14 requirements according to aerodrome codes would not be justified from a risk-based perspective.
- In some instances, the specific dimensions prescribed under Annex 14 are sufficient to provide safety levels (from a purely physical safeguarding perspective) very considerably in excess of that for the benchmark TLS (residual risk very much below 10^{-7} per movement) whereas in others, risks are at or above this TLS. The differences are most marked in the case of the level of safety provided by the lateral extent of the approach surface compared with that provided by its vertical extent at precision instrument runways (though consideration of technical safeguarding may provide some justification for the level of divergence of this surface).

Taking account of these findings, a series of design rule recommendations have been developed which seek to establish a more logical relationship between the runway designation and design requirement and to achieve more consistently an appropriate level of safety, as judged against the benchmark TLS.

Aerodrome Physical Dimensions

Length of Runway End Safety Provision

1. Runway end safety requirements should be defined according to the following criteria describing operations:
   - runway end safety in respect of overrun at runways meant for take-off;
   - runway end safety in respect of overrun at runways meant for landing;
   - runway end safety in respect of undershoot at runways meant for landing.
2. It would also appear to be appropriate from the perspective of achieving a uniform TLS to define RESA requirements separately in respect of overrun at runways meant for precision approach landing and those meant for non-precision/visual approach landing. However, there may be practical constraints on the benefit to be gained from increased RESA provision in the latter case such that it may be more pragmatic to adopt the same RESA standards and accept a difference in the residual risk per movement for the two cases. Additionally, although a correlation has been identified between the type of approach aids available and the frequency with which overrun incidents occur, it is difficult to conclusively identify and assess the nature of the precise causal dependencies with the available data;
3. Where practicable, the runway end safety requirements (combined length of runway end strip and RESA) applied to codes 1, 2, 3, & 4 should be the same.
4. The recommended RESA/runway end strip lengths are as follows:
   - Combined length of runway end strip and RESA not less than the current ICAO Annex 14 standard of 150 m in any runway case (basic requirement to meet a TLS of 10^{-7} per movement for average risk movements);
   - Combined length of runway end strip and RESA preferably approaching the current ICAO Annex 14 recommendation of 300 m in relation to take-off and landing overrun risk mitigation (objective to achieve a TLS of 10^{-8} per "average movement"[1] where practicable and a TLS of 10^{-7} per movement for "higher risk movements"[2]);
   - Combined length of runway end strip and RESA up to 500 m in relation to take-off and landing overrun risk mitigation, where practicable, for aerodromes at which there are a "significant" number of higher risk operations[2]: *i.e.* runway critical and/or non-precision/visual approach movements (practical limit of safety benefit from increased RESA provision).

[1] By "average movement" risks we refer to the risks averaged over movements undertaken with different levels of excess runway available and also, for landing operations, averaged over movements undertaken with different types of approach aid.

[2] "Higher risk movements" are those associated with runway limited operations (*i.e.* minimal excess runway available) and, for landing operations, non-instrument approach movements. It is noted that such movements are relatively common at many of the small-to-medium sized Norwegian aerodromes.

Runway Strip Width

5. Runway strip requirements should be defined separately according to two distinct safety functions:
    - the protection of aircraft from collision on the ground in the event of a lateral veer-off during landing or take-off;
    - the protection of airborne aircraft from collision whilst over-flying the runway strip, for example during a missed approach/balked landing.

    In the case of the former, the relevant portion of the runway strip should be adequately load bearing to accommodate the aircraft using the aerodrome though not necessarily prepared to the same standards as the graded area. Recommendations regarding the latter case are described separately under the OLS heading below.
6. The minimum width of strip required for risk mitigation in respect of veer-off should be defined as a function of reference code letter, and should be not less than the values set out in the table below (basic requirements for provision of a TLS of 10^{-7} per movement). (The strip width in the table is the distance from the runway centreline to the outer edge of the strip and is therefore half the total width of the strip.)

Half strip widths to mitigate veer-off risk to TLS of 10^{-7} per movement	
Runway code letter	**Strip width (m)**
A	60
B	65
C	70
D	80
E	85
F	90

7. Where practicable, that portion of the strip width should extend to 150 m, for runways of each code (objective to achieve a TLS of 10^{-8} per movement where practicable).

RESA Width

8. The width of the RESA should be defined as a function of the runway reference code letter, and be equivalent to the runway strip width, as set out in the above table (basic requirement for provision of a TLS of 10^{-7} per movement).
9. Where practicable, the RESA should extend to a distance of 150 m from the extended runway centre-line, for runways of each code (objective to achieve a TLS of 10^{-8} per movement where practicable).

Taxiway widths and separations

10. No changes to taxiway dimensions are recommended at present. (However, a preliminary assessment only has been made of taxiway risks. This suggests that the present Annex 14 requirements provide adequate safeguarding to deviation during taxiing operations, although the existing dimensions would appear to be somewhat cautious for larger aircraft.)

Obstacle Limitation Surfaces

11. For precision approach, three basic amendments to the existing Annex 14 design recommendations for the approach surface are made, namely:
    - a reduction in the lateral divergence angle (providing that this can also be justified from a technical safeguarding perspective);
    - a reduction in the gradient of the first surface slope;
    - the addition of a third approach surface for Cat I code 1&2 approach aerodromes.
12. The recommended dimensions for the approach surface are summarised as follows[1]:

Characteristic	Cat I codes 1&2	Cat II	Cat III
Divergence	10%	10%	10%
Dist from threshold[2]	60	60	60
Length of inner edge[2]	150	300	300
Length 1st section	3000	3000	3000
Slope 1st section[3]	1.4% (1.1%)	2.5% (1.9%)	2.5% (1.9%)
Length 2nd section	3600	3600	3600
Slope 2nd section	2.5%	2.5%	2.5%
Length 3rd section	8400	8400	8400
Slope 3rd section	0%	0%	0%

13. It is recommended that, for Cat II operations, the inner transitional surface may be truncated at a height of 35m with a new horizontal surface at this height connecting the top of the inner transitional surface to the slope of the transitional surface.
14. As a preliminary recommendation, a take-off surface gradient of 1.2% is suggested, representing a reasonable level of protection based on the requirement of aircraft to achieve this minimum take-off gradient in engine-out conditions.
15. In order to provide more definite recommendations for the OLS, further data collection, either from aircraft tracking or flight simulator studies, is required to assess the level of deviation during:
    - balked landings;
    - non-instrument approaches;
    - take-off.

[1] All distances in metres.
[2] The definition of the start and inner edge length are defined by the runway strip in Annex 14. It is suggested that where changes to the strip dimensions are suggested in the current study, the distance from the threshold of the approach surface remains at 60m as extending this would lead to reduced lateral deviation protection. Additionally, it is recommended that the inner edge length be set to the determined strip width, but with minimum values as shown in the table.
[3] Values in brackets show suggested gradients for glide slopes between 2.5° and 3°.

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Appendices

1 Introduction

This report summarises the findings of the risk analyses undertaken by AEA Technology on behalf of Luftfartstilsynet, the Norwegian Civil Aviation Authority (NCAA), in support of the development of aerodrome design rules. It is proposed that these rules will define the Norwegian requirements for the physical design of aerodromes that can provide for adequately safe traffic handling.

Currently, aerodrome design requirements in Norway are based primarily on the international standards and recommended practices of the International Civil Aviation Organization (ICAO), as set out in Annex 14 to the Chicago Convention [1]. The approach set out in Annex 14 is recognised as having provided an effective basis for the provision of aerodrome safety in the past and it is proposed that it will continue to provide the basis for Norwegian regulation in the future. However, taking account in particular of the special topographic conditions surrounding Norwegian aerodromes, it is anticipated that there may be some scope for improving the effectiveness of that basic framework as applied specifically in Norway. In addition, taking account of the operational experience that has been gained since many of the requirements of Annex 14 were defined, an objective assessment of their effectiveness may be of more widespread interest and provide a basis for more general refinement and future improvement of aerodrome design requirements.

Against this background, the objective of the study has been to illuminate the safety rationales behind the aerodrome design features prescribed by Annex 14 and to determine the design requirements that will enable a certain “target level of safety” (TLS) to be met. As part of the overall study, consideration has been given to determining an appropriate quantitative TLS.

The risk analysis has been undertaken with particular reference to the following aspects of aerodrome design:

- length and reference codes of runways and taxiways;
- runway and taxiway strips;
- runway end safety areas;
- separation distances between runways and taxiways;
- definition of obstacle limitation surfaces.

Essentially, the project objective has been to relate the residual risk associated with relevant operational hazards to the design features that provide protection against those hazards. This should allow definition of the dimensional requirements to achieve a desired TLS, according to the nature of operations at an aerodrome. (It should be noted that the dimensional requirements defined within the project are based on physical safeguarding only and do not account for technical safeguarding[1]; allowance for technical safeguarding may lead to increased restrictions in certain physical design rules, particularly in relation to obstacle limitation surfaces.) The rationale behind the adoption of this “risk-based” or

[1] Technical safeguarding relates to the protection of communication, navigational and surveillance (CNS) system signals from either physical or electromagnetic interference/obstruction.

"objectives-based" approach is simply that provision of safety involves sacrifices in terms of the cost and effort required to provide it and the foregoing of the use of land for other purposes. It is important to ensure that this effort and these sacrifices are properly directed so as to maximise the safety benefit derived from them.

The intention is that insights gained from operational experience, much of which has been gained since many of the ICAO Annex 14 requirements were defined, might support the development of more effective design requirements, tailored to local circumstances. The approach adopted has relied, to a large extent, on the development of empirical risk models based on operating experience. In adopting this approach, it is recognised that such models have their limitations. It is further noted that the resources available when conducting this study were not unlimited and it sought to address a wide range of issues. Notwithstanding these limitations, we believe that the "risk-based" approach offers real benefits and these could be enhanced by further and more detailed analysis to address the limitations of the work undertaken to date.

This account of the risk analysis process includes the following elements, described in turn below:

- a description of existing standards and arrangements at Norwegian aerodromes;
- a general account of the risk assessment process undertaken during the study;
- the presentation of the results of this risk assessment;
- recommendations for design rules based on the risk assessment results;
- some final conclusions to the study as a whole.

More detailed accounts of specific technical elements of the study have been described previously in the project interim report and a series of project working papers. Relevant aspects of the technical basis of the study are summarised in Appendices to this report.

2 Existing Standards and Practices

Existing international standards and recommended practices, as set out in ICAO Annex 14, identify a set of aerodrome dimensions intended to provide for adequate operational safety. (The full requirements under Annex 14 are not repeated here but a summary of relevant aspects is provided in Appendix 1 to this report.) Essentially, these dimensions can be seen as those required to provide adequate clearance between the aircraft and obstacles or other hazards so as to avoid collision and/or damage. We identify two distinct sets of requirements:

- those relating to the physical dimensions of aerodromes, primarily associated with the protection of aircraft during operations on the ground;
- obstacle limitation surfaces, essentially concerned with the protection of airborne aircraft.

In evaluating the safety functions of these dimensions and surfaces and the degree of protection provided by them, it is appropriate to consider two distinct operational scenarios:

- deviation about the intended path, as encountered during normal operations;
- specific fault sequences, outside normal operations, that are sufficiently foreseeable to warrant some level of risk mitigation.

In addition, we should recognise that there may be a further set of fault and accident sequences that are sufficiently unpredictable and uncommon that it is not practical to provide protection against them by means of aerodrome design. Similarly, other incident types may exist that, by their nature, may not be safeguarded against by physical aerodrome design features.

As regards physical characteristics on the ground, we identify the following key features for which Annex 14 identifies specific dimensional requirements:

- the widths of runways and taxiways and the separation distances between a runway and a parallel taxiway, or between a pair of parallel taxiways or taxiway and object, for which the safety rationale is understood to be as follows:
    - in the case of the width of the paved surface, to accommodate the outer gear wheel span and allow for an element of deviation from the runway and taxiway centreline and also protect against engine overhang of non-paved surfaces;
    - in the case of separation distances, to accommodate the wingspan with the outer main gear wheel on the edge of the paved surface with an additional safety margin in case the gear leaves the paved surface.
- the width of the runway strip, along the length of the runway, for which the safety rationale is understood to be as follows:
    - in the case of the graded area of the strip, to reduce the risk of damage to aircraft in the event of excursion from the runway paved surface;
    - in the case of the full strip width, to protect aircraft flying over the strip during take-off, landing and missed approach operations or protect against aircraft collision with obstacles during landing roll veer-off.

- the length of the runway end strip beyond the end of a runway and the runway end safety area (RESA) extending beyond that, for which the safety rationale is understood to be as follows:
    - to reduce the risk of damage to aircraft that undershoot or overrun the runway.

As regards the obstacle limitation surfaces, these are designed to protect airborne aircraft during a variety of airport related manoeuvres, covering:

- take-off and climb;
- approach and landing;
- missed approach and balked landing;
- manoeuvres in the vicinity of the aerodrome prior to approach and landing.

In the case of obstacle limitation surfaces, two distinct functions are identified:

- to restrict the intrusion of obstacles within flight paths thereby ensuring that flight paths remain acceptably safe;
- to provide for the identification and marking of obstacles to ensure that they can be avoided.

The requirements under Annex 14 are defined according to three different criteria relating to the nature of aircraft utilising an aerodrome and the nature of the associated operations:

- the reference code number of the aircraft that the aerodrome is intended to serve, as defined in accordance with the runway length requirements of the aircraft;
- the reference code letter of the aircraft that the aerodrome is intended to serve, as defined according to the width requirements of the aircraft, characterised in terms of wingspan and outer gear wheel span;
- whether the runway is used for take-off or approach operations and, in the case of approach operations, whether these are visual, non-precision instrument or precision instrument operations (either Cat I, II or III).

We identify the following function of the reference code system, according to ICAO Annex 14:

- the intent of the reference code system is to provide a simple method for interrelating the numerous specifications concerning the characteristics of aerodromes so as to provide a series of aerodrome facilities that are suitable for the aeroplanes that are intended to operate at the aerodrome;
- the code is selected for aerodrome planning purposes and, when applying Annex 14, the aeroplanes which the aerodrome is intended to serve are first identified and then the two elements of the code for those aeroplanes: aerodromes intended for use by those aeroplanes should meet the requirements for the identified codes.

Although not developed specifically for the purposes of regulation, Annex 14 requirements are often employed as a basis for aerodrome regulation. The starting point for regulation on this basis is that aerodromes that conform with Annex 14 requirements can be assumed to provide the basis for operational safety that meets international standards. Where specific requirements are not met, these non-conformances should be identified and evaluated and, if necessary, addressed by appropriate compensatory measures. In general, this is an element of approach to aerodrome safety regulation adopted in Norway, as well as many other countries.

If such aerodrome design requirements are to be employed as a basis for safety regulation it is important that the relationship between them and the level of safety provided is properly understood. This is especially important within the Norwegian context where the special topographic conditions often encountered in mountainous regions may lead to non-conformances with Annex 14 requirements. Such non-conformances may relate on the one hand to the penetration of obstacle limitation surfaces by terrain or, on the other, to difficulties in providing sites that can meet the requirements for aerodrome physical dimensions. Given the very considerable costs that might need to be incurred in these circumstances, to bring an aerodrome into compliance and the effort that might otherwise need to be expended on additional regulatory oversight, it is particularly important that the relationship between the aerodrome features and the safety they provide is properly understood.

In evaluating the ICAO Annex 14 aerodrome design requirements against a risk-based framework, it is appropriate to consider two distinct aspects:

- the dependence of design requirements on the three key criteria of reference code number, reference code letter and category of operation (instrument/non-instrument, take-off/landing) and whether the dependences under Annex 14 provide the most appropriate basis for provision of safety to a given level;
- the physical dimensions that are required in order for a given type of operation to meet a given TLS and whether the Annex 14 requirements provide safety to the desired level or are unnecessarily onerous, given the level of safety that they provide.

Although this study has been focused on the relationship between aerodrome design requirements and safety, it is recognised that operational practices and procedures are key elements in the provision of aviation safety and practical design requirements cannot be defined without some reference to these operational matters. In some cases, therefore, design requirements in excess of those defined here on the basis of safety provision may be necessary to meet operational needs.

3 Risk Assessment Process

The process for risk assessment undertaken during the study has comprised the following elements:

- Development of quantitative risk standards or "target levels of safety" (TLS) against which to evaluate the level of safety provided by the design features of interest;
- Functional Hazard Analysis (FHA) to identify hazards to operations and the relationship between aerodrome features and the mitigation they provide against those identified hazards;
- Development of quantitative risk models, typically allowing the characterisation of risk in terms of the likelihood of occurrence of certain hazard scenarios, the location of an aircraft during such an event in relation to the intended path and the safety margin provided by the relevant aerodrome design feature, and the severity of the incident consequences.

This risk assessment process was underpinned by an initial review of standards and practices and of aerodromes in Norway, as summarised above and described more fully in the project Interim Report. The risk assessment process involved extensive liaison between AEA Technology and the NCAA's working party. In particular, this process involved the development of a series of technical working papers describing the various hazard analysis and risk assessment studies. These working papers were distributed to the working party and reviewed at a series of project meetings. Here we summarise the main findings of each of the three primary elements of the risk assessment.

3.1 TARGET LEVELS OF SAFETY

The basic TLS against which to evaluate residual risk levels associated with the various aerodrome design features has been established primarily by reference to historical incident rates, taking account also of other quantitative standards employed, in particular though not exclusively within the aviation industry. In addition to developing a quantitative TLS, consideration has been given to the broader risk management framework in which quantitative standards may best be employed. The overall review process undertaken to support the development of quantitative TLS values is described in Appendix 2. Here we provide a summary of its primary findings.

On this basis we identify a fatal (total hull loss) accident rate for airport related accidents of approximately 0.2 per million movements (2 x 10^{-7} per movement) as the primary residual risk benchmark for "first world" operations. A number of distinct hazard scenarios contribute to this total rate and therefore, if this total risk "budget" is apportioned between different hazards, the TLS for any single hazard will be correspondingly lower than this overall rate. On this basis, we propose the use of a basic "benchmark" TLS of 10^{-7} per movement, recognising that we would wish to improve upon this where possible, such that a TLS of 10^{-8} per movement might be preferred where practicable. Risks below 10^{-9} per movement may generally be regarded as small and of minimal regulatory concern.

Having proposed these basic quantitative standards, we identify the need for caution when employing them and the need to give particular consideration to the circumstances in which they are to be applied. In the current context we note that overrun and controlled flight into terrain (CFIT) accidents on approach and landing are major contributors to the overall total hull loss rate of 2×10^{-7} per movement. We note further that accident rates vary significantly according to the nature of operations, with some types of operation exhibiting a risk that is somewhat higher than the recent historic average and others exhibiting a risk that is correspondingly lower. It may therefore not be realistic to expect that the TLS of 10^{-7} per movement based on the average accident can be generally achievable, even when apportioned between a number of hazard scenarios.

We note also that the severity of incident consequences is a further consideration in the setting of safety targets. Certain aspects of physical aerodrome safeguarding may protect against incidents that are unlikely to result directly in catastrophic consequences, such as low speed aircraft wingtip collisions during taxiing operations. The acceptable level of frequency with which such incidents occur will obviously be higher than for catastrophic events, and hence a higher TLS will be appropriate.

In addition, we note that operational practices and procedural measures as well as aerodrome design features contribute to airport safety. In some situations, safety improvements might be more effectively achieved through directing attention to such measures rather than increasing the safety margins provided by aerodrome design.

3.2 FUNCTIONAL HAZARD ANALYSIS

A Functional Hazard Analysis is a formal and systematic process for the identification of hazards arising from the undertaking of functions or operations associated with an activity. The purpose of the FHA in the context of this Aerodrome Design Rules study is to determine relevant hazards to aircraft associated with aerodrome operations (*e.g.* approach, landing, taxiing, take-off roll, and associated fault sequences) and the physical design of aerodromes. The FHA also enables the identification of the associated controls currently (or potentially) in place to manage these hazards. The output of the FHA is a systematic description of a comprehensive set of hazard sequences and the relevant mitigation/control measures, with particular reference to the risk mitigation functions of the various aerodrome design features. This preliminary hazard analysis provides an insight to support the series of risk analyses that have been undertaken to support the development of rational risk-based design rules.

The basic technique employed involves gathering together a multi-disciplinary team, with the purpose of identifying hazards by brainstorming in a workshop, or series of workshops. The key principle of the process is that it is a team effort, in which the brainstorming technique stimulates creativity, encourages expansive thinking and generates ideas. Structure in the workshop is provided by an experienced team leader (or “facilitator”) whose role is to systematically guide the team through the process. The operations under consideration are broken down into “nodes” or parts of the operations to make the assessment process manageable, and hazards are identified by the application of a set of "keywords" (or prompts) which help to ensure that the process is explored in detail and in a comprehensive way. The workshop findings were recorded using a risk register by the technical secretary and made available for review by workshop participants.

A detailed account of the functional hazard analysis workshop is presented in Appendix 4. The primary findings are summarised below. The types of operation and the associated hazard incident types are summarised in Table 1.

Table 1 Incident Types by Operational Phase

Operational Phase	Associated Incident Types
Take-off roll	Veer-off, Over-rotation, Under-rotation, Overrun, Collision
Rejected take-off	Veer-off, Overrun, Collision
Wheels-off to 35 feet	Veer-off, Over-rotation, Under-rotation, Overrun, Collision
Take-off climb out	Veer-off, under-rotation, Over-rotation, Collision
Circling	Collision
(Precision instrument) approach	Veer-off, Under approach point, Collision
Missed approach	Veer-off, Under-height, Collision
Balked landing	Veer-off, Under-height, Overrun, Collision
Landing	Land-short, Land-long, Land-offset, Veer-off, Overrun, Hard-landing, Collision
Taxiing	Veer-off, Collision

On the basis of the workshop output, a number of key generic causal factors for hazards associated with the various operational modes were identified, as summarised in Table 2.

Table 2 Key Generic Causal Factor by Operational Mode

Operational Modes	Key Generic Causal Factors	
Take-off roll	• Communications • Visibility • Surface conditions • High/low velocity/momentum	• Winds • Aircraft performance characteristics • Vortex shedding • Other vehicles
Rejected take-off	• Aircraft performance characteristics • Winds • Visibility	• Crew competency • Other vehicles
Wheels-off	• Icing (wings/engines) • Winds	• Vortex shedding
Take-off climb-out	• Icing (wings/engines) • Aircraft performance characteristics • Bird strike	• Winds • Vortex shedding • High/low velocity/momentum
Circling	• Loss of lights	• Loss of visual reference
Approach	• Communications • Aircraft performance characteristics • Winds	• Icing of wings/engines • High/low velocity/momentum
Missed Approach	• Faulty equipment (altimeter) • High/low velocity/momentum	• winds • Icing of wings/engines
Balked landing	• Vortex shedding • Winds • Crew experience/competency • Visibility	• Icing of wings/engines • High/low velocity/momentum • Aircraft performance characteristics • Other vehicles
Landing	• High/low velocity/momentum • Aircraft performance characteristics • Communications	• Surface conditions • Equipment failure (flaps)
Taxiing	• Pilot workload/error	• Visibility

3.3 RISK ANALYSIS

The risk analysis undertaken during the study was based primarily on review of operational experience, in particular accident and incident data, taking account of the findings of the Functional Hazard Analysis. On the basis of the information derived from this process, a series of quantitative risk models have been developed that describe a number of distinct hazard scenarios and these models enable the safety margins provided by the various aerodrome design features of interest to be evaluated. As indicated earlier, two distinct operational scenarios have been considered:

- deviation of aircraft about the intended path, as encountered during normal operations;
- specific fault sequences, outside normal operations, that may lead to deviation of an aircraft from its intended path and that are sufficiently foreseeable to warrant some level of risk mitigation.

The risk models have been developed primarily by reference to empirical data, derived from measurements during operation or from historical accident analysis. For example, the risk model in respect of the approach surface was based on the likelihood of deviation of an aircraft vertically from the intended glide slope and laterally from the extended runway centreline during approach and landing, as determined from operational measurement and from consideration of instrument landing system performance. In the case of overrun and undershoot risk, the models were derived from historical accident data on the frequency of occurrence of these events and the probability of touchdown or overrun a given distance from the runway.

In the development of the risk models, consideration was given to operational and external factors that may influence the level of risk and their possible inclusion within the model. The risk models developed and the aerodrome design features to which they relate are as follows:

- take-off and landing overrun risk models, in relation to the provision of runway end strip and runway end safety area (RESA);
- landing undershoot risk model, in relation to the provision of runway end strip and runway end safety area (RESA);
- lateral veer-off model, for take-off and landing operations, in relation to the width of the runway strip (in particular the graded area of the strip);
- taxiway deviation model, in relation to the separation distances between a runway and a parallel taxiway, between parallel taxiways and between an object and a taxiway;
- approach and landing deviation model, in relation to the approach and landing surfaces;
- missed approach/balked landing deviation model, in relation to the runway strip width, the inner and outer transitional surfaces and the balked landing surface.

The results of each of these elements of these risk analyses are presented below in Section 4.

4 Risk Assessment Results

Here we present a summary of the primary findings of the risk analysis undertaken to support the design rule development. Further detail on the process and the risk models derived from it are provided in Appendices 5 and 6.

4.1 OVERRUN RISK ANALYSIS

The overrun risk analysis was based on review of an extensive data set of historical take-off and landing overrun incidents. The main results of the analysis may be summarised as follows:

- There is a clear distinction between take-off and landing overrun risk, both in terms of the likelihood of an incident occurring and the likely distance travelled beyond the runway end in the event that an overrun occurs. Overrun is less likely on take-off than on landing but take-off overruns typically travel greater distances beyond the runway end. It is therefore appropriate to model take-off and landing overrun risks separately.
- The likelihood of overrun varies considerably according to the amount of runway available in excess of that required (as calculated in accordance with normal operating practices). In the case of landing incidents, where the landing distance required (LDR) is equal to the landing distance available (LDA), for the aircraft and runway in question, the likelihood of overrun is estimated to be at least ten times the "average" historical rate. For take-off incidents, where the accelerate stop distance required (ASDR) is equal to the accelerate stop distance available (ASDA) the likelihood of overrun is slightly below ten times the "average" rate. (The "average" rate is dominated by movements where there is a significant "excess" runway above the minimum required and where overrun is significantly less likely, even where an aircraft exceeds the ADSR or LDR during a given take-off or landing incident.) It is noted that runway length limited operations (*i.e.* operations with limited excess runway available) are relatively common at many of the small-to-medium size Norwegian aerodromes.
- For landing overrun, the rate of incidents appears to vary significantly according to the availability or lack of precision approach landing aids. Review of the incident records finds that non-precision/visual approach movements have an overrun rate approximately eight times higher than that for precision approach movements. This correlation may be due to a direct link between the lack of the precision approach aid and overrun risk, associated with the accuracy of hitting the intended touchdown zone, although we identify the possibility that the correlation may, at least in part, be associated with other factors (for example a higher frequency of movements with no "excess" runway at aerodromes with smaller runways that also lack precision approach aids (though our analysis finds no evidence for this) or the use of such aerodromes by smaller operators that may operate to lower safety standards).
- In summary, we identify the following rates of overrun incidents for different types of operation:
  - Take-off overrun: 0.33 per million movements;
  - Precision approach landing overrun: 0.6 per million movements;
  - Non-precision/visual approach landing overrun: 4.68 per million movements;

The above are "average" historical rates and, as discussed earlier, rates up to ten times higher or more are predicted where there is no "excess" runway available above that required.

- On the basis of historical incident data, the likely distance travelled beyond the runway end in the event of an overrun can be represented by a cumulative probability distribution function, describing the fraction of incidents (*N*) travelling a given distance (*x*) or more, of the : $N(x) = exp(- a x^n)$ (where *a* and *n* are constants). Take-off overrun incidents travel further beyond the runway end, on average, than landing overrun incidents and different functions are required to describe take-off and landing overrun. These functions can be employed to estimate the proportion of incidents that would be protected by a RESA extending to any chosen distance from the runway, as considered further below.
- The potential dependence of overrun distance on other operational parameters, in particular aircraft type, was also considered. Separate data sets comprising turbo-prop and jet aircraft and aircraft above 100,000 lbs and below 50,000 lbs MTOW were analysed. No significant differences could be identified between the overrun incident characteristics exhibited by the different data sets and no clear dependence on aircraft type could be identified.
- A variety of other parameters can be identified that may influence overrun risk but these cannot be readily factored into a quantitative risk model. However, it is instructive to consider the causal and contributory factors identified for overrun incidents. These are summarised below in turn for take-off and landing incidents.
- Of 32 take-off incidents reviewed, for 17 cases it is explicitly stated that a rejected take-off was involved and it would appear that several other incidents involved a conventional rejected take-off. A variety of initiators for the rejected take-off were identified, including engine problems (4 cases), landing gear faults (5 cases), bird strike (2 cases), false warnings (2 cases) and pitot fault (2 cases). Use of the wrong runway was identified as the cause of the incident in 3 cases. Faulty or incorrect setting of control surfaces was identified in several instances and in one case, miscalculation of aircraft weight is identified. In 3 cases, a wet runway was identified as contributing to the overrun and in 2 cases braking problems were identified. In summary, within the above types of incident, a number of more typical scenarios can be identified (*e.g.* the conventional rejected take-off) for which the design rules should provide adequate protection.
- A wide variety of causal factors contributing to the landing overrun are identified, and in many cases multiple factors are identified. Factors identified include the following:
    - Landing long;
    - Excess speed;
    - Poor approach;
    - Tailwinds;
    - Adverse crosswinds;
    - Wet or icy runway;
    - Brake system failure;
    - More general aircraft systems failure;
    - Landing on the wrong runway;
    - Poor visibility.

Of 93 landing incidents reviewed, wet or icy runways are identified as contributory in 38 incidents but in only 9 of these cases is this the only causal factor identified. Landing long, a poor approach and excess speed (or combination of these factors) are identified as relevant factors in 46 cases. Aircraft faults are identified in 21 incidents, including 16 cases of brake system faults, 1 case of a landing gear fault and 4 cases of more general aircraft system failure (fuel starvation, power plant failure, electrical system failure). Selection of the wrong runway was identified in 6 cases. As for the take-off incidents, we can identify a number of more typical scenarios that any design rules developed on the basis of the proposed risk model should address.

- In the case of both take-off and landing overrun, we can identify a limited number of what might be considered more gross failures or errors (*e.g.* selection of the wrong runway) which may not be so readily protected against by (dimensional) aerodrome design features. Such incidents tend to be associated with aircraft travelling longer distances from the runway.

In summary then, a generic risk model has been developed from the above analysis and is based on the following:

- the frequency of occurrence of overrun incidents, with a separate rate being identified for take-off, precision approach landing and non-precision/visual approach landing and a factor being applied to take account of the available “excess” runway;
- a cumulative probability distribution function describing distance travelled in the event of occurrence of an overrun, in terms of the fraction of overruns travelling a given distance or more, with separate functions being employed for take-off and landing incidents.
- the severity of the incident consequences: for the current purposes it is assumed that any aircraft that travels beyond the RESA may potentially be in collision with an obstacle or run down an embankment suffering potentially catastrophic consequences (total hull loss and/or fatalities).

On the basis of this model, the residual risk can be calculated for the three various types of operation for various lengths of runway end strip and RESA provision. For the current purposes, the residual risk associated with the runway end strip and RESA lengths according to Annex 14 standards and recommended practices have been estimated and are set out in Table 3 below.

Table 3 Residual overrun risk (per million movements) associated with ICAO Annex 14 specifications

Runway Code	Strip plus RESA		Take-off		Precision approach landing		Non-precision/ visual approach landing	
	Std	***Rec.***	**Std**	***Rec.***	**Std**	***Rec.***	**Std**	***Rec.***
1 non-instrument	30 m	*150 m*	0.277	*0.138*	-	-	3.670	*1.389*
2 non-instrument	60 m	*180 m*	0.233	*0.116*	-	-	2.879	*1.089*
1/2 instrument	150 m	*180 m*	0.138	*0.116*	0.178	*0.140*	1.389	*1.089*
3/4	150 m	*300 m*	0.138	*0.058*	0.178	*0.053*	1.389	*0.412*

The identified residual risk is that for the “average” movement with “excess” runway available. Where no “excess” runway is available the take-off risks will be slightly below ten times higher and the landing risk slightly more than ten times higher than those in the table.

Similarly, the model can be employed to determine the length of runway end strip and RESA required to meet a given TLS. For a TLS of 10^{-7} per movement, the following distances would be required:

- take-off “average” movement case: 206 m;
- take-off “no excess runway” movement case: 603 m;
- precision approach landing “average” movement case: 221 m;
- precision approach landing “no excess runway” movement case: 505 m;
- non-precision/visual approach landing “average” movement case: 475 m.

Given the exponential nature of the distribution function, the safety benefit provided by any given increment in the combined length of runway end strip and RESA reduces progressively at distances further from the runway end and it is instructive also to consider the proportion of incidents predicted to be contained within defined distances beyond the runway. These are tabulated in Table 4 (together with results obtained from the undershoot analysis described in the following section).

Table 4: Proportion of incidents contained within a given strip end /RESA distance

Distance (m)	Fraction of take-off overruns contained	Fraction of landing overruns contained	Fraction of undershoots contained
0	0	0	0
50	0.252	0.333	0.543
100	0.439	0.555	0.693
150	0.582	0.703	0.777
200	0.688	0.802	0.831
250	0.767	0.868	0.869
300	0.824	0.912	0.896
350	0.870	0.941	0.916
400	0.903	0.961	0.932
450	0.927	0.974	0.944
500	0.945	0.983	0.953

From Table 2 we see that of the order of 90% of incidents are contained within the first 300m, which represents the ICAO Annex 14 recommended practice at codes 3 & 4 runways and that a small proportion (5% or less) travel further than 500m. This emphasises the decreasing safety benefit associated with increasing the RESA length further from runway. Whereas 90% of incidents would be contained within a RESA extending over the first 300m this would be improved to around 95 to 98% by increasing the RESA by a further 200m to a total of 500m.

We conclude that the risk model and the relationship between RESA length and residual risk it defines provides a basis for establishing risk-based design rules for RESA provision. Key points to note arising out of the risk analysis that can inform that process are as follows:

- There is no apparent distinction between overrun risk at codes 1 & 2 runways and the risk at codes 3 & 4 runways that would support a risk-based justification for a difference in the design requirement in respect of the runway end strip and RESA, as currently prescribed by ICAO Annex 14: meeting a chosen TLS would require the same standard for all runway codes;

- Neither is there a risk-based justification for a lesser requirement for runway end strip and RESA at non-instrument runways compared with that for instrument runways, as currently prescribed by ICAO Annex 14: the risk at non-instrument runways is identified as higher than that at precision instrument runways which would, if anything, justify a greater requirement in the non-instrument case (though the precise nature of any causal relationship between the type of approach available and the overrun risk is difficult to determine on the basis of the available data);
- Given the dependence of residual risk on operational parameters that differ significantly between aerodromes, it may not be practical to define design requirements to meet a single TLS in all cases. Specifically, the issues to be addressed are the critical dependence of overrun risk on the amount of "excess" runway available and the availability of precision approach aids. The incident statistics upon which the basic benchmark TLS of 10^{-7} per movement is derived are dominated by movements at larger aerodromes where precision approach aids are typically available and where there is often a significant length of "excess" runway. This TLS cannot be readily achieved by increased RESA provision at smaller aerodromes where precision approach aids are lacking and there is little or no "excess" runway for typical movements.
- A key consideration in evaluating the RESA requirement, relevant to the previous point, will be the safety benefit that any given increment in RESA length provides. This safety benefit diminishes significantly at greater distances from the runway end, putting a practical limit on RESA length around the current recommendation for codes 3 & 4 runways.

4.2 UNDERSHOOT RISK ANALYSIS

The undershoot risk analysis that has been undertaken is similar in principle to the overrun risk analysis presented above. It is based on the review of historical accidents and has led to the development of a quantitative risk model comprising:

- the likelihood of occurrence of an undershoot accident on landing; and
- the probability distribution of the distance by which the aircraft undershoots the runway threshold in the event that an undershoot occurs.

Another key feature of the undershoot risk analysis similar to the overrun analysis is the identified dependence of incident likelihood on the availability or lack of precision approach landing aids (though again, the nature of the causal relationship between approach aid provision and incident frequency is difficult to determine). As regards consequences, it is assumed that any aircraft that touches down before the RESA may potentially be in collision with an obstacle or embankment and so suffer potentially catastrophic consequences (total hull loss, fatalities).

The main findings of the analysis are as follows:

- The likelihood of undershoot is, on average, somewhat lower than that for overrun and is approximately four times less likely than landing overrun. The average undershoot rate we derive from available incident statistics is 0.25 per million movements.

- The undershoot rate shows a significant correlation with the availability or lack of precision approach aids, being roughly six times more likely for movements in the absence of precision approach aids. On this basis, we derive undershoot rates as follows:
  - Precision approach undershoot rate: 0.17 per million movements;
  - Non-precision/visual approach undershoot rate: 1.08 per million movement.
- The undershoot location can be described in terms of a cumulative probability distribution function describing the fraction of incidents in which the aircraft touches down a given distance or more from the threshold, as follows: $N(x) = exp(- a x^n)$. Compared with overrun, the distribution of incident locations falls off more rapidly with distance from the runway, at least for the region of primary interest closer to the runway.
- No clear dependence of undershoot risk on aircraft type (jet versus turboprop or aircraft size) has been identified.
- Taking together the lower rate of incidents and the rapid decline in the cumulative probability distribution function for undershoot compared with overrun, undershoot is identified as representing less of a risk than overrun and hence the RESA length required to meet a given TLS in respect of undershoot is typically less than that required in respect of overrun.

On the basis of this model, the residual undershoot risk can be calculated for various types of operation for various lengths of runway end strip and RESA provision. As before, the residual risk associated with the runway end strip and RESA lengths according to Annex 14 standards and recommended practices have been estimated and are set out in Table 5 below.

Table 5 Residual undershoot risk (per million movements) associated with ICAO Annex 14 specifications

Runway Code	Strip plus RESA		Precision approach landing		Non-precision/ visual approach landing	
	Std	*Rec.*	Std	*Rec.*	Std	*Rec.*
1 non-instrument	30 m	*150 m*	-	-	0.606	*0.241*
2 non-instrument	60 m	*180 m*	-	-	0.451	*0.203*
1/2 instrument	150 m	*180 m*	0.038	*0.320*	1.389	*0.203*
3/4	150 m	*300 m*	0.038	*0.018*	1.389	*0.112*

Similarly, the model can be employed to determine the length of runway end strip and RESA required to meet a given TLS in respect of undershoot. For a TLS of 10^{-7} per movement, the following distances would be required:

- precision approach: 24 m;
- non-precision/visual approach: 330 m.

As is the case for overrun, the exponential nature of the distribution function is such that the safety benefit provided by any given increment in the combined length of runway end strip and RESA reduces progressively at distances further from the runway end. The proportion of undershoot incidents contained within a given distance is summarised in Table 4 (together with results obtained from the overrun analysis described in the previous section). It can be seen that, as for overrun, the vast majority of incidents (90%) are contained within the first 300 m before the threshold.

The conclusions to be drawn from the undershoot risk analysis are similar in principle to those drawn from the overrun risk analysis:

- There is no apparent distinction between the undershoot risk at codes 1 & 2 runways and the risk at codes 3 & 4 runways that would support a risk-based justification for a difference in their design requirements in respect of the runway end strip and RESA, as currently prescribed by ICAO Annex 14;
- Neither is there a risk-based justification in respect of undershoot risk for a lesser requirement for runway end strip and RESA at non-instrument runways compared with that for instrument runways, as currently prescribed by ICAO Annex 14: the risk at non-instrument runways is identified as higher than that at precision instrument runways which would, if anything, justify a greater requirement in the non-instrument case;
- Given the dependence of residual risk on operational parameters, specifically the availability or lack of precision approach aids, it may not be practical to define design requirements to meet a single TLS in all cases.
- The diminishing safety benefit of increasing RESA provision at greater distances from the runway end is a key consideration in evaluating the RESA requirement and places a practical limit on RESA length around the current recommendation for codes 3 & 4 runways.

4.3 LATERAL VEER-OFF RISK ANALYSIS

The lateral veer-off risk analysis addresses lateral deviation from the runway during take-off and landing operations. In this context, we identify three primary hazard scenarios:

- Lateral veer-off beyond the runway paved area, where the outer gear wheels are contained within the graded area.
- Lateral veer-off beyond the runway paved area where the outer gear wheels are not contained within the graded area but where the wing tip is contained within the runway strip width.
- Lateral veer-off beyond the runway and collision on the ground, with an object, (aircraft wingtip excursion beyond the runway strip) during either take-off or landing roll.

As with the overrun and undershoot risk analysis, the approach to analysis of lateral veer-off risk is based on the estimation of both likelihood of a veer-off event and the likely extent of deviation from the runway centreline in the event of veer-off, as derived from historical incident data. However, in this case we are dealing with lateral deviations and it is necessary to take account of the widths of the aircraft, *i.e.* wingspan and outer gear wheel span, compared with the widths available.

It is important to recognise the identified safety functions of the graded area of the strip and the full strip width. The graded area of the strip only can be assumed to provide an adequate safe load bearing surface for an aircraft. The area beyond the graded area up to the full strip width should be obstacle free so as to protect an airborne aircraft but need not be load bearing and could include an embankment down to water, or other hazard to aircraft that veer-off the runway. In many cases, the full strip may provide a safe load bearing surface for aircraft but there are other instances in Norway in which it would not. In those cases where the strip width does not provide a safe load bearing surface, aircraft subject to the second hazard scenario would be exposed to potentially catastrophic consequences and would not travel further to a point at which the wingtip deviates beyond the full strip width, as in the third scenario.

The general findings of the risk analysis are as follows:

- Recorded veer-off events are more frequent for landing than for take-off and we derive the following rates on the basis of the number of incidents identified:
    - Veer-off frequency during take-off: 0.19 per million movements;
    - Veer-off frequency during landing: 0.56 per million movements.
- Landing veer-off events are significantly more frequent (approximately seven times more frequent) for movements where precision approach aids are lacking, compared with those where precision approach aids are available. The veer-off rates for landing movements, broken down according to approach type, are therefore as follows:
    - Precision approach landing veer-off rate: 0.364 per million movements;
    - Non-precision/visual approach landing veer-off rate: 2.58 per million movements.
- The distance of veer-off from the runway centreline can be described by a cumulative probability distribution function of the form, $N(x) = exp(- a x^n)$. (The deviation as identified by the model is essentially the mid-point of the aircraft and the aircraft is assumed to be aligned parallel to the main axis of the runway. This is a simplifying assumption that deserves some further consideration when applying the model and interpreting the results. It is also noted that the available data for smaller-scale veer-off incidents is likely to be limited due to the nature of incident reporting and hence the derived model is somewhat uncertain, particularly for such veer-off distances) Lateral veer-off distances are, on average, greater for take-off than for landing movements.
- No clear dependence of deviation distance on aircraft type can be identified from the available data. However, there is a suggestion that the veer-off distance on take-off may increase with the take-off distance required (and hence reference code number). This would seem logical on the basis that, if an aircraft starts to deviate to the side of the runway along a given heading in relation to the runway axis, its lateral deviation will be greater the greater the distance it travels. The data set available is too small to allow any correlation to be identified with confidence. For landing veer-off, the larger data set gave no indication of a correlation. On the contrary, if anything, the data set suggests that smaller aircraft deviate further on average than large aircraft, though this finding is of limited statistical significance.

On the basis of the above analysis a basic risk model can derived, describing the likelihood of deviation to a given distance or more from the runway centreline, separately for take-off, precision approach landing and non-precision/visual approach landing movements. This has been applied to determining the likelihood of either outer gear wheel deviation or wing tip deviation a given distance from the runway centreline for aircraft of different letter codes, having specific regard to the ICAO Annex 14 requirements for different aerodrome reference codes. Since any given code accommodates aircraft with a range of outer gear wheel span and wingspan, we determine an upper and lower risk for each aerodrome code, corresponding with the upper and lower limits of the aircraft dimension for the code in question. The estimated risks cover a wide variety of combinations of runway designation and aircraft reference codes. Further details concerning the risk analysis and the residual risk associated with these different combinations is described in Appendix 4. Here we provide a brief summary of the estimated risks.

A key point to note is that ICAO Annex 14 requirements are dependent upon both the aerodrome number and letter code. However, the risk analysis identifies no clear dependence of the deviation on aircraft type. (The deviation, as identified in the model, is essentially the mid-point of the aircraft and so the deviation of the outer edge of the gear wheel or of the wingtip will vary with the aircraft dimension.) From a risk-based perspective, it is not logical according to the findings of the risk model, to define the lateral dimension requirements as a function of the reference code number which relates to runway length requirements rather than lateral clearance requirements of aircraft.

As regards deviation of the gear wheel from the runway, the deviation risk for runway widths meeting Annex 14 requirements is found to cover a fairly small range for all runway reference codes. This risk is estimated to be in the range of 0.13 to 0.3 per million movements for take-off and precision approach and in the range of 1.5 to 2.24 per million movements for non-precision/visual movements. Given that deviation from the runway onto the graded area of the strip results in comparatively minor consequences, these risk levels are considered acceptable, at least from a safety perspective.

As regards gear wheel deviation beyond the graded area, the consequence must be regarded as potentially catastrophic. According to the runway and aircraft reference code, the risk is again estimated to cover a relatively small range for all cases and is in the range of 0.06 to 0.15 per million movements for take-off and precision approach movements and 0.46 to 1.41 per million movements for non-precision/visual movements. In summary, on the basis of the risk analysis we therefore predict that the Annex 14 requirements for the width of the graded area provide a residual risk at around the TLS of 10^{-7} per movement for take-off and precision approach movements. Given the higher incident rate for non-precision/visual movements the Annex 14 requirements provide a residual risk around 10^{-6} per movement.

The risk of wingtip deviation beyond the full strip width has (in those cases where the full strip width can support an aircraft such that it can deviate further beyond the graded area of the strip) a consequence which is again regarded as potentially catastrophic (potential collision with obstacle). Distinctly different ICAO Annex 14 requirements for the full strip width are defined for instrument and non-instrument runways, in addition to the requirement being dependent on the reference code. For take-off and precision approach movements, the residual risk lies in the range of 10^{-7} to 10^{-8} per movement, according to the runway code. For non-precision/visual movements, the residual risk lies in the range of 10^{-6} to 10^{-7} per movement, according to the runway code.

In summary, from a safety perspective, we identify the following primary conclusions concerning the runway strip widths and lateral veer-off risk:

- Two distinct lateral veer-off hazard scenarios that lead to serious consequences can be identified that relate on the one hand to deviation of the gear wheels beyond the graded area of the strip and deviation of the wingtip beyond the obstacle free zone provided by the full strip width: a risk-based approach to defining strip width requirements should accommodate both scenarios.

- The ICAO Annex 14 requirements for strip width according to runway designation are not logical from a risk-based perspective, in particular concerning the dependence on reference code number: this leads to a range of residual risks for different runway codes.
- Given the dependence of residual risk on operational parameters, specifically the availability or lack of precision approach aids, it may not be practical to define design requirements to meet a single TLS in all cases.

Finally, it is worth considering the impact on the risk predictions of the simplifying assumption in the model that the aircraft remains aligned parallel with the main axis of the runway during the veer-off incident. Evidently, the aircraft must be non-aligned to some extent during a veer-off. An aircraft may then be more at risk of nose gear rather than outer main gear wheel deviation beyond the graded area or of nose rather than wingtip deviation outside the total strip width. Given the relative length to width dimensions of typical aircraft, the risk is likely to be broadly similar in either case and, within the limits of the risk model, this simplification is not considered likely to impact significantly on the validity of the risk predictions.

In addition to veer-off to the side of the runway, we identify the risk of lateral deviation beyond the runway end, in the event of an overrun. Review of accidents shows that some degree of lateral veer-off from the runway extended centreline is common during overrun incidents. On the basis of the veer-off observed during overrun, a cumulative probability distribution function can be derived to describe the likelihood of deviation beyond a given distance. The distribution is essentially similar to that observed for lateral deviation to the side of the runway, as described above, and provides a basis for establishing a risk-based design requirement for RESA width.

4.4 TAXIWAY DEVIATION RISK ANALYSIS

The physical dimensions of taxiways are defined through a range of design rules. With regard to the protection of aircraft deviating during taxiing, the design rules have been considered in two respects:

- the width of taxiways, in relation to the risk of aircraft excursion from the taxiway and the graded portion of the strip; and
- the separation distances between parallel taxiways and between taxiways and physical obstacles, in relation to the risk of collision.

The risks associated with lateral deviation during both runway operations (*i.e.* landing and take-off roll) and taxiing operations have also been considered with respect to runway-to-taxiway separation distances.

Risk models for the deviation of aircraft during taxiing operations have been developed from empirical taxiing monitoring data. Taxiing deviation monitoring data is presently being collected as part of an ongoing international study into the development of appropriate design rules for taxiways that includes the FAA and BAA. Some preliminary monitoring data from Anchorage have been supplied by the FAA and this has enabled the development of simple risk models for the NCAA design rules project. However, several problems with the development of such models at present have been identified:

- A lack of information on the causal and influencing factors behind taxiing deviation that makes the construction of detailed models difficult.
- Because of the inability to assess causal factors of deviation, extrapolation of the results to the Norwegian case is uncertain.
- The presently available data set comprises some 3000 events and so extrapolation beyond the data is required to assess the risks at the levels of 10^{-6} to 10^{-7} per movement. Such extrapolation is fraught with uncertainty and the development of sophisticated analysis techniques to address this issue is beyond the scope of the present study.
- In order to assess design rules to meet a TLS framed in terms of the risk per taxiing movement, the taxiing risks need to be integrated over the whole taxiway route and over whole aerodromes. This presents a number of difficulties:
  - the model requires knowledge of the length, nature and frequency of use of the taxiways, all of which are aerodrome and taxiway specific, thus making the derivation of generic rules problematic;
  - the precise method of integration requires an improved understanding of the taxiing paths in order to prevent double counting of the overall risk of deviation beyond the taxiway/taxiway separation limits.

Resolution of the above issues is not possible within the constraints of the current project or with the level of data presently available. However, it is noted that the ongoing international studies being undertaken by the FAA and BAA will attempt to address and resolve these problems. Unfortunately the timescales for the completion of these international studies are beyond the timeframe of the Norwegian Aerodrome Rule project. In the meantime, a simple quantitative assessment of individual taxiway sections in isolation has been undertaken, including qualitative consideration of how these risks may be used as the basis for generic design rules (see Appendix 5 for further details). To overcome the problems of extrapolation beyond the limits of the available data, a range of curves has been fitted to the data to provide an envelope around the risks of greater levels of deviation.

In particular we have assessed the risks associated with the current Annex 14 recommendations against a defined TLS (as collisions during taxiing are unlikely to lead to catastrophic consequences, a TLS of 5 x 10^{-6} per movement is suggested). Through consideration of these risks, we conclude that the current Annex 14 recommendations are likely to provide adequate safeguarding for all taxiing operations and that the basis of the current reference system, which defines the taxiway dimensions as a function of aircraft wingspan and wheelspan, is appropriate.

Results of the assessment suggest that the risks more closely challenge the TLS for the smaller aircraft (*i.e.* codes A to C) and we find that the risks associated with the current Annex 14 dimensions are at worst in the region of 10^{-6} to 10^{-7} per movement on any taxiway section. (The risk levels are similar in relation to all the assessed aspects of taxiway design, including strip width and separation distances). It is also found the present Annex 14 recommendations are likely to be somewhat cautious for larger aircraft (*i.e.* codes D to F), with the risks for code F aircraft generally estimated to be of the order of 10^{-11} per movement or lower for all aspects of taxiway deviation risk. However, given the uncertainties in the method of assessment and that the taxiway strips provide other forms of protection (*e.g.* safeguarding against FOD engine ingestion) reductions in the taxiway dimensions are not recommended at present.

One important finding from the assessment of the deviation monitoring data is that no strong correlation was found to exist between the aircraft size and the level of deviation from the taxiway centreline. It may be noted that this finding is contrary to the underlying principles on which the Annex 14 taxiway dimensions have been based and this largely explains the higher levels of caution found to exist for taxiways designed for larger aircraft.

Nonetheless, the limitations of the present study are emphasised and it is suggested that the recommended design rules based on this analysis are best viewed as being preliminary and that they should be reviewed at a later date in the light of the findings of the more detailed FAA/BAA studies.

4.5 OBSTACLE LIMITATION SURFACE RISK ANALYSIS

During airborne operations, aircraft may deviate about their intended flight path. Depending on the characteristics of the obstacle environment around the flight path, such deviation may expose the aircraft to the risk of collision. Review of aircraft accident data from around the world shows that Controlled Flight Into Terrain (CFIT) represents a significant proportion of total hull loss incidents. Around aerodromes the risk of aircraft collision with obstacles (including terrain) is safeguarded through the application of Obstacle Limitation Surfaces (OLS). As such, an assessment of the risks associated with obstacle collision during airborne aerodrome operations and the development of risk-based OLS to safeguard against such events are highly relevant in the context of the development of aerodrome design rules. A full description of the assessment of these surfaces is provided in Appendix 6, but a summary of the analysis is provided here.

The broad purpose of the OLS is to define the volume of airspace around the aerodrome that should ideally be kept free from obstacles so as to ensure that the intended aircraft operations are adequately safeguarded and to prevent the aerodromes from becoming unusable by the growth of obstacles around them. The OLS are the main safeguarding surfaces for approaching aircraft, either during an entirely visual approach or during the visual segment of an instrument approach. The characteristics of the OLS are defined by ICAO in Annex 14 and a summary of the ICAO requirements and recommendations for the OLS is provided in Appendix 1. It should be noted that a second set of surface criteria is also specified by ICAO in PANS-OPS [2] that is intended for use by procedure designers for the construction of instrument flight procedures and for specifying minimum safe altitudes/heights for each segment of the procedure. For these procedures, the PANS-OPS surfaces take precedence over the OLS.

The PANS-OPS procedures and associated minimum heights may vary with aircraft speed, the type of navigation aid utilised and the equipment fitted to the aircraft. The Annex 14 OLS, on the other hand, are intended to be of a permanent nature and it is these surfaces that are enacted as part of national planning consultation schemes. A further distinction between the PANS-OPS and Annex 14 OLS is that the former guarantees obstacle clearance above the surfaces, while the Annex 14 OLS are essentially used to identify and control obstacles but do not guarantee obstacle-free airspace above the surfaces. The aim of the present study is to assist in the development of aerodrome design rules rather than flight procedures. Therefore, it is the development of permanent surfaces of the type described in Annex 14 (*i.e.* the OLS) that has been the subject of the risk assessment study.

Assessment of deviation of aircraft during airborne operations requires understanding of the vertical and lateral displacement of the aircraft from its intended path and at all points along that path. The three-dimensional nature of this problem means that the assessment of such risks is more complex than the essentially one- or two-dimensional problems presented by aircraft deviation during ground operations. The data requirements for the development of risk models for airborne operations are therefore more onerous than is the case for ground operations. Additionally, the nature of airborne deviation and incident reporting is such that, unlike assessment of most ground operation incidents, development of the deviation model is more reasonably developed from operational monitoring data rather than review of actual incident reports.

Each of the different surfaces defined in Annex 14 is devised to safeguard against deviation in the various airborne operations in around the aerodrome. In the project Functional Hazard Analysis (see Appendix 4) the key risks associated with aircraft deviation were assessed in relation to the OLS and the following operational modes and their key associated safeguarding surfaces[1] were identified as being of particular importance:

Operation	**Key Safeguarding Surfaces**
Balked landing	Balked landing surface, transitional surfaces, inner horizontal surface
Landing[2]	Approach surfaces, transitional surfaces
Approach	Approach surfaces
Missed approach (precision only)	Approach surfaces, transitional surfaces, inner horizontal surface
Take-off	Take-off surface, transitional surfaces, inner horizontal surface

The aim of the study was to develop OLS such that the risk of aircraft penetration of these surfaces during the above operations is maintained within the TLS. By so doing, it is ensured that all obstacles contained below these surfaces pose an acceptable risk of collision for aircraft without the need for further assessment. The surfaces thus represent a screening criterion enabling specific and detailed risk assessment to be focused only on those obstacles of potential significance and also to help ensure that all new or planned obstacles that may pose a significant potential collision risk are captured within the planning process. It stressed that the surfaces derived from the assessed are developed from a physical safeguarding perspective only and do not account for technical safeguarding (*i.e.* protection of CNS signals). Allowance for technical safeguarding may lead to increased restrictions in certain physical design rules, particularly in relation to obstacle limitation surfaces.

For precision approach, landing and missed approach operations, the key source of deviation data on which to build the risk model was identified as the aircraft location distributions

[1] Other surfaces were also identified that play a lesser role in safeguarding during the considered operations (see Appendix 6 for further details)
[2] Defined as from the Missed Approach Point (MAPT) to touchdown

developed by ICAO for the Collision Risk Model (CRM) [3]. The deviation distributions underpinning the CRM were based on collection and analysis of positional data for aircraft during actual precision approach and landing operations and, for missed approaches, on flight simulator studies. Through the selection of broadly conservative assumptions regarding, for example, the approach angle, Obstacle Clearance Height (OCH) and speed, these distributions were used to assess the dimensions and characteristics of the OLS required to control the risk of penetration of the surfaces to within the TLS.

Assessment of the precision approach and landing operations shows that, according to the CRM location distributions, the lateral deviation of aircraft during such operations is small relative to the safeguarding provided by Annex 14 in the recommended divergence of the approach surface. Indeed, it is noted that the Annex 14 recommendation for a divergence of 15% on the precision approach surface may be reduced to 10% (*i.e.* equal to that recommended for the take-off surface) while still maintaining the risk of lateral penetration of the surface by the aircraft within 10^{-8} per movement (and generally much lower).

For vertical deviation during precision approach and landing, the risk of vertical penetration of the approach surfaces was assessed using the underlying CRM distribution data in conjunction with the undershoot distribution model (see Section 4.2) to enable extrapolation from the CRM data down to touchdown[1]. The risks of vertical deviation below the existing Annex 14 approach surfaces were generally found to be small at distances beyond the first few kilometres from the runway threshold, except for Cat I code 1&2 operations and it is noted that these risks may be suitably reduced by provision of a third approach surface akin to that recommended in Annex 14 for the other precision approach runways types.

The risks of deviation below the approach surface during precision approach were found to be greater within the final approach/landing segment between the OCH and the touchdown point. The risk of penetration of the first approach surface (incidents per precision approach) have been assessed as follows:

Table 6 Integrated Risk of Vertical Penetration of the First Approach Surface (Incidents per Movement)

Approach Type	2.5° Glide Slope	3° Glide Slope	3.5° Glide Slope
Cat I codes 1&2	3.42×10^{-03}	5.69×10^{-05}	1.70×10^{-06}
Cat I codes 3&4	1.85×10^{-04}	2.90×10^{-06}	1.11×10^{-07}
Cat II Flight Director	2.76×10^{-06}	5.59×10^{-09}	1.71×10^{-10}
Cat II Autopilot	9.38×10^{-07}	1.71×10^{-09}	4.71×10^{-11}

It may be seen from review of the above risk values that the less restrictive approach surface definition for Cat I code 1&2 runway approaches is not supported by the assessment. Furthermore, glide slopes below 3° may require very restrictive approach surface gradients in order to meet a surface penetration frequency of 10^{-7} per approach movement.

For missed precision approach operations, the key OLS are identified as the inner transitional and transitional surfaces, the inner horizontal surface and the runway strip width. The CRM aircraft deviation data have been used as the basis of the risk-based derivation of suitable definitions of these surfaces. The assessment has found that the current Annex 14 inner

[1] The CRM model and data is only applicable to the precision segment down to the OCA/H.

transitional surface dimensions provide adequate protection against the risk of collision with ILS equipment and aircraft *etc.* for Cat I operations. However, it is noted that the less restrictive surface gradient required for code 1&2 runways, combined with the shorter strip width requirements for these runways, results in a much lower safety margin. It is suggested that the inner transitional surface dimensions are made consistent across all runway code numbers to remove this anomaly.

For Cat II approach the risk of penetration of the inner transitional surface is greater (though still well within the TLS) due to the lower OCH assumed in the assessment. It is suggested that the risk may be suitably maintained within the TLS by truncating the inner transitional surface to 35m (from the Annex 14 height of 45m).

Overall, assessment of the risk of aircraft penetrating the transitional surface during missed approach operations has found that the existing Annex 14 surface requirements provide adequate protection relative to the TLS. However, it is noted that there appears to be no justification based on the CRM data in providing a distinction between code 1&2 and code 3&4 runways. For the transitional surfaces, a key driver behind the risk of penetration is the wingspan of the aircraft. It may therefore be beneficial to consider defining separate dimensions for these surfaces for different aircraft wingspans (and hence runway code letters).

The transitional and inner transitional surfaces, together with the strip width, also provide protection against collision for aircraft during balked landing operations. Data for the assessment of lateral deviation during landing operations, including balked landings, have been assessed from flight-simulation studies by the Obstacle Clearance Panel (OCP) Working Group [4]. This study found that the lateral deviation from the runway centreline is contained within a ±10m deviation from the runway centreline with a probability of 10^{-7} per landing operation. Even for a wingspan of 80m, this would mean that the outer wing tip of the aircraft would remain comfortably within the 150m runway strip required for code 3&4 runways at a TLS of 10^{-7} per movement. Nonetheless, a number of reservations have been identified with regard to the use of the OCP data, in particular in relation to the method of sampling and the extrapolation of Boeing 747 data to other aircraft. It should therefore be noted that all recommendations regarding the OLS in relation to balked landing are prone to high levels of uncertainty. In order to provide more assurance in this area, further data collection studies, for example flight simulation studies, would be required.

For take-off operations, little data has been identified for the performance of a quantified risk assessment of the collision risks. However, arguments based on the frequency with which single engine failures occur during take-off of multiple engine aircraft are made which suggest that a take-off surface gradient of 1.2% may represent a reasonable level of protection based on the requirement of aircraft to achieve this minimum take-off gradient in engine-out conditions.

Within the CRM, data are only available for precision approaches and it is difficult to extrapolate this data to assess the risks associated with non-precision and visual approaches. Nonetheless, some general points are offered:

- In the initial stages of approach below the minimum descent height for visual and non-precision approaches, the aircraft will have good visual contact with the aerodrome to ensure collision risks with obstacles are well managed. As such, the use of less restrictive approach surfaces in Annex 14 for these types of operations than for precision approaches may be justified.

- However, the higher instance of overrun and undershoot for non-precision/visual approach suggests that the touchdown position of the aircraft in these operations is less accurate than is the case for precision approach. This suggests that the vertical and lateral deviation of the aircraft in the segment prior to touchdown is greater for non-precision/visual landings than for precision. This further suggests that the first approach surface should, in fact, be more restrictive for these operations than for precision approach landing. This is contrary to the Annex 14 requirements. (Though, as noted earlier, further research into the apparent differences in touchdown accuracy between precision and non-instrument approaches is required to identify the actual causal factors for this observed phenomenon. It maybe, for example, that the differences are due to other factors that may be correlated with non-instrument operations, *e.g.* a higher incidence for instrument approaches of smaller aircraft or smaller airline operators.)

5 Design Rule Recommendations

Drawing on the findings of the above risk assessment, a series of risk-based design rules have been developed in respect of the key aerodrome physical characteristics and obstacle limitation surfaces. From the risk analyses, it has been concluded that a number of features of the reference code system do not appear to be logical from a risk-based perspective. In particular, we identify no objective basis for greater provision of runway end safety areas at runways of higher code number or for the differences in runway strip widths required. Also, we often identify higher risks associated with non-precision and visual approach operations and can see no TLS based argument for many of the differences between ICAO Annex 14 requirements for instrument and non-instrument or precision and non-precision approach runways.

The conclusions of the study can be summarised in terms of recommendations for risk-based aerodrome design rules. We consider these recommendations for the various aerodrome physical dimensions and obstacle limitation surfaces in turn.

Aerodrome Physical Dimensions

Length of Runway End Safety Provision

1. Runway end safety requirements should be defined according to the following criteria describing operations:
   - runway end safety in respect of overrun at runways meant for take-off;
   - runway end safety in respect of overrun at runways meant for landing;
   - runway end safety in respect of undershoot at runways meant for landing.
2. It would also appear to be appropriate from the perspective of achieving a uniform TLS to define RESA requirements separately in respect of overrun at runways meant for precision approach landing and those meant for non-precision/visual approach landing. However, there may be practical constraints on the benefit to be gained from increased RESA

provision in the latter case such that it may be more pragmatic to adopt the same RESA standards and accept a difference in the residual risk per movement for the two cases. Additionally, although a correlation has been identified between the type of approach aids available and the frequency with which overrun incidents occur, it is difficult to conclusively identify and assess the nature of the precise causal dependencies with the available data;

3. Where practicable, the runway end safety requirements (combined length of runway end strip and RESA) applied to codes 1, 2, 3, & 4 should be the same.
4. The recommended RESA/runway end strip lengths are as follows:
   - Combined length of runway end strip and RESA not less than the current ICAO Annex 14 standard of 150 m in any runway case (basic requirement to meet a TLS of 10^{-7} per movement for average risk movements);
   - Combined length of runway end strip and RESA preferably approaching the current ICAO Annex 14 recommendation of 300 m in relation to take-off and landing overrun risk mitigation (objective to achieve a TLS of 10^{-8} per "average movement"[1] where practicable and a TLS of 10^{-7} per movement for "higher risk movements"[2]);
   - Combined length of runway end strip and RESA up to 500 m in relation to take-off and landing overrun risk mitigation, where practicable, for aerodromes at which there are a "significant" number of higher risk operations[2]: *i.e.* runway critical and/or non-precision/visual approach movements (practical limit of safety benefit from increased RESA provision).

Runway Strip Width

5. Runway strip requirements should be defined separately according to two distinct safety functions:
   - the protection of aircraft from collision on the ground in the event of a lateral veer-off during landing or take-off;
   - the protection of airborne aircraft from collision whilst over-flying the runway strip, for example during a missed approach/balked landing.

   In the case of the former, the relevant portion of the runway strip should be adequately load bearing to accommodate the aircraft using the aerodrome though not necessarily prepared to the same standards as the graded area. Recommendations regarding the latter case are described separately under the OLS heading below.
6. The minimum width of strip required for risk mitigation in respect of veer-off should be defined as a function of reference code letter, and should be not less than the values set out in the table below (basic requirements for provision of a TLS of 10^{-7} per movement). (The strip width in the table is the distance from the runway centreline to the outer edge of the strip and is therefore half the total width of the strip.)

[1] By "average movement" risks we refer to the risks averaged over movements undertaken with different levels of excess runway available and also, for landing operations, averaged over movements undertaken with different types of approach aid.
[2] "Higher risk movements" are those associated with runway limited operations (*i.e.* minimal excess runway available) and, for landing operations, non-instrument approach movements. It is noted that such movements are relatively common at many of the small-to-medium sized Norwegian aerodromes.

Half strip widths to mitigate veer-off risk to TLS of 10^{-7} per movement	
Runway code letter	**Strip width (m)**
A	60
B	65
C	70
D	80
E	85
F	90

7. Where practicable, that portion of the strip width should extend to 150 m, for runways of each code (objective to achieve a TLS of 10^{-8} per movement where practicable).

RESA Width

8. The width of the RESA should be defined as a function of the runway reference code letter, and be equivalent to the runway strip width, as set out in the above table (basic requirement for provision of a TLS of 10^{-7} per movement).
9. Where practicable, the RESA should extend to a distance of 150 m from the extended runway centre-line, for runways of each code (objective to achieve a TLS of 10^{-8} per movement where practicable).

Taxiway widths and separations

10. No changes to taxiway dimensions are recommended at present. (However, a preliminary assessment only has been made of taxiway risks. This suggests that the present Annex 14 requirements provide adequate safeguarding to deviation during taxiing operations, although the existing dimensions would appear to be somewhat cautious for larger aircraft.)

Obstacle Limitation Surfaces

11. For precision approach, three basic amendments to the existing Annex 14 design recommendations for the approach surface are made, namely:
    - a reduction in the lateral divergence angle (providing that this can also be justified from a technical safeguarding perspective);
    - a reduction in the gradient of the first surface slope;
    - the addition of a third approach surface for Cat I code 1&2 approach aerodromes.

12. The recommended dimensions for the approach surface are summarised as follows[1]:

Characteristic	Cat I codes 1&2	Cat II	Cat III
Divergence	10%	10%	10%
Dist from threshold[2]	60	60	60
Length of inner edge[2]	150	300	300
Length 1st section	3000	3000	3000
Slope 1st section[3]	1.4% (1.1%)	2.5% (1.9%)	2.5% (1.9%)
Length 2nd section	3600	3600	3600
Slope 2nd section	2.5%	2.5%	2.5%
Length 3rd section	8400	8400	8400
Slope 3rd section	0%	0%	0%

13. It is recommended that, for Cat II operations, the inner transitional surface may be truncated at a height of 35m with a new horizontal surface at this height connecting the top of the inner transitional surface to the slope of the transitional surface.

14. As a preliminary recommendation, a take-off surface gradient of 1.2% is suggested, representing a reasonable level of protection based on the requirement of aircraft to achieve this minimum take-off gradient in engine-out conditions.

15. In order to provide more definite recommendations for the OLS, further data collection, either from aircraft tracking or flight simulator studies, is required to assess the level of deviation during:

- balked landings;
- non-instrument approaches;
- take-off.

[1] All distances in metres.

[2] The definition of the start and inner edge length are defined by the runway strip in Annex 14. It is suggested that where changes to the strip dimensions are suggested in the current study, the distance from the threshold of the approach surface remains at 60m as extending this would lead to reduced lateral deviation protection. Additionally, it is recommended that the inner edge length be set to the determined strip width, but with minimum values as shown in the table.

[3] Values in brackets show suggested gradients for glide slopes between 2.5° and 3°.

References

1 International Standards and Recommended Practices: Aerodromes, Annex 14 to the Convention on International Civil Aviation, Vol. 1.

2 Procedures for air Navigation Services: Aircraft Operations. Vol. II, Construction of Visual and Instrument Flight Procedures, ICAO Doc. 8168-OPS/611.

3 Manual on the Use of the Collision Risk Model (CRM) for ILS Operations, ICAO Doc. 9274-AN/904.

4 L. Boniface, *et al*, Preliminary Findings of Monte-Carlo Simulation Study of Balked Landings in Support of the NLA OFZ Study, OCP Working Group of the Whole, Coolangatta, Australia, 1998.

Appendices

CONTENTS

Appendix 1: Summary of ICAO Annex 14 Design Requirements

Appendix 1: Summary of ICAO Annex 14 Design Requirements

This appendix provides a summary of the primary requirements of Annex 14 relevant to aerodrome design. The requirements are promulgated as *Standards* and *Recommended Practices* which are defined as follows:

- *Standard:* Any specification for physical characteristics, configuration, … the uniform application of which is recognised as necessary for the safety or regularity of international air navigation and to which Contracting States will conform in accordance with the Convention; in the event of impossibility of compliance, notification to the Council is compulsory under Article 38.
- *Recommended Practice:* Any specification for physical characteristics, configuration, … the uniform application of which is recognised as desirable in the interest of safety, regularity or efficiency of international air navigation and to which Contracting States will endeavour to conform in accordance with the Convention.

Appendices to Annex 14 provide additional guidance supporting the defined *Standards* and *Recommended Practices.* In addition, relevant guidance is provided by the Aerodrome Design Manual, Part 1 Runways, and Part 2 Taxiways, Aprons and Holding Bays and the Airport Services Manual Part 6, Control of Obstacles, which are closely associated with the specifications in Annex 14.

Requirements are defined according to the category of aerodrome, defined in terms of the aerodrome reference code and the nature of operations at the runway. In the current context we are concerned with the following aspects of aerodrome design:

- length and reference codes of runways and taxiways;
- runway and taxiway strips;
- runway end safety areas;
- separation distances between runways and taxiways;
- definition of obstacle limitation surfaces.

We summarise below the basis of the reference code system and then consider the Annex 14 requirements in respect of each of the above elements of aerodrome design.

A1.1 Runway Reference Codes

All aerodromes are given reference codes, which are assigned to every runway, taxiway and stand. The code is composed of two elements that are related to aeroplane performance characteristics and dimensions. The first element is a number based on the aeroplane reference field length and the second is a letter based on the aeroplane wing span and outer main gear wheel span. ICAO Annex 14 identifies the rationale for reference codes as follows:

"The intent of the aerodrome reference code is to provide a simple method for interrelating the numerous specifications concerning the characteristics of aerodromes so as to provide a

series of aerodrome facilities that are suitable for the aeroplanes that are intended to operate at the aerodrome."

In the aerodrome planning and development process, the reference code is selected by reference to the aeroplane types that are intended to use the aerodrome. The aerodrome requirements of the intended aeroplane types are dependent upon the aeroplane physical and performance characteristics and these requirements form the basis of the reference code system. The requirements are translated into *Standards* and *Recommended Practices* in respect of runway aerodrome physical characteristics and are defined according to the aerodrome reference code, so as to ensure that the aerodrome is suitable for the intended aeroplane types. The suitability of the aerodrome for use by other aircraft types can then be determined from the reference code.

In addition, for runways, the reference code is supplemented by characteristics related to the associated runway procedures, in particular precision, non-precision and non-instrument landing procedures.

A1.1.1 Reference Code Number

The code number corresponds to the highest value of the aeroplane reference field lengths of the aeroplanes for which the runway is intended.

The ICAO Aerodrome Design Manual defines the aeroplane reference field length as:

"the minimum field length required for take-off at maximum certified take-off mass, sea level, standard atmospheric conditions, still air and zero runway slope, as shown in the appropriate aeroplane flight manual prescribed by the certifying authority or equivalent data from the aeroplane manufacturer."

The actual runway length should be adequate to meet the normal operational requirements and potential fault sequences of the aeroplanes for which the runway is intended. It should be not be less than the longest length determined by applying the corrections for local conditions to the operations and performance characteristics of the relevant aeroplanes.

Although Annex 14 identifies the minimum field length required for take-off as the basis for defining the reference code number, other runway length requirements relating to performance characteristics are relevant in determining safe operation, specifically the accelerate/stop distance required and the landing distance required. The definitions of these distances are as follows:

Take-off distance required (TODR): for all engines operating, the gross distance to lift off and climb to 35 ft, increased by 15%; or, for an engine failure at or above decision speed, the gross distance to lift off and climb to 35 ft, but without an additional 15% increment.

Take-off run required (TORR): similar to but less than the TODR, being either, for all engines operating, the gross distance to lift off plus <u>half</u> the distance required for climb to 35 ft, increased by 15%; or, for an engine failure at or above decision speed, the same distance but without an additional 15% increment.

Accelerate/stop distance required (ASDR): the gross distance to accelerate to the decision point (V1), suffer an engine failure no later than that point and bring the aircraft to rest; or, the gross distance to accelerate to the decision point (V1), and then bring the aircraft to rest. In the UK this is referred to as ‘Emergency Distance’.

Landing distance required (LDR): The normal approach to certification (in the UK) is based on a gross *unfactored landing distance*, representing a theoretical minimum, consistent achievement of which requires a high level of piloting skill and favourable conditions, and the use of braking effort that would cause passenger discomfort in the ensuing deceleration. To provide an operationally realistic performance level, this distance is multiplied by a field length factor to obtain the Flight Manual landing distance required. Under European requirements, the factor employed varies from 1.43 for propeller aircraft to 1.67 for jet aircraft on dry runways. Additional credit for jets with reverse thrust is not normally given. The higher figure for jet aircraft reflects the fact that they tend to be aerodynamically clean and operate at higher speeds.

In this context, it should be noted that Norwegian practice has been to base the code on whichever is the longest of the following three key operational distances: the take off runway available (TORA), the accelerate-stop distance available (ASDA) and the landing distance available (LDA) (see below for definitions of these distances). The CAA’s Working Party has been considering alternative methods for determining reference codes, based on either the properties of the aerodrome, for example the longest announced runway length, the longer of the ASDA and TORA, or the shortest LDA, or the properties of air traffic. These include, for example, the operating aeroplane reference field length, the approach speed or momentum, and the most frequent or largest aircraft type handled.

The basic safety rationale behind these distances and their use in defining the aerodrome reference code number is therefore that the runway length must be matched to aeroplane performance in respect of normal take-off and landing operations, with some margin for safety, and to performance in respect of specific fault sequences (engine failure at different stages of take-off).

The relationship between reference code number and aeroplane reference field length, as defined in Annex 14, is shown below:

Table A1-1: Aeroplane Reference Field Length

Code Number	Aeroplane Reference Field Length
1	Less than 800m
2	800m up to but not including 1200m
3	1200m up to but not including 1800m
4	1800m and over

The aircraft requirements are reflected in the aerodrome declared distances:

Take-off run available (TORA): the length of runway declared available and suitable for the ground run of an aeroplane taking off.

Take-off distance available (TODA): The length of the declared take-off run available plus the length of the clearway, if provided.

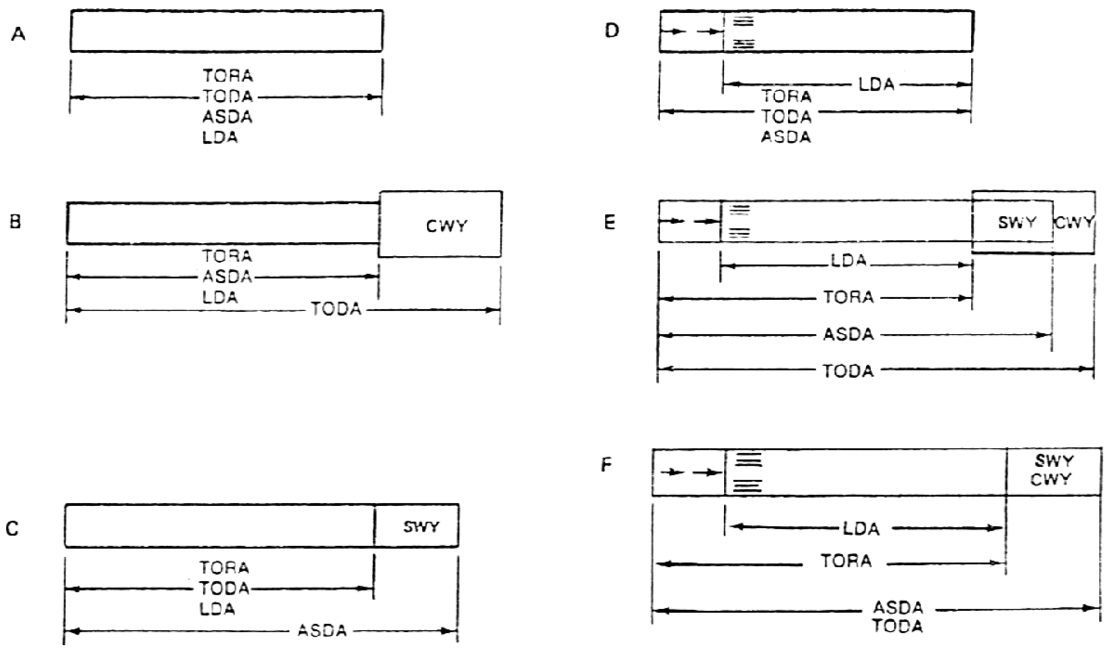
Accelerate stop distance available (ASDA): The length of the declared take-off run available plus the length of the stopway, if provided.

Landing Distance Available (LDA): The length of runway which is declared available and suitable for the ground run of an aeroplane landing.

These declared distances, which will be dependent not only on the length of the runway itself but also on the availability of any stopway or clearway, are illustrated diagrammatically in Figure A1-1 below.

There is an operational requirement to adjust the aircraft mass to suit the runway distances available, such that the calculated runway length required is below the available runway length, for the particular operation under consideration.

Figure A1-1: Aerodrome declared distances for various runway configurations (ICAO Aerodrome Design Manual Figure 3-1).



Whereas, a defined safety margin is factored into the definition of the required distances, Annex 14 evidently accepts implicitly that a proportion of operations will be executed in a manner such that the available runway length is not sufficient and specifies the requirement for a runway end safety area, as described further in Section A1.3, to protect against these occurrences. As regards the level of safety provided at an aerodrome, the issues of the available runway length and the provision of runway end safety areas would appear to be linked.

A1.1.2 Reference Code Letter

The code letter corresponds to the greatest wingspan or the greatest outer main gear wheel span (whichever gives the more demanding code letter) for which the facility (that is the aerodrome) is intended.

The relationship between the reference code letter, wing span and outer main gear wheel span are shown below:

Table A1-2: Wing Span and Outer Main Gear Wheel Spin

Code Letter	Wing Span	Outer Main Gear Wheel Span
A	Up to but not including 15m	Up to but not including 4.5m
B	15m up to but not including 24m	4.5m up to but not including 6m
C	24m up to but not including 36m	6m up to but not including 9m
D	36m up to but not including 52m	9m up to but not including 14m
E	52m up to but not including 65m	9m up to but not including 14m
The outer main gear wheel span is the distance between the outside edges of the main gear wheels		

The reference code letter impacts upon aerodrome design characteristics including:

- Runway width
- Taxiway width
- Taxiway curves
- Taxiway junctions and intersections
- Taxiway separation distances
- Taxiway/runway separation distance
- Taxiway strip width
- Apron stand separation distances

The safety rationale behind these distances is:

- The width of the paved surface must fit the outer gear wheel span and allow for an element of deviation from the centreline.
- Clearance from obstacles and other aircraft must be adequate to accommodate the wing span with the outer main gear wheel on the edge of the paved surface and a safety margin in case the gear leaves the paved surface.
- Safe transit along the paved surfaces should be able to be undertaken at a practical speed without the requirement for continual acceleration or deceleration.
- Engine overhang of non-paved surfaces should be minimised.

Logically, the requirements under the different code letters increase with aircraft size. We consider minimum separation distances for taxiways more specifically in Section A1.4.

A1.1.3 Runway Operations/Type of Approaches

Approaches may be divided first into visual approaches and instrument approaches. Instrument approaches are divided into non-precision and precision approaches. This section discusses the operational parameters for precision and non-precision approaches.

A ***precision approach*** is an instrument approach with lateral and vertical guidance from the final approach point (FAP) to the touchdown zone, with system accuracy, integrity and obstacle clearance (including go-around) guaranteed until the descent limit (decision height) is reached.

A ***non-precision approach*** is an instrument approach with lateral guidance only from the final approach fix (FAF) to the runway environment. The descent limit is the minimum descent height (MDH), and obstacle clearance is guaranteed if the approach is discontinued no farther than the missed-approach point (MAP).

The ***obstacle clearance height (OCH)*** is the height which is calculated to clear all obstacles by a defined margin within a particular area and is the lowest height above the elevation of the relevant runway threshold or above the aerodrome elevation used in establishing compliance with the appropriate obstacle clearance criteria.

The ***decision height (DH)***is the height during an instrument approach at which a missed approach must be initiated if the required visual reference to continue the approach has not been established.

The ***minimum descent height (MDH)*** is the lowest height to which an aircraft can descend during a visual or non-precision approach before establishing visual reference with the runway.

The decision height/minimum decision height is determined in part by considering obstacles that could affect the approach of a particular aircraft. The area in which obstacles need to be considered when setting a decision height is partly dependent on the landing aids in use at an aerodrome. The more accurate the landing aids supporting an approach and the slower the approach speed of the aircraft, the smaller will be the obstacle consideration area.

Non-precision approach

As indicated above, a non precision approach is an instrument approach to landing which does not use electronic glidepath guidance.

A pilot must ensure that the minimum descent height for a non-precision approach is not lower than:

- The obstacle clearance height for the category of aircraft being flown;
- The system minima for the approach aids.

A pilot can continue an approach below the minimum descent height only if at least one of the following visual references for the intended runway is distinctly visible and identifiable to the pilot:

- Element of the approach light system
- The threshold
- The threshold markings
- The threshold lights
- The threshold identification lights
- The visual glide slope indicator
- The touchdown zone or touchdown zone markings
- The touchdown zone lights
- Runway edge lights
- Other visual references accepted by the authority

Precision approach

An instrument approach to landing using an instrument landing system (ILS), microwave landing system (MLS) or precision approach radar (PAR) for guidance in both azimuth and elevation.

The categories of precision approach are:

- Category 1 operation

  A precision instrument approach and landing with a decision height not lower than 200ft (60m) and with a runway visual range (RVR) of not less than 550m.

- Category 2 operation

  A precision instrument approach and landing with a decision height below 200ft (60m) but not lower than 100ft (30m) and a runway visual range of not less than 300m.

- Category 3 operation

  Category 3 operations are sub-divided as follows:

  I Category 3A

  A precision instrument approach and landing with a decision height lower than 100ft (30m) and a runway visual range not less than 200m.

  II Category 3B

  A precision instrument approach and landing with a decision height lower than 50ft (15m), or no decision height and a runway visual range lower than 200m but not less than 75m.

The precision approach aids for each of the above approach categories are ILS, MLS and PAR. For category 1 approaches, a pilot must ensure that the decision height to be used is not lower than:

- The minimum decision height specified in the aeroplane flight manual
- The minimum height to which the precision approach aid can be used without the required visual reference
- The OCH for the category of aeroplane
- 200ft

A pilot can continue an approach below the minimum descent height only if at least one of the following visual references for the intended runway is distinctly visible and identifiable to the pilot:

- Element of the approach light system
- The threshold
- The threshold markings
- The threshold lights
- The threshold identification lights
- The visual glide slope indicator
- The touchdown zone or touchdown zone markings
- The touchdown zone lights
- Runway edge lights

Consideration needs to be given to the topography of the surrounding area to an aerodrome when selecting and positioning precision approach aids. For example:

- The minimum descent height for a precision approach may not be achievable due to the topography

- A glide slope may not be projected accurately as a result of obstacles

- Atmospheric/climatic conditions could generate a false glide slope

When considering siting precision approach aids at small and low utilisation aerodromes, consideration should also be given to the cost/benefits of such aids in addition to the above. The safety benefits per aircraft movement could be seen as negligible when compared to the introduction of similar aids at a higher utilisation aerodrome.

A1.2 Runway Strip

The runway strip is a defined area including the runway and any associated stopway (if provided) that is intended to:

- To reduce the risk of damage to aircraft running off a runway; and
- To protect aircraft flying over it during take-off or landing operations.

The length and width of the runway strip varies depending on the aerodrome reference code number and whether aids are used for the approach.

Annex 14 specifies the following standards in respect of runway strip length (before the threshold and beyond the end of the runway or stopway):

Table A1-3: Runway Strip Length

Aerodrome Reference Code No.	**Extension beyond threshold/runway/stopway**	
	Instrument runway	**Non-Instrument runway**
1	60m	30m
2	60m	60m
3	60m	60m
4	60m	60m

Annex 14 specifies standards and recommended practices in respect of runway strip width and for the graded area within the strip width. The safety rationale for the graded area of the runway strip is to:

- Minimise the potential damage to an aircraft that lands before the threshold, overshoots the runway or slews off it sideways. This is optimised by ensuring the runway strip has an appropriate level of evenness, is of suitable load-bearing capacity, and is free of obstacles.

The strip width as a whole has a broader role of keeping the areas either side of the runway free of obstacles. Standards and recommended practices relating to runway strip width and graded areas are summarised in Table A1-4 below (with standards being shown in normal type and recommended practices in italics, in accordance with Annex 14 convention).

Table A1-4: Runway Strip Width and Graded Area

Code No.	**Precision approach runway**		**Non-precision approach runway**		**Non-instrument runway**	
	Strip width	Graded area	Strip width	Graded area	Strip width	Graded area
1	75m	*40m*	*75m*	*40m*	*30m*	*30m*
2	75m	*40m*	*75m*	*40m*	*40m*	*40m*
3	150m	*75m*	*150m*	*75m*	*75m*	*75m*
4	150m	*75m*	*150m*	*75m*	*75m*	*75m*

Note that the widths in Table A1-4 are the widths including the paved area of the runway, where distances are measured from the centreline of the runway to the outer edge of the strip or graded area. The total strip widths, measured between the outer edges of the strips or graded areas on either side of the runway, are therefore twice the values given in the table.

It is worth noting that the requirements for width of the strip are greater for Codes 3 & 4 aerodromes than for Codes 1 & 2 aerodromes. This would be consistent with an increased wing span and hence requirement for greater clearance when an aircraft deviates from the runway centre-line. The other basic point to note is the requirement for a wider strip at precision and non-precision approach runways, compared with non-instrument approach runways. The rationale for this difference is not evident from Annex 14.

However, some insight may be gained from the Airport Services Manual Part 6 which addresses the related issue of the control of obstacles. A basic assumption made in connection with the assessment of obstacles in that context is that, during execution of an instrument landing procedure, aeroplanes may continue their descent below the heights allowed under non-instrument flight procedures and may therefore be considerably closer to the runway without having confirmation that they are correctly aligned with the runway. On this basis, assuming that runway alignment using instruments, prior to visual reference with the runway being established, is not as reliable as visual alignment, a requirement for a wider strip width at instrument runways may seem appropriate.

A1.3 RESA (runway end safety area)

The RESA is a symmetrical area about the extended runway centre line and adjacent to the end of the strip, primarily intended to reduce the risk of damage to an aeroplane undershooting or overrunning the runway.

The basic Annex 14 *standard* is that a RESA shall extend from the end of the runway strip to a distance of at least 90m.

There is, in addition, an Annex 14 *recommended practice* that, as far as is practicable, the RESA should extend from the end of the runway strip to a distance of at least:

- 120m for Code 1 and 2 aerodromes
- 240m for Code 3 and 4 aerodromes

It should be noted that the RESA lies beyond the runway strip which is 60 m in length, except for non-instrument Code 1 runways for which the strip length is 30 m.

The safety rationale for RESAs, as stated in Annex 14, is that:

- *A runway end safety area should provide a cleared and graded area for aeroplanes which the runway is intended to serve in the event of an aeroplane undershooting or overrunning the runway* (Annex 14, 3.4.7);
- *Consideration should be given to providing an area long enough to contain overruns and undershoots resulting from a reasonable combination of adverse operational factors* (Annex 14, Attachment A, Section 9).

A fundamental question to be addressed in this context will be what constitutes a reasonable combination of adverse operational factors that should be considered, this being a question that is related very much to the setting of appropriate Target Levels of Safety, as discussed further in Appendix 2.

We note here also the recommendation for a longer RESA at Code 3 and 4 aerodromes, but do not identify any rationale for this in Annex 14. Indeed, in our experience, overrun incidents are typically more common at aerodromes with shorter runways.

Annex 14 also specifies that the RESA be at least twice the width of the runway. Evidently, this width will accommodate veer-off from the extended runway centre-line during an overrun. It may be noted that the minimum width of RESA at a Code 4 runway of 45 m width, will be 90 m, significantly less than the 150 m width of the runway strip.

Finally, we note that the current RESA requirements were introduced by an amendment to Annex 14 in 1999. It is our understanding that this amendment reflects the recognition by ICAO of the relative significance of overrun risk, as demonstrated by recent historical accident experience.

A1.4 Minimum Separation Distances for Taxiways and Runways

In the case of taxiway-to-runway clearances, the identified safety rationale behind Annex 14 requirements is that "the separation distances are based on the concept of the wing of an aircraft centred on a parallel taxiway remaining clear of the strip." This rationale appears to assume that the safety margin provided by the runway strip should be adequate to protect against a collision, taking account of potential deviation both from the runway centre-line and from the taxiway centre-line, although deviation of an aircraft from the taxiway centre-line is not explicitly taken into account. The taxiway-to-runway minimum separations prescribed for the aerodromes of different reference codes in Annex 14 have the status of recommended practices. Annex 14 makes the recommendation that minimum separation distances should not be less that those specified "except that it may be permissible to operate with lower taxiway separation distances at existing aerodromes if an aeronautical study indicates that such lower separation distances would not adversely affect the safety or significantly affect the regularity of operations of aeroplanes." We consider the nature of such aeronautical studies further below.

Although the terms of reference for the current project are concerned only with taxiway-to-runway clearances, it is instructive to consider in addition the rationale supporting Annex 14 requirements for taxiway-to-taxiway and taxiway-to-object minimum separation distances.

Requirements for these minimum separations (specified as recommended practices) are defined according to the aerodrome reference code. The basis of the separation distances prescribed in Annex 14 is explained in the Aerodrome Design Manual, as follows:

The distances are based on the maximum wingspan of a group and on the deviation of one aircraft from the taxiway centre line a distance equal to the wheel to edge clearance for that group.

The basic safety rationale behind these distances is therefore that clearance from obstacles and other aircraft must be adequate to accommodate the wing span with the outer main gear wheel on the edge of the paved surface and a safety margin in case the gear leaves the paved surface. For the case of aircraft passing on parallel taxiways, the rationale does not explicitly take account of the potential deviation of both aircraft although this will implicitly be taken into account by the increment, as explained further below.

The Design Manual notes that "Even in instances where a particular aircraft design (as a result of an unusual combination of large wingspan and narrow gear span) might result in the wing tip extending farther than the centre line distances, the resulting clearance distance would still be considerably more than that required for aircraft to pass." Apparently then, ICAO Annex 14 finds that the safety margin provided by the current requirements is considerable.

The rationale for the ICAO minimum taxiway separation distance requirements is defined in more detail in *The Aerodrome Design Manual Part 2.* For taxiway-to-taxiway or taxiway-to-object cases the separation distance (V) is defined in terms of the wingspan (Y), the maximum lateral deviation (X) and a further increment (Z) that provides an additional safety margin. The lateral deviation (X) is determined according to the main gear span (U) and the taxiway width (W).

$$V = \frac{Y}{2} + \left(\frac{W}{2} - \frac{U}{2}\right) + Z$$

The increments required for aerodromes corresponding with the different reference codes are prescribed in the design manual.

The guidance in the design manual on aeronautical studies relating to minimum separation distances provides further insight into the safety rationale. Issues to be addressed in taxiway design, based on aeronautical studies, include:

- Collision with another aircraft, vehicle or object;
- Run-off from paved surfaces; and,
- Engine damage from ingestion.

In the current context, collision is the issue of primary concern.

According to the Design Manual *"the separation distances … are intended to provide a safe wing tip clearance by accounting for the anticipated deviation of a manoeuvring aircraft from the taxiway centre-line in terms of:*

a) Taxiing accuracy achieved in the day-to-day operation; and,

b) Inadvertent excursions/run-off."

The guidance identifies deviations observed in day-to-day operation, gathered in a study undertaken at London Heathrow Airport, which would support an aeronautical study. No guidance is provided on inadvertent excursion/run-off and its evaluation in an aeronautical study.

A1.5 Obstacle Limitation Surfaces

Obstacle limitation surfaces define the airspace around an aerodrome that is to be maintained free from obstacles so as to permit intended aeroplane operations at an aerodrome to be conducted safely and to prevent an aerodrome from becoming unusable as a result of the growth of obstacles around the aerodrome. Terrain and objects that penetrate the obstacle limitation surfaces are considered to be obstacles.

We consider first the general nature of these obstacle limitation surface and then summarise the obstacle limitation surface requirements at different types of runway.

The basic specifications of obstacle limitation surfaces are provided by Annex 14. Further insight into their safety rationale is provide by the Airport Services Manual Part 6. In addition to the basic obstacle limitation surfaces prescribed by Annex 14, we note the significance of PANS-OPS surfaces (those relating specifically to the protection of precision approach procedures) in securing a safe operating environment at an aerodrome. A further aspect that deserves attention in this context is the principle of shielding.

A1.5.1 Types of Surface

The following obstacle limitation surfaces are defined in Annex 14:

- Outer horizontal surface
- Conical surface
- Inner horizontal surface
- Approach surface
- Inner approach surface
- Transitional surface
- Inner transitional surface
- Balked landing surface
- Take-off climb surface

The general form and location relative to the runway of these obstacle limitation surfaces are illustrated in the Figures A1-2 and A1-3.

Figure A1-2: Obstacle limitation surfaces (Taken from ICAO Annex 14)

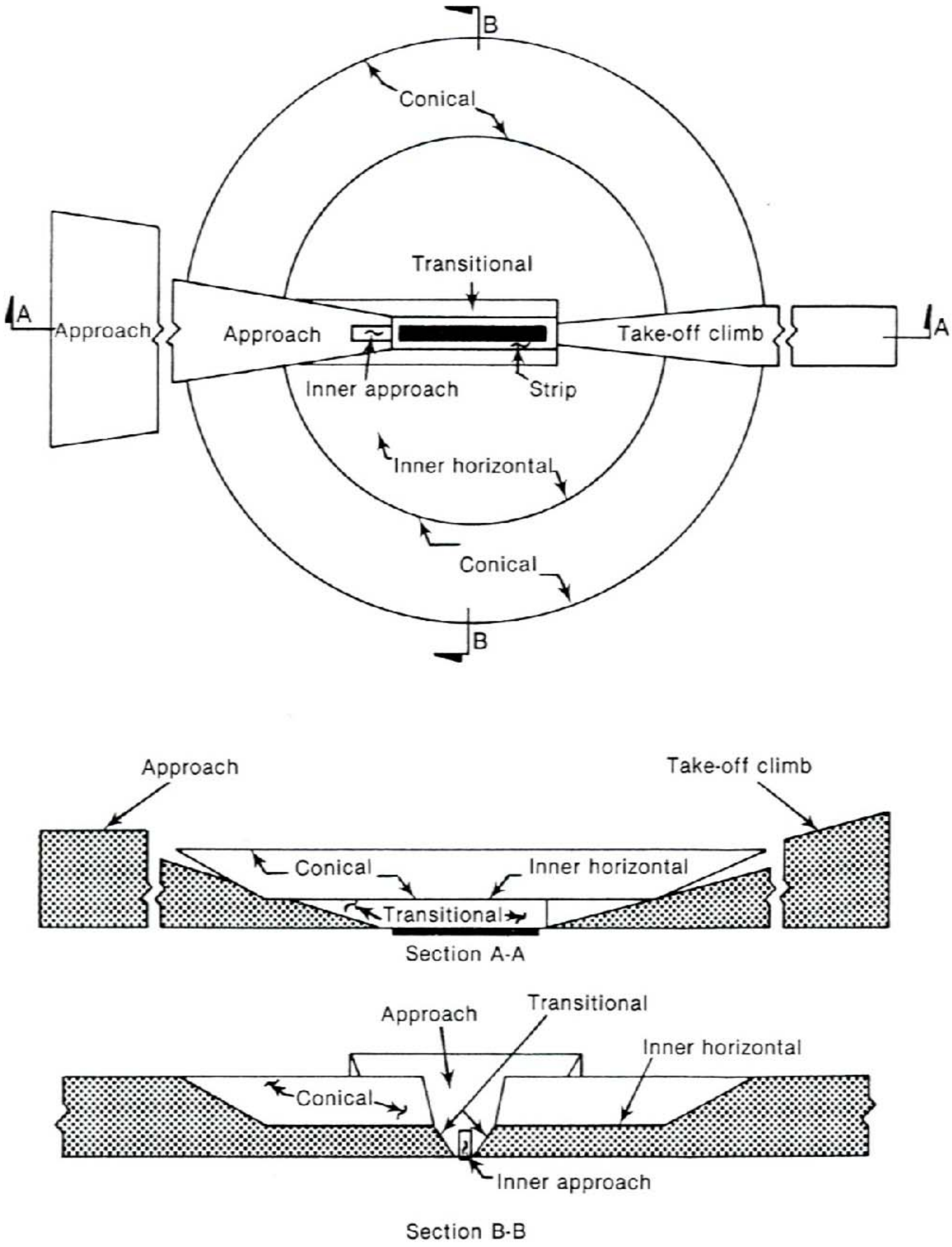
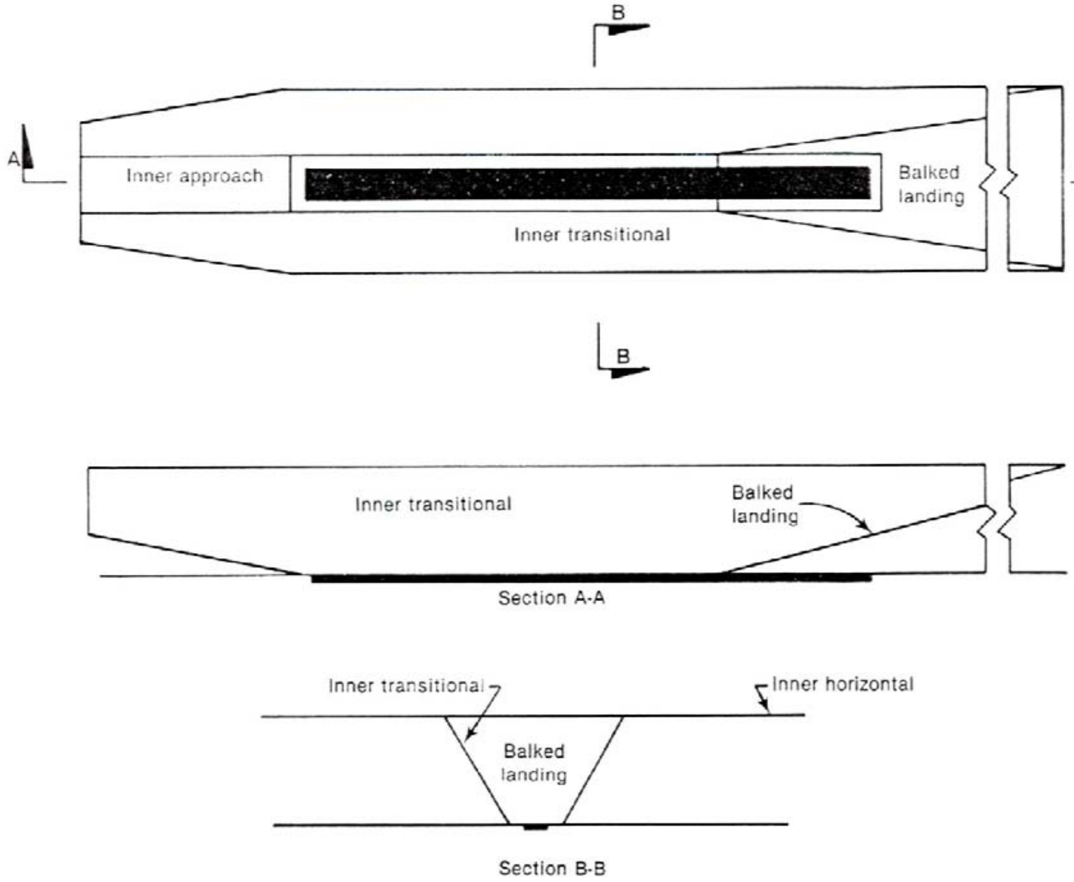


Figure A1-3: Inner approach, inner transitional and balked landing obstacle limitation surfaces (Taken from ICAO Annex 14)



The different surfaces are described in turn below. The outer edges of the runway strip define the beginning of the obstacle limitation surface. Some surfaces are directly in the line of flight for an aircraft that is landing or taking off (approach surface, inner approach surface, transitional surface, inner transitional surface, balked landing surface, take-off climb surface) and are evidently related to the provision of an obstacle free environment for the safe execution of specific aerodrome operations. Other surfaces (outer horizontal, conical and inner horizontal) surround the aerodrome but do not penetrate the approach or take-off path for normal operations. They are less obviously related to specific runway operations and would appear to be more concerned with providing an obstacle free environment more generally in the vicinity of the aerodrome.

Take-off climb surface

The take-off climb surface is located at the end of the take-off run available or the end of the clearway when a clearway is provided. The surface slopes up uniformly along its length from the runway end and fans out symmetrically about the extended runway centre-line. Annex 14 does not provide justification for the gradient of the slope and angle of the divergence of the boundaries of the surface. It can be expected that the specified gradient(s) should reflect the nature of the aircraft for which the airport is designed and that it would be reasonable to select the minimum angle as the achievable climb for an engine-out departure plus a margin of safety to ensure no interference with obstacles. However, it is interesting to note that the Annex 14 surface gradients are generally steeper than the certification requirements for aircraft in an engine out situation. For twin engine aircraft this is 2.4% gross and 1.6% net. This is reflected in Annex 14 which says that, if practicable, a 1.6% slope should be considered. The angle of divergence can be expected to take account of the likely lateral displacement of aeroplanes on take-off, having regard, for example, to possible cross-wind conditions.

Where the local environment allows, a straight take-off climb surface (i.e. one following the extended runway centre-line) will normally be defined. Where necessary, a curved take-off climb surface can be defined. For a take-off path involving a turn the definition of the geometry of the surface becomes complex but it conforms to the same basic criteria as those for a straight surface.

Approach surface

The approach surface is an inclined surface or combination of surfaces that diverges from the runway and precedes the runway threshold. The basic geometry is essentially the same as that for the take-off climb surface.

The primary safety rationale behind the parameters of the slope is:

- To provide a zone free of obstacles through which an aeroplane can approach the aerodrome at the intended angle, adjusted to include a suitable safety margin, and not suffer from obstacle interference. An appropriate safety margin should take into account the aeroplane design parameters and relevant fault sequences or abuse cases.

In addition, the approach surface may help:

- To provide a clear view of the runway for visual approaches.
- To provide an acceptable operating environment for landing aids, ensuring that they can perform within their designed parameters and that there is also an additional margin of safety.

Inner approach surface

The inner approach surface is a rectangular portion of the approach surface that immediately precedes the runway threshold.

The safety rationale for this surface is essentially the same as for the approach surface, but defined with more specific regard to the requirements in the region closer to the runway. Together with the inner transitional and balked landing surfaces, it defines a volume of airspace in the immediate vicinity of a precision approach runway that is known as the obstacle free zone.

Transitional surface

The transitional surface is a complex surface that runs along the side of the runway strip and along part of the side of the approach surface, sloping upwards and outwards to meet with the inner horizontal surface. As indicated above, it is a part of the obstacle free zone and its safety rationale, as set out in the Airport Services Manual Part 6, is, together with the approach surface, to protect an aeroplane in the final phase of the approach-to-land manoeuvre.

In addition, it may help to:

- provide a clear view of the runway for visual approaches.
- provide an acceptable operating environment for landing aids, ensuring that they can perform within their designed parameters and that there is also an additional margin of safety.

Inner transitional surface

The inner transitional surface is similar to the transitional surface but is situated closer to the runway. As indicated above, it forms part of the obstacle free zone. The safety rationale for the inner transitional surface is understood to be essentially the same as that for the transitional surface, but defined with more specific regard to the requirements in the region close to the runway. Annex 14 states that the inner transitional surface is designed to be:

The controlling obstacle limitation surface for navigation aids, aircraft and other vehicles that must be near the runway and which is not to be penetrated except for frangible objects.

Balked landing surface

The balked landing surface is an inclined plane located at a specified distance after the threshold, extending between the inner transitional surface, and also forms a part of the obstacle free zone.

The safety rationale for the balked landing surface is evidently similar to that for the transitional and inner transitional surfaces but defined more specifically with respect to the requirements for balked landings. For example, the surface for a precision approach code 3 or 4 runway is based on a gradient of 3.33%, the lowest permitted for an all engine balked landing, and the assumption that a balked landing will be initiated no later than the end of the touchdown zone.

Inner horizontal surface

The inner horizontal surface is a circular plane at a height of 45m, centred on the aerodrome with a radius that is dependent on runway length. The inner horizontal surface is intersected by the approach surfaces and the take-off climb surface meaning that the safety rationale cannot be directly related to the final stages of approach or of take-off.
The Airport Services Manual Part 6 identifies the safety rationale for the inner horizontal surface as being to protect airspace for visual circling prior to landing. It further states that certain sectors of the visual circling areas may not be essential to aircraft operations and, provided that procedures can be established to ensure that aircraft do not fly in these sectors, the protection afforded by the inner horizontal surfaces need not extend into these sectors.

Outer horizontal surface

The outer horizontal surface is a horizontal circular plane around the aerodrome, beyond the limits of the inner horizontal surface and conical surface (see below). As described in guidance set out in the Airport Services Manual Part 6, the outer horizontal surface is concerned primarily with provision of a safe operating environment for aircraft performing wide visual circuits, on arrival routes, or on departure or missed approach climb-paths. In this context, a distinction might be drawn between different types of obstacle. For example, it is recommended that high masts and other skeletal structures should be avoided because of their relatively inconspicuous character.

Similar objections would not apply to topographical features infringing the outer horizontal surface. For example, the guidance notes specifically that tall structures would not be of immediate significance if they are proposed to be located in:

a) an area already substantially obstructed by terrain or existing structures of equivalent height; and

b) an area which would be safely avoided by prescribed procedures associated with navigational guidance when appropriate.

The UK CAP168 states that the outer horizontal surface is only applicable to aerodromes with a declared runway length greater than 1,100m. The minimum radius of the outer horizontal surface ranges between 10,000m and 15,000m depending on runway length. With respect to the different types of approach discussed earlier, Annex 14 makes no direct reference for the need of an outer horizontal surface. In line with the safety rationale for the outer horizontal surface indicated above, CAP 168 states that the surface is there to:

- Facilitate practicable and efficient instrument approach procedures,
- Ensure safe visual manoeuvring in the vicinity of an aerodrome.

Thus the specification of an outer horizontal surface is concerned with protecting the wider environment so as to maintain the broadest range of options for approach procedures and other procedures that might enhance operational efficiency. Infringements can be accepted provided that the potential operational efficiency implications can be tolerated.

Conical surface

The conical surface is a sloping surface that marks a transition (where applicable) from the outer horizontal surface to the inner horizontal surface. The inner radius is dependent on the inner horizontal surface and varies between 2,000m to 4,000m. The above comments made in connection with the inner and outer horizontal surfaces apply equally to the conical surface. According to the Airport Services Manual Part 6, together with the Inner Horizontal Surface, its purpose is to protect airspace for visual circling prior to landing.

Obstacle Free Zone (OFZ)

The inner approach surface, inner transitional surface and the balked landing surface are only required by Annex 14 for category II and III precision approach runways. The UK CAA has declared an obstacle free zone for all precision approach runways. The safety rationale for this is to:

- Protect aeroplanes from fixed and mobile obstacles during category I, II and III operations when approaches are continued below the decision height and during any subsequent missed approach with all engines operating normally.
- Provide protection to aircraft that have descended to a height of less than 100 feet which have been correctly aligned with the runway at that height by visual reference to the runway or approach lighting.
- Provide safe passage for an aircraft that has initiated a missed approach not later than the end of the touchdown zone. The specified OFZ distance (dependent on runway size) is sufficient for the pilot to make any necessary changes to the aircraft configuration, achieve a positive climb rate of a specified minimum (dependent on runway size) and a deviation from track not greater than the specified splay either side of the centreline.

PANS-OPS Surfaces

The Annex 14 surfaces described above define the basic areas of airspace in the vicinity of aerodromes that should, ideally, be kept free from obstacles. The definition of these surfaces may have immediate safety implications or, alternatively, operational efficiency implications. Some are evidently more critical than others, with immediate implications for the safety of runway related operations. Others, further from the runway and its extended centre-line may be less critical since procedural measures or notification and marking/lighting may be sufficient to manage the risk of collision. In addition, instrument runways have associated with them PANS-OPS surfaces which relate specifically to the requirements of instrument approach and landing procedures.

The design of procedures must take account of the obstacle environment in the vicinity of the aerodrome and, in addition to the basic Annex 14 surfaces, it is useful to define PANS-OPS surfaces that characterise the air space that should be kept clear in order to maintain adequate safety during operation according to instrument procedures. For example, these will protect against collision during a missed approach during execution of landing according to an instrument procedure.

In some instances, PANS-OPS requirements may exceed those of Annex 14: i.e. the PANS-OPS surfaces may extend into airspace not protected by Annex 14 surfaces. In some circumstances, it may therefore be advantageous to restrict the obstacle environment beyond the basic Annex 14 surfaces, in order to optimise operational efficiency and the potential for use of instrument procedures.

Definition of PANS-OPS surfaces is supported by the ICAO Collision Risk Model. The model has been used to design the obstacle assessment surfaces (OAS) which establishes a volume of airspace inside which it is assumed the flight paths of aeroplanes making ILS approaches will be contained with sufficiently high probability. The OAS was designed against an overall risk budget of one accident in 10 million approaches.

It may therefore be appropriate during the course of the study to take account of not only the basic Annex 14 surface but also the PANS-OPS surfaces. Nevertheless, it is recognised that Annex 14 provides the basis requirements for aerodrome design and that, where adequate

PANS-OPS surfaces are not provided by the basic Annex 14 surfaces, an operational restriction is inherently accepted within the framework provided by Annex 14.

A1.5.2 Obstacle Limitation Surface Requirements

Annex 14 prescribes requirements for obstacle limitation surfaces on the basis of the intended use of the runway (i.e. take-off or landing) and with regard to the category of aerodrome. The main requirements are set out primarily as standards, specifying which surfaces shall be defined for a given category of aerodrome and the geometry and dimensions of those surfaces.

Non-instrument runways

The Annex 14 standard is that the following obstacle limitation surfaces, of defined geometry and dimension, shall be established for non-instrument runways:

- Conical surface
- Inner horizontal surface
- Approach surface
- Transitional Surface

In addition, the standard requires that *"new objects or extensions of existing objects shall not be permitted above the approach or transitional surface except when, in the opinion of the appropriate authority, the new object or extension would be shielded by an existing immovable object."*

Annex 14 identifies recommended practices in relation to existing objects as follows:

- *"new objects or extensions of existing objects should not be permitted above the conical or inner horizontal surfaces"* and "*existing objects above any of the surfaces required should as far as practicable be removed"* subject to the following exemption *"except when, in the opinion of the appropriate authority, the new object or extension would be shielded by an existing immovable object, or after aeronautical study it is determined that the object would not adversely affect the safety or significantly affect the regularity of operations of aeroplanes."*

Non-Precision approach runways

The Annex 14 standard is that the following obstacle limitation surfaces, of defined geometry and dimension, should be established for non-precision approach runways:

- Conical surface
- Inner horizontal surface
- Approach surface
- Transitional Surface

In addition, the standard requires that *"new objects or extensions of existing objects shall not be permitted above an approach surface within 3000 m of the inner edge or a transitional* *surface except when, in the opinion of the appropriate authority, the new object or extension would be shielded by an existing immovable object."*

As for non-instrument runways, Annex 14 identifies recommended practices in respect of existing objects, although in this case the requirement is that new objects or extensions of existing objects should not be permitted *above the approach surface within 3,000m of the inner edge* as well as above the conical or inner horizontal surfaces.

Precision approach runways

The Annex 14 standard is that the following obstacle limitation surfaces, of defined geometry and dimension, shall be established for Category I runways:

- Conical surface
- Inner horizontal surface
- Approach surface
- Transitional Surface

Category II and III runways also require, as a standard:

- Inner approach surface
- Inner transitional surface
- Balked landing surface

Annex 14 recommends that the above surfaces also be established for Category I runways.

Further Annex 14 standards are that:

- *"fixed objects shall not be permitted above the inner approach surface, the inner transition surface and the balked landing surface, except for frangible objects which because of their function must be located on the strip. Mobile objects shall not be permitted above these surface during the use of the runway for landing";* and
- *"new objects or extensions of existing objects should not be permitted above the approach or transitional surfaces, except when (in the opinion of the appropriate authority) the new object or extension would be shielded by an existing immovable object."*

Recommended practices in respect of existing objects are also identified, essentially the same as those identified above for non-instrument and non-precision runways.

Runways meant for take-off

The Annex 14 standard is that a take-off climb surface, of specified geometry and dimensions, shall be established at runways meant for take-off.

An important recommended practice is that *"the operational characteristics of aeroplanes for which the runway is intended to be used should be examined to see if it is desirable to reduce the slope specified … when critical operating conditions are to be catered for."*

Recommended practices in respect of existing objects are also identified, essentially the same as those identified above for approach runways.

Other object and objects outside the obstacle limitation surfaces

Annex 14 identifies recommended practices relating to the review of obstacles outside the limitation surfaces, for example by use of aeronautical studies, having regard to the nature of operations at an aerodrome.

Recommendations in respect of other objects are as follows:

- *"Objects which do not project through the approach surface but which would nevertheless adversely affect the optimum siting or performance of visual or non-visual aids should, as far as practical, be removed";* and
- *"Anything which may, in the opinion of the appropriate authority after aeronautical study, endanger aeroplanes on the movement area or in the air within the limits of the inner horizontal and conical surfaces should be regarded as an obstacle and should be removed in so far as practicable."*

Shielding

Whereas the above requirements normally apply to the various types of runway, as indicated by the Annex 14 standards and recommendations, under certain circumstances, the principle of shielding may be employed to permit a more logical approach to restricting new construction and prescribing obstacle marking/lighting in the vicinity of natural terrain or other existing immovable obstacles. In principle, an obstacle that penetrates an Annex 14 surface may be permitted in cases where that surface is already penetrated and where the penetrating object shields the proposed new structure from collision with an aeroplane. Although ICAO has provided some guidance on possible approaches for the assessment of shielding, comprehensive methodologies for determining the extent of shielding provided by an object or natural terrain have not been prescribed. Shielding is not identified as an issue to be addressed by the current study and this note on shielding is added for completeness only.

Appendix 2: Review of "Acceptable" Risk Levels

Appendix 2: Review of “Acceptable” Risk Levels

The objective of this element of the study is to establish a basis for defining appropriate quantitative risk criteria that may be used to determine “acceptable” risk levels associated with aerodrome operations and to define related “target levels of safety” (TLS).

This evaluation starts by considering some of the broader experience in the use of quantitative criteria in industrial safety management in order to provide an insight into the underlying principles behind this approach. Specific consideration is then given to examples of the application of quantitative criteria in aviation. Next, the historic accident record, which provides a fundamental reference for defining risk in aviation, is reviewed. Finally, a series of recommendations are made concerning the quantitative risk reference standards that may support the development of quantitative target levels of safety for aerodrome operations and relevant factors to be considered in this process.

The review has led to the conclusion that it is not appropriate to define any specific and uniformly applicable, quantitative TLS values applicable to aerodrome operations. As is explained in this evaluation, the setting of an appropriate TLS is linked to the nature of the risk and the practicability of reducing it. Defining a TLS for a given operation therefore requires a thorough understanding of the associated risk. In the context of this overall study, the TLS values appropriate to given aerodrome operations have been proposed after completion of this review, in light of the findings of the more detailed risk analysis studies to be undertaken during the course of the project.

In accordance with the above outline, this account of the evaluation of “acceptable” risk levels comprises the following sections:

- Underlying principles;
- TLS application in aviation;
- Review of historic accident record;
- Recommendations.

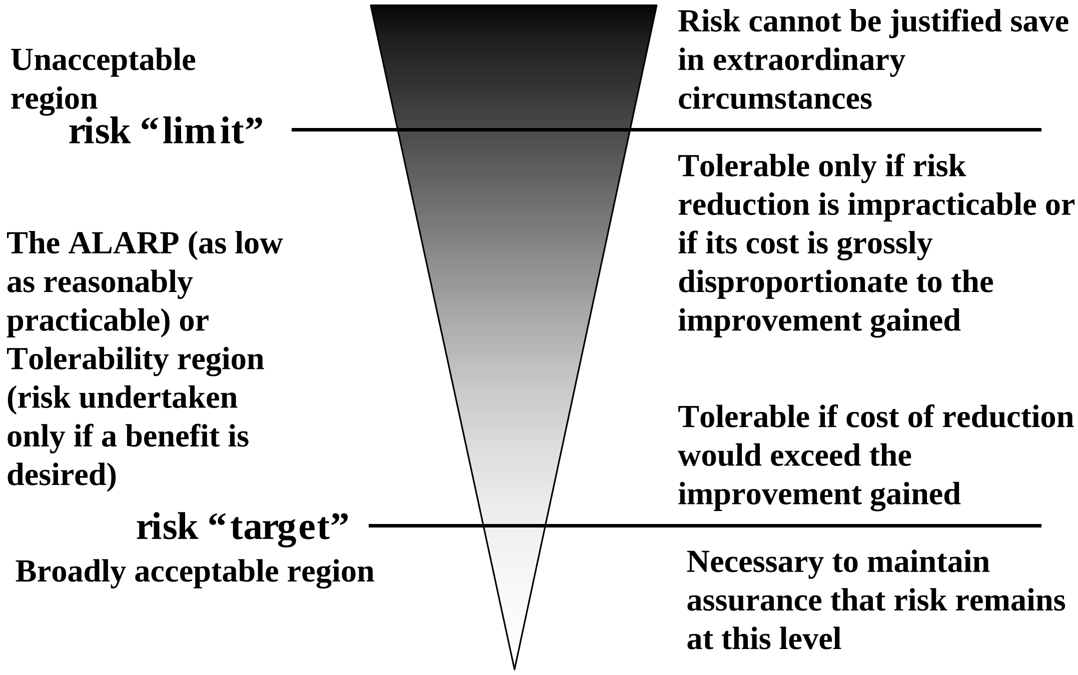
These elements are considered in turn below.

A2.1 Underlying Principles

Here we review experience of the use of quantitative risk criteria in industrial sectors other than aviation, first to demonstrate the general utility of the quantitative approach and its validity as a regulatory tool and second to identify specific features of the approach of relevance to its application in the aviation sector. We consider first the basic approach to the use of quantitative standards in risk management and then identify a number of issues relating to risk assessment, associated with its implementation.

There is extensive experience in the use of the quantitative approach to support safety management in higher hazard industrial activities. In particular we identify the international adoption of the approach in the nuclear sector (see for example ICRP guidance[1,2,3]) and its more general adoption in safety regulation, for example in the UK and the Netherlands [4,5,6,7,8]. The main features of the approach may be summarised by means of the UK "risk tolerability" concept, illustrated in Figure A2-1.

Figure A2-1: Risk Tolerability and "ALARP" in UK Safety Regulation



We use this example from UK safety regulation as a convenient illustration, recognising that it is typical of the generic features encountered in the wider international application of the approach. The approach is "objectives-based" rather than "prescriptive": that is to say it defines requirements in terms of an objective that should be met, rather prescribing specific technical or other measures that should be adopted. A practical difficulty in implementing this approach arises from the potential ambiguity that may exist, in particular where there are competing objectives to minimise risk at economically viable costs, while maintaining the benefits of continued operation, often at sites where past land-use decisions have done little to minimise the potential conflict.

In the UK, this objectives-based approach to safety regulation was established as a key element of the 1974 Health and Safety at Work Act, after a review which found that "regulations that lay down precise methods of compliance have an intrinsic rigidity and their details may quickly be overtaken by new technological developments … whenever practicable, regulations should be confined to statements of broad requirements in terms of objectives to be achieved." The basic regulatory framework establishes a requirement for risks to be managed *so far as is reasonably practicable.*

Of course, broad statements of objectives are very much open to interpretation and may result in some ambiguity. As regulators, the UK Health & Safety Executive began to interpret, in practice, at what level a risk might be judged to be *as low as reasonably practicable*

(ALARP). The proposal to build a nuclear power station at Sizewell in South East England then focused the debate and led to the establishment of a defined “risk tolerability” framework, together with quantitative risk criteria, representing a practical mechanism to address the need for both clarity and flexibility in safety regulation.

The key features to be drawn from this summary illustration are:

- The adoption of both “limits” and “targets”;
- The application of cost-benefit considerations;
- The recognition that “acceptable” risk will vary between different hazard scenarios.

The approach relies on the application of two distinct types of criterion:

- An equity-based criterion, which seeks to quantify the concept that individuals have some unconditional right to a basic level of protection;
- A utility-based criterion, which sets standards in respect of the incremental risk management benefit gained from implementation of a given risk management measure, having regard to its cost.

In general, the definition of quantitative standards in respect of these two types of criteria has been based on practical experience of the current status, with the recognition of a general objective to achieve improvement in the future. The upper “limit” level of risk is typically established on the basis of historic accident experience, both within a given sector and across other activities in industrial society, as being the highest level of risk normally encountered and implicitly accepted. The “target” level of risk is established as being a risk that is low, compared with society’s historic experience of risk but which is seen to be practicably achievable.

Similarly, the cost-benefit criterion can be set quantitatively, by reference to practical experience of the financial cost per hypothetical life saved for available measures to reduce risk. This value has often be referred to as the “value of a statistical life”. The concept of the “value of life” in this context may raise ethical questions in the minds of some and it is important to clarify the proper meaning of this term. It is more correctly identified as the price that society, in practice, has been prepared to pay for reducing risk, taking account of the other demands on financial resources. Its use allows the identification of the most cost effective measures for reducing risk and hence provides for the maximum reduction in risk per unit of financial expenditure. Rather than suggesting that the use of the concept is somehow morally unacceptable, it may more rationally be argued that it would be morally unacceptable not to employ it and therefore miss opportunities to deploy risk management resources in the most cost-effective manner.

Within this context, a fundamental point to be recognised is that society has other demands on resources and must make value judgements on the allocation of the available resources to meet safety management and other objectives. It is appropriate for the practical purposes of allocating resources for industrialised society to accept that, given the current practical status, some lower risks should not attract undue regulatory attention (see, for example, Rimington 1997 [9] or Norder [10]).

Beyond these fundamental points there are a number of other relevant features of this framework that deserve specific comment, as follows:

- The importance of public perception in determining “acceptable” risk levels;
- The distinction between standards for “new” and “existing” situations;
- The concept of “risk apportionment” between hazards when determining overall “acceptable” risk levels.

We consider each of these issues in turn below.

Clear differences between public perception of one or another risk are observed in practice, with related differences in expectations for safety standards. This is of specific relevance in the case of aviation, for which there are relatively high public expectations and, consequently, high safety standards. Risk levels considered acceptable in one context cannot automatically be transferred to other situations.

It is explicitly recognised in a number of regulatory contexts that, although a given level of risk may be accepted for some “existing” situations, the same level of risk may not be considered acceptable for “new” developments. UK risk management guidance explicitly identifies a need for a higher standard for new installations than for existing installations, where the standards applied to new facilities are practicably achievable. ICRP guidance also draws a distinction between the standards applicable to “planned practices” and “intervention” situation. Essentially, this reflects the differences in the practicability of risk reduction in the different situations.

Finally, we identify the application of the concept of “risk apportionment” to support the development of target safety levels. Essentially, the approach involves the establishment of an overall target safety level comprised of the sum of risks associated with a set of hazards. Risk apportionment is the process of allocating target safety levels to the component hazards. The approach is rational and straightforward in principle. However, case study experience indicates that, in practice, care needs to be taken in implementing the concept.

Where the individual component hazards and associated risks are well understood, and the targets subject to the risk are well understood as, for example, at a site comprising a number of hazard operations, or a region comprising a number of specific sites, the approach might be effectively applied. However, attempts have been made to apply the approach more generically in national policy development. Such attempts may encounter problems, unless supported by an adequate understanding of the real component risks. Adopting a simplistic generic approach to risk apportionment, an overall risk limit, say 1 in 10,000 risk of fatality per annum, might be apportioned equally between some arbitrarily chosen number of potential hazards, say 100, on the basis that individuals may be subject to risk from each of the hazards. The apportioned risk limit for each hazard then becomes 1 in a million per annum. In practice, this risk limit may be found to be very stringent for some individual hazards. Certain groups may be exposed to a risk in excess of the individual risk limit for one specific hazard but those groups are generally unlikely to be exposed to sufficient real risks from the nominal other 99 hazards for the total risk to exceed the overall risk limit. Different hazards carry different risks and it may not be practicable to apportion risk equally in a simplistic fashion. Effective risk apportionment requires an understanding of the individual hazards in question, the associated risk exposures and the scope for risk reduction.

In summary, we identify the following underlying principles that support the effective use of quantitative risk criteria in safety regulation:

- Risk limits, representing the maximum risk that is considered tolerable in a given situation;
- Risk targets, representing aspirations for achieving low risk, which are to be attained where possible but which, in recognition of practical constraints, are not mandatory;
- Cost-effectiveness criteria, by which the most effective measures for reducing risk can be identified;
- The establishment of quantitative values for risk limits, risk targets and cost effectiveness criteria, by reference to historical experience of risk;
- The adoption of different quantitative standards in respect of different types of hazard as a result of practical differences between them, for example concerning the level of risk and the availability and costs of measures to reduce it;
- The distinction between "existing" and "new" situations and the establishment of different standards for the two cases, taking account of the practicability of risk reduction;
- The adoption of different quantitative standards in respect of different types of hazard as a result of differences in public perception and expectation for different hazards;
- The practical apportionment of risk between different hazards, for the purposes of targeted risk management.

We put forward the above principles as a basis for setting quantitative targets to support the current study. In addition, other risk management principles drawn from experience in these other sectors may be of relevance. For example, implementation of the above objectives-based approach requires that hazards be assessed in order to quantify their associated risks. A number of practical issues arise in the risk assessment process which may be of relevance in the current context. Certain practices have been developed to address various issues which are generic to risk assessment and analogous features can be identified in the application of quantitative risk management techniques in the aviation sector. Two elements that we currently identify in this respect are the following:

- The concept of "design basis accidents". A design basis accident is a fault sequence which the system is designed to accommodate without safety implications. The use of this concept may help to provide some clarity in the risk-based aerodrome design process, by ensuring that the off-normal operations that should be accommodated by the design are identified and distinguished from other, less frequent hazardous events which may result in serious safety consequences and be responsible for the residual "acceptable" risk.
- The concept of "critical groups". This concept addresses the fact that some groups may be more at risk from a particular hazard than others. It provides for the definition of the target group which acts as the primary reference in the risk assessment process and is therefore very much linked to the issue of quantitative criteria. During the assessment of aviation risks it will be important to identify similar references. For example, it will be important to distinguish between average operation and operations most exposed to risk, according to aerodrome physical characteristics and aircraft performance.

These and similar issues will be considered in further detail during the detailed risk analysis phase of the project.

A2.2 Application of Quantitative Criteria in Aviation

We consider here the general role of quantitative criteria in current aviation safety regulatory practice and identify a number of specific examples of the application of quantitative criteria in aviation safety management. The following section then looks more specifically at specific examples which provide models for the development of risk criteria for use in the current study.

The basic approach to aerodrome design promulgated by ICAO, as set out in Annex14, is essentially prescriptive. Specific engineering design requirements are identified and defined in terms of *Standards* and *Recommended Practices*, as described earlier. Nevertheless, ICAO Annex 14 does allow some scope for the use of a more objectives-based approach in some circumstances. It identifies the possible use of so-called “aeronautical studies” to support the aerodrome design process and for deviation from the usual Annex 14 prescriptions in some cases, which again has been considered earlier in this report. The nature of aeronautical studies is not defined by ICAO Annex 14 (and correspondingly, neither are any quantitative risk criteria) though it can be argued that they would include studies involving quantitative risk analysis and the demonstration that an appropriate level of safety has been met. A key starting point is therefore that ICAO practices allow for the use of quantitative risk-based approaches to aerodrome design, in some cases at least.

ICAO Annex 14 does establish some quantitative safety related criteria in relation to the provision of “aeronautical data” (see Annex 14 Section 2.1.2). Contracting states are required to ensure the integrity of aeronautical data within quantitatively defined data integrity levels, as follows:

- critical data, integrity level 1×10^{-8};
- essential data, integrity level 1×10^{-5};
- routine data, integrity level 1×10^{-3}.

In addition, various ICAO working groups have employed quantitative criteria as the basis for the development of prescribed standards. In particular we note the quantitative criteria defined by the ICAO All Weather Operations Panel (ICAO AWOP), in respect of approach and landing accidents (and those defined by the ICAO Obstacle Clearance Panel (ICAO OCP) in relation to collision with obstacles). Key quantified targets identified are as follows:

- Risk of hull loss during all phases from all causes: 1×10^{-7} per flight hour or 1.5×10^{-7} per mission (ICAO AWOP).
- Risk of accident on approach and landing from all causes: 1×10^{-8} per mission (ICAO AWOP).
- Risk of collision with obstacle due to aircraft being laterally off-path or beneath the approach path: 1×10^{-7} per approach (ICAO OCP).

These criteria were established by reference to historic accident rates, taking account of apportionment between different flight phases, where appropriate.

A recent review [11] of target levels of safety, undertaken on behalf of Eurocontrol has identified a number of target levels that have been established by various aviation regulatory authorities, for example in the area of air traffic management, aircraft certification and aircraft operations. These identified target levels of safety are summarised in Appendix 3 and include standards relating to air traffic management defined by various ICAO working groups, as discussed above, aircraft certification standards and operational performance criteria defined by JAA. In particular, we note JAR 25.1309 which, historically, represents a key development in the use of quantitative criteria in aviation safety management. The basis for JAR 25.1309 is discussed in more detail in Section A2.3.1 below. Many of the other TLS examples are essentially derived from the principles laid out in JAR 25.1309 but, rather than being generic in nature, are applied to specific aircraft systems or operations. A significant proportion are concerned with aircraft systems in the context of aircraft certification, whereas others address operational issues related to system performance.

The typical measure of the TLS examples is risk per flight hour though several are in terms of the probability of “failure on demand” (i.e. failure during a specific operation requiring the system in question). However, for the proposed application within the current study, it is considered more appropriate to measure aerodrome operational risk in terms of the risk per movement during landing or take-off. (In this context, one movement is one take-off or landing operation and, for aggregated accident rates, will typically be the average of the risk for these two distinct operations.) It is not considered appropriate to transfer these quantitative standards directly to the definition of aerodrome design requirements.

Elsewhere in aerodrome safety regulation, examples of the use of quantitative risk-based approaches can be identified. For example, risk-based arguments have been presented [12] to support the approval of new aerodrome developments, in cases where identifiable hazards are not specifically addressed by prescriptive ICAO standards. The basic TLS adopted in these cases has typically been a fatal accident rate of 1 in 10^{-9} per movement for a single hazard, on the basis that an individual hazard should not make a significant contribution to the total observed accident rate. We are aware also of the use of risk-based arguments to support the licensing process and the continued operation of existing facilities, for example where deviations from ICAO standards are encountered or particular hazards are identified by the regulatory authorities. However, given the nature of the licensing process, such examples of the use of quantitative criteria are not generally publicly available.

Finally, we identify a quantitative *“benchmark level of safety”* considered by the UK CAA in draft guidance [13] on requirements for runway end safety area provision. In this case, a distinction was made between the benchmark overrun rate (no more than 0.5 per million movements) and the benchmark “serious” overrun rate (no more than 1 in 10 million movements). The derivation of these safety targets is considered in further detail in Section A2.3.2.

Although not dependent upon quantitative criteria, it is worth noting at this point the use by ICAO of both Standards and Recommendations. In principle, the approach is analogous to the use of limits and targets in the risk tolerability concept discussed earlier. It allows some flexibility to take account of specific circumstances at individual aerodromes. It provides a basis for accommodating an existing situation whilst seeking to establish improvements in new facilities.

A2.3 Example Applications

As has been discussed in the preceding sections, quantitative standards have typically been set by reference to recent historical experience of accidents, recognising the objective of achieving improvement in the future . Here we describe in further detail the development of criteria on this basis to illustrate that process. The examples described are first the JAR 25.1309 Safety Criticality Classification and Risk Tolerability Scheme, which, historically, represents an important development in aviation safety management. Secondly we describe the development of criteria for assessing runway end safety provision requirements, which is of direct relevance to the current study.

A2.3.1 JAR 25.1309 Safety Criticality Classification and Risk Tolerability Scheme

The JAR 25.109 safety criticality classification and risk tolerability scheme in the context of aircraft certification represents a significant application of the use of quantitative risk criteria in aviation safety management. The approach is entirely consistent with that of risk tolerability and ALARP applied to industrial and nuclear safety, described earlier in the introductory section on underlying principles. We provide a summary account of the system and the basis for the quantitative risk criteria established within it. The system represents an important historical development in aviation safety and provides a model for development of risk criteria appropriate to aerodrome design.

The Civil Aviation Authorities of certain European Countries have agreed common comprehensive and detailed aviation requirements (referred to as the Joint Airworthiness Requirements (JAR)) with a view to minimising Type Certification problems on joint ventures and also to facilitate the export and import of aviation products. The JAR are recognised by the Civil Aviation Authorities of the participating countries as an acceptable basis for showing compliance with their national airworthiness codes. In this context, the JAR 25 provides a system for the quantitative classification of failures in safety systems in terms of both the severity of the consequence and the likelihood of occurrence of the fault condition. Such an approach recognises that zero risk cannot, in practice be realised. The measures of consequence and likelihood within this safety classification system are summarised in Table A2-1 and Table A2-2 below.

The criteria were developed by reference to the historical accident record that indicates that the risk of a serious accident due to operational and air-frame related causes is approximately 1 per million hours of flight. It is further noted that about 10 per cent of the total can be attributed to failure conditions caused by problems associated with the aircraft's systems. It is considered reasonable that serious accidents caused by systems should not be allowed at a higher probability than this previous historic rate in new aircraft designs. On this basis it is therefore required that, for new designs, the probability of a serious accident from all such failure conditions be not greater than 1 per ten million flight hours (1×10^{-7} per flight hour). For the purposes of assessment and evaluation of an aircraft comprising numerous systems, it has been arbitrarily assumed that there may be about 100 potential failure conditions that may seriously compromise safety. Assuming further that the total target of 1×10^{-7} per flight hour may be apportioned equally among the systems and their fault conditions, the upper risk limit for a single failure condition leading to serious consequences of 1×10^{-9} per flight hour is derived. Such reasoning provides the basis for the "risk tolerability matrix" shown in Table

A2-3 which provides the basis for evaluating the acceptability of identified levels of residual risk.

This approach to safety management recognises that it is unrealistic to expect to achieve zero risk. Some risk may have to be tolerated to secure the benefits of an activity. Risks must therefore be balanced with the benefits, having regard to the practicability of achieving further risk reduction. The example risk tolerability scheme, as set out in Table A2-3, requires that an event with catastrophic consequences with a frequency of occurrence of 1 in 1000 million flight hours or greater be considered unacceptable. An event with catastrophic consequences and a lower likelihood, less than 1 in 1000 million flight hours, may be considered acceptable. However, such risk should be subject to review and demonstration that further risk reduction is not practicable before acceptance. Similarly, the risk tolerability scheme requires that an event with hazardous consequences with a frequency of occurrence of 1 in 10 million flight hours or greater be considered unacceptable. Again, a lower likelihood of this consequence, less than 1 in 10 million flight hours, may be considered acceptable, subject to review and demonstration that further risk reduction is not practicable.

Table A2-1: JAR 25 Safety Criticality Classification: Consequence

Catastrophic	Hazardous	Major	Minor
• loss of aircraft • multiple fatalities	• a large reduction in safety margins; • physical distress or a workload such that flight crew cannot be relied upon to perform its tasks accurately or completely; • serious injury or death of a relatively small number of the occupants	• significant reduction in safety margins; • a reduction in the ability of the flight crew to cope with adverse operating conditions as a result of increase in workload or as a result of conditions impairing its efficiency; • injury to occupants.	• nuisance; • operating limitations: emergency procedures.

Table A2-2: JAR 25 Safety Criticality Classification: Likelihood of Occurrence

Extremely improbable	Extremely remote	Remote	Reasonably probable	Frequent
Extremely unlikely, if not inconceivable, to occur.	Unlikely to occur when considering several systems of the same type, but nevertheless, has to be considered as being possible.	Unlikely to occur during total operational life of each system but may occur several times when considering several systems of the same type.	May occur once during the total life of a single system.	May occur once or several times during operational life.
< 10^{-9} per flight hour	10^{-7} to 10^{-9} per flight hour	10^{-5} to 10^{-7} per flight hour	10^{-3} to 10^{-5} per flight hour	1 to 10^{-3} per flight hour

Table A2-3: JAR 25 Safety Criticality Classification: Risk Tolerability Matrix

	Probability of Occurrence				
Severity	Extremely Improbable	Extremely Remote	Remote	Reasonably Probable	Frequent
Catastrophic	Review	Unacceptable	Unacceptable	Unacceptable	Unacceptable
Hazardous	Review	Review	Unacceptable	Unacceptable	Unacceptable
Major	Acceptable	Review	Review	Review	Review
Minor	Acceptable	Acceptable	Acceptable	Acceptable	Review

The criteria set out in JAR 25 were established to facilitate the assessment and evaluation of aircraft safety in respect of the certification of new aircraft. Given the specific application for which the above risk tolerability criteria were established, it would not necessarily be appropriate to apply them directly in this case. However, the process adopted for establishment of the criteria, by making reference to historic rates and recognising that we should like at least to match if not better the historic safety performance, is a generally sensible and valid approach. It is employed not only in the aviation industry but also in many other risk management situations, as described earlier.

A2.3.2 *"Benchmark Level of Safety"* in relation to Runway End Safety

In developing guidance [13] on runway end safety area provision the UK CAA considered the use of a *"benchmark level of safety"* in quantitative terms as a basis for establishing RESA requirements. Although the draft guidance was subsequently superseded by guidance that adopted a more qualitative approach, the establishment of the benchmark level of safety represents a useful example of the process for establishing target levels of safety.

The basic approach is analogous to that for JAR 25.1309 described above. It takes the current level of risk as a fundamental reference point and seeks to achieve an identified level of improvement.

First, a world-wide fatal accident rate of one in two million movements is identified (0.5×10^{-6} fatal accidents per movement). Analysis of these accidents indicates that approximately 10% involve an aircraft overrun. On this basis, a world-wide fatal overrun rate of 1 in 20 million movements is derived (0.5×10^{-7} fatal accidents per movement). From recent UK experience over a 20 year period (1975-1996), an overrun rate of 26 in 25.5 million movements (1.02×10^{-6} overruns per movement) of which 14 were identified as being "serious". On this basis, a "serious" overrun rate of 14 in 25.5 million movements (0.55×10^{-6} overruns per movement) was derived. (It was observed that the aerodromes that accounted for all of the reported overrun incidents accounted for only 22% of all movements. This implies that the overrun risk at those aerodromes reporting overrun incidents is somewhat higher than the average. The statistical rate at this subset of aerodromes is approximately four times higher than the UK average. This is a key observation of fundamental importance to this study.)

As regards future levels of safety, the UK CAA's Safety Regulation Group (SRG) presented the following argument in its draft guidance. "*SRG believes that there should be an industry-wide objective to maintain and where possible improve UK safety levels. For hazardous events such as overruns, SRG believes that, as a minimum, it should aim to keep the absolute number of these events constant even though aviation activity is expected to increase at a rate of 4% per annum into the foreseeable future. To achieve this, SRG has calculated that there should be a 33% reduction in the total number of hazardous events over the next 10 years.*

On this basis, a target of a 33% reduction in the absolute number of overruns is proposed. On this basis, the future benchmark levels of safety proposed were:

- An overrun rate of no more than 0.5 per million movements (0.5×10^{-6} overruns per movement);
- A serious overrun rate of no more than 1 per 10 million movements (1×10^{-7} serious overruns per movement).

The fundamentals of the approach are therefore:

- the use of the historical *average* accident rate as a primary basis for establishing a safety target;
- the setting of an aspirational target for future improvement.

The approach appears to be quite rational and reasonable in principle, but it may be worth considering its implications in practice. According to the distribution of risk among aerodromes, a target based on the average value may be quite demanding. If the overrun rate is four times higher than the national average at certain aerodromes, reducing risk to the national average may represent a significant challenge. That will depend upon the reasons for the observed differences between incident rates. We would therefore urge caution in the setting of quantitative targets simply on the basis of average accident rates. It may be necessary to accommodate differences in risk level for different types of operation and the process of target setting may need to be informed by a good understanding of the issues.

It is worth noting that the overrun incidents occurred predominantly at shorter runways. Inevitably, for any given aircraft, operations at shorter runways are likely to be subject to higher overrun risk than those at longer runways. Overruns are more common for operations where there is less excess runway length compared with the specified requirement. Inherently, regulation according to ICAO Annex 14 accepts this, and essentially sets a minimum standard that will generally be exceeded. This is an important issue that deserves specific attention. It may be appropriate to consider both the risk for the most frequent on average operations and also the minimum standard applicable to the operations at highest risk. In setting criteria, it will be appropriate to make the same distinction.

A2.3.3 Obstacle Assessment in the Design of Instrument Procedures

As has already been mentioned elsewhere in this report, a Collision Risk Model has been applied by ICAO in relation to the assessment of obstacles and the associated risk of collision, in the context of the design of instrument landing procedures.

In the first instance, the model has been used to design the obstacle assessment surfaces (OAS), as specified in PANS-OPS, which establish a volume of airspace inside which it is assumed the flight paths of aeroplanes making ILS approaches will be contained with sufficiently high probability. The OAS was designed against an overall risk budget of one accident in 10 million approaches. In this context, ICAO adopts a TLS of 10^{-7} accidents per movement. The probable flight paths are based on identified tolerances in positioning, for example related to the tracking of ILS beams, and the consideration of various operations of which the missed approach is of particular relevance.

The obstacle assessment surfaces provide a basic reference by means of which the obstacle environment in the vicinity of the aerodrome can be taken into account in the design of instrument landing procedures. Outside these surfaces the risk of collision is deemed to be acceptably low and aeroplanes would need normally only to be protected from obstacles that penetrate these surfaces and hence where the risk of collision exceeds the TLS of 10^{-7} accidents per movement.

It is important to note further that guidance on assessment of obstacles under the Airport Services Manual Part 6 recognises that the specified obstacle assessment surfaces are relatively simple plane surfaces, intended to describe a relatively complex shape and allow for easy manual application. As a result, the specified OAS are considered to be overprotective in certain areas. As identified in the Airport Services Manual Part 6, this may unnecessarily prevent aeroplanes operating to low minima which, in terms of the actual risk, might otherwise be considered acceptable. It is also noted that, where there is a high density of obstacles below the OAS, the total risk associated with collision with any one of the obstacles present may no longer be insignificant compared with the identified TLS. Under such circumstances, it is recommended that a more sophisticated approach to the assessment of collision risk be adopted, in which the effects of objects individually and collectively is evaluated by means of the Collision Risk Model. Thus, the guidance promotes the assessment of individual cases on their specific merits rather than the adoption of simplistic prescriptive rules.

Overall, the Collision Risk Model and its use in the design of instrument procedures represents an important endorsement by ICAO of the concept of the TLS and its use to avoid the unnecessary restriction of operations on grounds of safety.

A2.4 Historic Accident Record

As described above, the identified examples of quantitative risk criteria have typically been developed on the basis of historical accident rates. We propose to adopt this basic approach. In order to provide a firm basis for setting criteria relevant to the specific hazards under consideration, having regard for example to the principle of effective apportionment of risk, it is appropriate to consider this historical accident data in further detail. We consider first the baseline accident rate. Next we consider the apportionment of risk between different phases of flight and according to accident type or causal factor.

A2.4.1 Baseline Accident Rate

A number of studies [14,15,16] into aircraft accident rates have been undertaken in the last ten years or so and these have provided a generally consistent picture of the overall risks of aircraft loss during operation. The values obtained vary to some extent according to the data set that is evaluated. In particular, it is to be noted that a higher rate is observed for world statistics as a whole than for so-called “first world” operations, comprising essentially operations within and between “western” countries. “First world” operations are considered to be most representative of activities in Norway and are therefore adopted here as the basis for establishing the relevant accident rate.

A further important observation is that the accident rate varies between different aircraft types. In defining accident statistics it is therefore appropriate to divide aircraft into different classes.

For the current purposes we propose to adopt the aircraft accident rates estimated in a recent UK study [14] undertaken by the Department of Environment, Transport and the Regions (DETR), in connection with third party risk at airports, which provides a thorough and comparatively up-to-date account. The DETR report provides a summary of aircraft accident rates according to aircraft type. These give the accident rates per million movements, derived from aircraft accident (total losses) and movement statistics in the period 1979 to 1995. These rates are averages for “First World” operations and are summarised in below in Table A2-4.

Table A2-4: "First World" Total Loss Accident and Overrun Rates

Aircraft type	Total loss accident rate (crashes per million movements)
Class I Jets	1.11
Class II-IV Jets	0.15
Executive Jets	0.27
Turboprops T1	0.27
Turboprops T2	0.73
Piston-engine	3
Miscellaneous	3

The categories of aircraft, as defined in the DETR report, are as follows:

- Class I Jets: First generation jets, e.g. Comet, Boeing 707
- Class II Jets: Second generation jets, e.g. Boeing 727, VC-10
- Class III Jets: Early wide bodied jets, e.g. Boeing 747, Tristar
- Class IV Jets: Subsequent types, e.g. Airbus 310, Boeing 757
- T1 Turboprops: those with first delivery in and after 1970
- T2 Turboprops: those delivered earlier

It is found that accident rates for Class II, III and IV jets are similar and, given the potential difficulties in distinguishing between types in the accident rate estimation process, these types have been grouped together. The crash rate determined is per million movements, where one movement is equivalent to half a take-off and half landing movement. The quoted rates refer to "airport related" total hull losses, where an airport related accident is one occurring during the approach, landing, take-off or initial climb phases of flight. These statistics provide a basic benchmark for the risk relevant to aerodrome operations.

A2.4.2 Risk Apportionment

The above accident statistics relate to airport operations as a whole, presented in terms of risk per movement. It will be instructive also to consider in further detail the apportionment of risk between phases of flight and accident type/causal factor.

Breakdown between Phases

The data set in the DETR study identified four separate accident types with the following relative frequencies:

- landing non-overrun crashes, 52%;
- landing overrun crashes, 20%;
- take-off non-overrun crashes, 20%;
- take-off overrun crashes, 8%.

There are two key features to note from the above. First, total hull loss landing accidents are more frequent than take-off accidents, by a factor of approximately 2.5. Second, overruns are a significant contributor to total hull losses as a whole, comprising 28% of the total.

Other studies [15,16] have focused more specifically on the apportionment of risk between all of the different phases of flight and causal factors. An estimate of the breakdown of risk exposure between different phases and the fraction of time spent within each phase is given in Table A2-5.

Table A2-5: Breakdown of risk exposure between flight phases

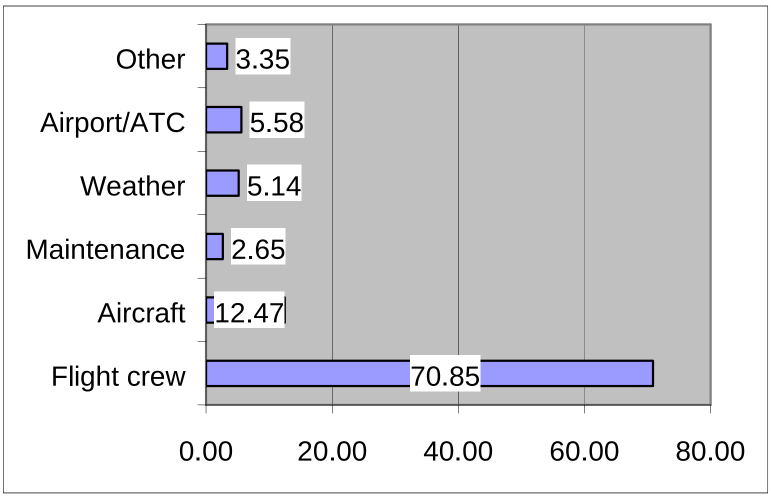
Load, taxi, unload	Take-off	Initial climb	Climb	Cruise	Descent	Initial approach	Final approach	Landing
	28.7%		Percent of accidents				41.1%	
3.3%	17.6%	11.1%	6.5%	5.2%	3.3%	11.8%	16.3%	24.8%
	2%		Percent of flight time				4%	
	1%	1%	13%	60%	10%	11%	3%	1%

The data in Table A2-5 emphasises the concentration of risk exposure in the phases of take-off and climb and final approach and landing and the relatively small amount of time spent in these phases. It is evident from this that it would not be appropriate to employ a uniform safety target in terms of risk exposure per hour of flight, as employed in JAR 25, across all phases of flight and that a risk criterion in terms of risk per movement would appear more appropriate.

Breakdown between Causal Factors

These studies have also considered the primary factors responsible for causing aviation accidents. For the world-wide commercial jet fleet over the period 1976-1990, an estimate [16] of the percentage breakdown is given in Table A2-6 below.

Table A2-6: Breakdown of Aviation Accident Primary Causes



Clearly, flight crew error is identified as the primary cause in the majority of cases (though it is to be stressed that the above figure is based on world-wide data and may not be fully representative of "first-world" operations. Aerodrome design therefore may have an important role in addressing some flight crew related accident scenarios. We note that a relatively small proportion of accidents are attributed to Airport and ATC causal factors, compared with aircraft faults. Such data can inform the risk apportionment process. Of course, the observation that aerodrome features themselves are not the primary cause of hull losses does not mean they do not have a potentially important role to play in reducing the rate of such incidents, for example by providing for mitigation of accident consequence in the event of the occurrence of certain fault sequences.

We have already noted the difference in accident rates for different aircraft types. There is also some indication that there may be differences in accident rates between different aerodromes, with accident rates being higher at smaller, less well equipped aerodromes. It is, important at this point to note the distinction between a correlation between an observed accident rate and a given risk factor and a causal relationship. (We might consider, for example, whether the observed difference in accident rates between aircraft types is because of the differences in aerodromes they use or whether the higher accident rate at smaller aerodromes is associated with the aircraft that use them.)

Nevertheless, it is worth considering such correlation and we identify here a specific study [17] that addressed the relationship between accidents and the available approach-and-landing aids. In this particular study, which may or may not be relevant to the Norwegian situation, it was found that there is a significant correlation:

- there appears to be a five-fold increase in risk among commercial aircraft flying non-precision approaches, compared with those flying precision approaches.

Interestingly, no significant correlation between accident risk and the presence of high terrain in the vicinity of the aerodrome was observed. It may therefore be appropriate to take account of such issues when establishing target levels of safety.

A2.5 Recommendations

On the basis of the above we make the following recommendations concerning target levels of safety for use in the subsequent stages of this study:

- The historical airport related accident rate for aircraft of 0.2×10^{-6} per movement is proposed as a basic risk benchmark for setting target levels of safety in respect of aerodrome design, based on the average recent historical risk for "first world" modern jet and turboprop aircraft operations, whilst recognising that other aircraft types may have a different historical accident rate.
- Recognising the apportionment of the total risk between hazards, a basic benchmark aspirational risk "target" for the fatal accident rate is proposed of 10^{-8} to 10^{-9} per movement for any given aerodrome design related hazard. Such levels of safety are judged likely to be achievable, at least in some cases. Given the risks encountered more generally in aviation, it is not considered appropriate to devote resources to the reduction of risk below the level of 10^{-9} fatal accidents per movement. In any event, we consider it

doubtful whether meaningful risk analyses can be undertaken to address the negligible level of risk below this value.

- In addressing individual hazards, apportionment of total risk between different elements of the system should be informed by a thorough understanding of the risk, developed by means of detailed risk analyses, and should not be arbitrarily assigned.
- The term “benchmark” is adopted here to signify that the proposed value should not be viewed as fixed and absolute, having regard to practical issues encountered in addressing specific hazards in real aerodrome situations. In particular, it should be noted that the “benchmark” is an average and that, inevitably, some operations may be more and others less at risk than this average. Different levels of risk may be associated with different operations, covering different aircraft types and aerodrome facilities. In line with experience in the use of the “risk tolerability” framework approach, this suggests that it may be appropriate to accept a risk “limit” of perhaps ten times the average or more, according to the specific circumstances. The process of setting safety “limits” and “targets” should be informed by a thorough understanding of the specific risk, developed by means of detailed risk analyses.
- In this respect we identify an important distinction between the most frequent operation at an aerodrome and the operation at highest risk (see Section A2.3.2). In setting criteria, it will be appropriate to identify the type of operation to which it applies. It may be appropriate to consider separately the risk for the most frequent or average operation and the operations at highest risk.
- It may be appropriate to employ cost-benefit considerations in determining where, between the proposed “limit” and aspirational “target” risk level, target levels of safety should be set for individual hazards, having regard to the costs and safety benefits that may be obtained by implementation of other aviation safety measures.

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Appendix 3
Summary of Aviation Target Levels of Safety

Table A3-1: Summary of Aviation Target Levels of Safety

Quantified TLS	**Risk Addressed**	**Source**	**Basis**
Application to ATM			
4×10^{-8} to $1.5\ 10^{-8}$ fatal accidents per flight hour per dimension (longitudinal, lateral and vertical).	Mid-air collision of aircraft during oceanic (North Atlantic) phase of flight, from all causes.	ICAO NATSPG	Jet aircraft historical fatal accident rate (1959-1966). TLS set on the assumption that 10% of accidents were due to collisions. An improvement factor of 2 to 5 is applied, divided between the three flight dimensions.
2.1×10^{-9} mid-air collisions per flight hour in vertical dimension.	Mid-air collision for oceanic and en-route flight phases, associated with loss of procedural vertical separation caused by aircraft system failure.	CAA	Historical fatal accident data for US civil aircraft.
5×10^{-9} mid-air collisions per flight hour per dimension (longitudinal, lateral and vertical).	Mid-air collision of any aircraft for the period 2000-2001 for en-route flight phase.	ICAO RGCSP	Fatal accident data for jet aircraft on scheduled air services.
1×10^{-7} aircraft accidents per flight hour or 1.5×10^{-7} per mission.	Aircraft total hull loss during all flight phases from all causes.	ICAO AWOP	Historical accident data for commercial jet fleet for the period 1959-1990.
1×10^{-8} aircraft accidents per mission.	Aircraft accident at the approach and landing phases from all causes.	ICAO AWOP	Apportionment of the figure for all phases of flight.
1×10^{-7} obstacle collisions per approach.	Collision with obstacles due to aircraft that are laterally off-path or below approach path.	ICAO OCP	Historical accident data extrapolated and factored for improvement.

Quantified TLS	Risk Addressed	Source	Basis
1 x 10^{-8} aircraft accidents per operation.	Fatal accident/hull loss during movement on the aerodrome due to failure of Advanced Surface Movement Guidance and Control System.	ICAO AWOP	Historical accident rates from world-wide data and US National Transportation Safety Board data for US operations.
2.5 x 10^{-8} aircraft accidents per flight hour or 3.5 x 10^{-8} accidents per movement.	Aircraft accident due to an ATM failure from all causes, applied to commercial air transport in the ECAC region.	ECAC	ECAC "ATM Strategy for 2000+" objective *"to ensure that the number of ATM induced accidents and risk bearing incidents do not increase and, where possible, decrease."* Based on 6.7% decrease per annum until 2010 of maximum annual ATM contribution to accidents of 0.655 accidents per annum.
Application to Aircraft Certification			
1 x 10^{-5} probability per flight hour of catastrophic sonic failure.	Catastrophic failure due to sonic fatigue cracks.	JAA (JAR 25.571(d))	AMJ-25.1309 – "improbable". Based on considerations historically associated with fail-safe design.
1 x 10^{-5} probability per flight hour of a lightening strike on the insulated portion.	Catastrophic effects of lightening strike.	JAA (ACJ 25.581)	AMJ-25.1309 – "improbable".
0.99 or 0.9 probability with 95% confidence, for setting design values that assure material strength if a failure would result in loss of integrity.	Structural failures caused by material variability.	JAA (JAR 25.613)	Statistical analysis.
1 x 10^{-5} probability per flight hour of inadvertent operations of each lift and drag control device.	Unsafe flight caused by inadvertent operation of lift and drag control devices.	JAA (JAR 25.697)	AMJ-25.1309 – "improbable".
1 x 10^{-5} probability per flight hour of failures of systems used to inhibit the landing gear aural warning.	Failure of landing gear aural warning from all causes.	JAA (JAR 729(e)(6))	AMJ-25.1309 – "improbable".
1 x 10^{-5} probability per flight hour of complete failures of braking system due to single tyre failure.	Common mode failure brake failure e.g. associated with pipeline	JAA (ACJ 25.735(b))	AMJ-25.1309 – "improbable".

Quantified TLS	Risk Addressed	Source	Basis
	failure.		
1 x 10^{-5} probability per operation of erroneous closed and locked door indicator.	Failure of door locking mechanism.	JAA (JAR 25.783(e))	AMJ-25.1309 – "improbable".
1 x 10^{-9} probability per flight hour of inadvertent opening of doors	Explosive decompression from inadvertent opening of doors	JAA (JAR 25.783(f))	AMJ-25.1309 – "extremely remote".
1 x 10^{-9} probability per flight hour of the indication of dangerously incorrect information without a warning being given to the pilot.	Unsafe flight due incorrect display of information concerning bank and pitch indicators.	JAA (ACJ 25.1303(b)(5)2 .1)	AMJ-25.1309 – "extremely remote".
1 x 10^{-9} probability per flight hour of catastrophic failure condition. 1 x 10^{-7} probability per flight hour of hazardous failure condition. 1 x 10^{-5} probability per flight hour of major failure condition.	Failures of aircraft systems or associated components.	JAA, (JAR 25.1309)	Historical accidents from the 1960s. TLS set on the basis of following assumptions: • Accident probability is c. 1 per million flight hours; • 10% are due to aircraft systems failures; • there are 100 systems subject to potential failure.
1 x 10^{-5} probability per flight hour of failure of alerting system.	Loss of function of crew alerting system.	JAA (AMJ 25.1322(8))	AMJ-25.1309 – "improbable".
1 x 10^{-7} probability per flight hour of failure of the automatic pilot to initiate go-around.	Unsafe flight due to failure of automatic initiation of automatic pilot.	JAA (ACJ 25.1329(4.2) (d))	AMJ-25.1309 – "extremely remote".

Quantified TLS	Risk Addressed	Source	Basis
1×10^{-9} probability per flight hour of any failure condition occurring within the normal flight envelope with an effect on one of the following: • a load on any of the structure greater than its limit load; • exceedance of an airspeed halfway between V_{MO}/M_{MO} and V_{DF}/M_{DF}; • A stall; • A normal acceleration of less than a value of 0 g; • Bank angles of more than 60º en route or more than 30º below a height of 1000 ft; • Hazardous degradation of the flying qualities of the aeroplane; • Hazardous height loss in relation to minimum permitted height for automatic pilot use; • Engagement or disengagement of a mode leading to hazardous consequences.	Unsafe flight due to all causes leading to the described effects.	JAA (ACJ 25.1329 (5.2.2))	AMJ-25.1309 – "extremely improbable".
1×10^{-9} probability per flight hour of failures which would result in the loss of the normal and alternate systems.	Unsafe flight due to loss of engine control systems, from all causes, including control panel and wire bundle fires.	JAA (ACJ 25.1351(d)(3))	AMJ-25.1309 – "extremely improbable".

Quantified TLS	Risk Addressed	Source	Basis
1 x 10^{-5} probability of failure of the automatic reserve performance (ARP) during the critical time interval which prevents the insertion of the required thrust or power, 1 x 10^{-9} probability of failure of the ARP during the critical time interval which results in a significant reduction in thrust power.	Reduced thrust or power caused by failures or combinations of failures in the ARP system during the time critical interval.	JAA (Appendix I-25.4(a) to JAR 25)	AMJ-25.1309 – “improbable” and “extremely improbable”.
1 x 10^{-9} probability of the concurrent existence of an ARP system or engine failure during the time critical interval.	Engine failure	JAA (Appendix I-25.4(b) to JAR 25)	AMJ-25.1309 – “extremely improbable”.
1 x 10^{-5} probability of the inadvertent operation of the ARP system.	Unsafe flight due to all causes leading to inadvertent operation of the ARP system.	JAA (Appendix I-25.4(c) to JAR 25)	AMJ-25.1309 – “remote”.
1 x 10^{-9} probability of failures per flight hour that result in loss of altitude display or of displaying hazardously misleading roll or pitch altitude, speed, altitude or navigational and positional information on both pilot’s displays.	Hull loss due to loss of or display of misleading information by electronic systems used for guidance, control or decision making by pilots.	JAA (AMJ-25.11)	AMJ-25.1309 – “extremely improbable”.
1 x 10^{-7} probability per flight hour of display of dangerously incorrect roll and pitch altitude on any single primary altitude display.	Hull loss due to loss of information and display of misleading information by electronic systems used for guidance, control or decision making by pilots.	JAA (AMJ-25.11)	AMJ-25.1309 – “extremely remote”.

Quantified TLS	Risk Addressed	Source	Basis
1 x 10^{-5} probability per flight hour of loss of primary altitude, airspeed, altitude, vertical speed, slip/skid indication display to both pilots; loss of stabilising heading in the flight-deck and all navigation information, and presentation of misleading information slid/skip or side slip information, heading information, flight crew procedures and weather information.	Hull loss due to loss of information and display of misleading information by electronic systems used for guidance, control or decision making by pilots.	JAA (AMJ-25.11)	AMJ-25.1309 – "improbable"
1 x 10^{-7} hazardous events per flight hour of engine operation.	Engine failure.	JAA (ACJ-E510 and JAP APU 6.2)	AMJ-25.1309 – "extremely remote".
1 x 10^{-5} major events per flight hour of engine operation.	Engine failure.	JAA (ACJ-E510 and JAP APU 6.2)	AMJ-25.1309 – "remote".
1 x 10^{-3} minor events per flight hour of engine operation.	Engine failure.	JAA (ACJ-E510 and JAP APU 6.2)	AMJ-25.1309 – "reasonably probable".
1 x 10^{-7} probability per flight hour of a fault, in either the engine automatic controlling system or any associated instrumentation systems, resulting in the inadvertent operation of the other	Inadvertent engine automatic control system operation.	JAA (JAR E.50(c))	AMJ-25.1309 – "extremely remote".
1 x 10^{-5} shaft failures per hour of engine operation.	Compressor,/fan and turbine shaft failure.	JAA (JAR E.850(b))	AMJ-25.1309 – "remote".
1 x 10^{-8} failures per hour of operation of the complete propeller and its control system, resulting in hazardous effects.	Propeller failure.	JAA (JAR P.70(d))	Based on historical data.

Quantified TLS	Risk Addressed	Source	Basis
Application to Aviation Operations			
0.05×10^{-3} in-flight engine shutdowns per flight hour for 120 minutes maximum flight time; 0.02×10^{-3} in-flight engine shutdowns per flight hour for 180 minutes maximum flight time.	Engine failure in extended range two engine operations (ETOPS).	FAA	A basic target level of safety for ETOPS is that it be as good as the level achieved by current 3- and 4-engine wide-bodied aeroplanes.
1×10^{-6} and 1×10^{-5} for an acceptable average and limit probability, respectively, of a longitudinal touchdown earlier than a point on the runway 60 m from the threshold.	Unsafe landing, due to excessively short longitudinal touchdown, associated with touchdown performance of automatic landing systems.	JAA (ACJ-AWO.131 (1.4))	AMJ-25.1309 – “improbable”.
1×10^{-6} and 1×10^{-5} for an acceptable average and limit probability, respectively, of a longitudinal touchdown beyond the end of the touchdown zone lighting, 900m from the threshold.	Unsafe landing due to excessively long longitudinal touchdown, associated with touchdown performance of automatic landing systems.	JAA (ACJ-AWO.131 (1.4))	AMJ-25.1309 – “improbable”.
1×10^{-6} and 1×10^{-5} for an acceptable average and limit probability, respectively, of a lateral touchdown with the outboard landing gear greater than 21 m from the runway centreline, assuming a 45 m runway.	Unsafe landing due to excessive lateral displacement of touchdown, associated with touchdown performance of automatic landing systems.	JAA (ACJ-AWO.131 (1.4))	AMJ-25.1309 – “improbable”.
1×10^{-6} and 1×10^{-5} for an acceptable average and limit probability, for the sink rate for structural limit load.	Unsafe landing due to excessive sink rate, associated with touchdown performance of automatic landing systems.	JAA (ACJ-AWO.131 (1.4))	AMJ-25.1309 – “improbable”.

Quantified TLS	Risk Addressed	Source	Basis
1 x 10^{-6} and 1 x 10^{-5} for an acceptable average and limit probability, of a bank angle such that the wing tip touches the ground before wheels.	Unsafe landing due to excessive bank angle, associated with touchdown performance of automatic landing systems.	JAA (ACJ-AWO.131 (1.4))	AMJ-25.1309 – “improbable”.
1 x 10^{-6} and 1 x 10^{-5} for an acceptable average and limit probability, of a lateral velocity or slip angle for structural limit load.	Unsafe landing due to excessive lateral or slip angle, associated with touchdown performance of automatic landing systems.	JAA (ACJ-AWO.131 (1.4))	AMJ-25.1309 – “improbable”.
1 x 10^{-5} probability per flight hour of incorrect displaying of guidance commands by the flight director system (or alternative form of information display) to the pilot when credit is taken for an excess-deviation alert.	Loss of information or incorrect information in relation to CAT 2 operations.	JAA (JAR AWO.263)	AMJ-25.1309 – “remote”
1 x 10^{-7} probability per flight hour of the radio altimeter providing false height information, leading to hazardous situation.	False height information from information display fault in relation to CAT 2 operations.	JAA (JAR AWO.268)	AMJ-25.1309 – “extremely remote”
1 x 10^{-3} probability that the excess-deviation alerts fail to operate when required.	Unsafe flight in CAT 2 operations due to failure of excess deviation alert.	JAA (JAR AWO.269)	AMJ-25.1309 – “frequent”
1 x 10^{-9} probability for a catastrophic effect if a go-around is carried out without external visual references according to standard procedures; 1 x 10^{-4} probability that the aeroplane, with all engines operating, will touch the ground during this procedure.	Hull loss during go-around in absence of external visual reference, in minimum approach break-off height CAT 3 operations.	JAA (JAR AWO.313)	AMJ-25.1309 – “extremely improbable”

Quantified TLS	Risk Addressed	Source	Basis
0.05 probability, when the automatic ground control or head-up ground roll guidance is being used, that the point on the aeroplane centre line between the main wheels will deviate more than 8.2 m from the runway centreline on any one landing; 1 x 10^{-4} probability, when the operation is predicted on the provision of fail-operational ground roll control, that the outboard landing gear will deviate to a point more than 21.3 m from the runway centre-line while the speed is greater than 40 knots.	Unsafe landing due to excess displacement of aeroplane from runway centre-line, in minimum approach break-off height CAT 3 operations.	JAA (JAR AWO.338(b))	AMJ-25.1309 – "improbable"
Compliance of automatic landing system with the provisions of JAR-AWO.161, and of the radio altimeter and excess deviation alerts with the provisions of JAR-AWO.268 and JAR-AWO.269, respectively.	Unsafe landing due to failure of automatic landing systems in CAT 3 operations.	JAA (JAR AWO.361)	AMJ-25.1309
1 x 10^{-3} probability of failure resulting in the loss of automatic landing control capability below decision height.	Automatic landing control capability failure leading to unsafe flight, in fail-passive automatic landing systems in CAT 3 operations.	JAA (JAR AWO.365 (a))	AMJ-25.1309 – "frequent"
1 x 10^{-3} probability of total loss of the landing system below the alert height.	Unsafe landing due to loss of landing system, in fail-passive automatic landing systems in CAT 3 operations.	JAA (JAR AWO.365 (a))	AMJ-25.1309 – "extremely remote"

Quantified TLS	Risk Addressed	Source	Basis
Compliance with JAR-AWO.161, where a head-up display or other form of guidance display is fitted for use in the event of automatic landing system failure.	Unsafe landing in CAT 3 operations.	JAA (JAR AWO.263)	AMJ-25.1309
1×10^{-3} probability of the display of incorrect guidance information to the pilot during the take-off run and of the loss of take-off guidance during take-off.	Unsafe take-off due to take-off guidance system failure in low visibility.	JAA (JAR AWO.461)	AMJ-25.1309 – “remote”

Appendix 4: Functional Hazard Analysis

Appendix 4: Aerodrome Design Rules Functional Hazard Analysis Summary Report

A4.1 INTRODUCTION

To support the development of risk-based aerodrome design rules, the risks associated with the various elements of aerodrome design need to be understood and quantified. As a first step in this process, a prioritised set of potential safety risks needs to be identified and a Functional Hazard Analysis (FHA) has been undertaken in order to achieve this. This appendix describes the FHA process and its application to the Aerodrome Design Rules project and provides a summary of the FHA output.

A4.2 OVERVIEW OF THE FHA PROCESS

A Functional Hazard Analysis is a formal and systematic process for the identification of hazards arising from the undertaking of functions or operations associated with an activity. The purpose of the FHA in the context of the Aerodrome Design Rules project is to determine relevant hazards to aircraft associated with aerodrome operations (*e.g.* approach, landing, taxiing, take-off roll, and associated fault sequences) and the physical design of aerodromes. The FHA also enables the identification of the associated controls currently (or potentially) in place to manage these hazards. The output of the FHA is a systematic description of a comprehensive set of the hazard sequences and the relevant mitigation/control measures, with particular reference to the risk mitigation functions of the various aerodrome design features. This preliminary hazard analysis provides the basis for a series of risk analyses that are to be undertaken to support the development of rational risk-based design rules.

The formal process for hazard identification within the FHA is similar to that adopted in “HAZOP” studies. HAZOP stands for **haz**ard and **op**erability study. The HAZOP technique has been developed over a number of years and is a well recognised and effective technique for identifying potential hazards on plant, processes and systems and also problems which could prevent efficient operation. It is equally applicable to the study of hazards in the aviation industry and is now in common use in that industry sector.

The basic HAZOP technique involves gathering together a multi-disciplinary team, with the purpose of identifying hazards by brainstorming in a workshop, or series of workshops. The key principle of the process is that it is a team effort, in which the brainstorming technique stimulates creativity, encourages expansive thinking and generates ideas. Structure in the workshop is provided by an experienced team leader (or “facilitator”) whose role is to systematically guide the team through the HAZOP or FHA. The process is broken down into “nodes” or parts of the process to make the process manageable, and hazards are identified by the application of a set of "keywords" (or prompts) which help to ensure that the process is explored in detail and in a comprehensive way. The workshop is recorded using a risk register by the technical secretary; in the Aerodrome Design Rule project workshop an Excel-based in-house AEA Technology risk register was used with projection equipment to enable the register to be viewed by all participants during discussions.

In addition to the identification of hazards, the FHA process has also been used to evaluate their significance, through preliminary estimates of the likelihood and consequence of the identified hazard scenarios. This enables the identification of those significant events that merit detailed risk modelling. Within the FHA process, the preliminary evaluation of the risk significance is undertaken by assessing each identified risk in terms of the likelihood of occurrence and severity of the consequence should the risk be realised. Both the likelihood and severity associated with the risks are assessed on suitably calibrated point scales (*e.g.* on a scale of 1 to 5) within the FHA workshop.

A4.3 AERODROME DESIGN RULE FHA WORKSHOPS

A three-day FHA workshop was undertaken at the AEA Technology premises in Risley on the 14th to 16th May 2001. The participants in the Workshop provided a broad range of expertise and knowledge, including pilots, airside operations and flight operations. A full list of participants and their roles in the workshop is provided in Table A4-1.

Table A4-1 FHA Workshop Participants

Name	Organisation	Role
Jon Hancox	AEA Technology	Facilitator
Chris Kingscott	AEA Technology	Technical secretary
Bjoern Bo	NCAA	Participant (flight operations)
Tomm Alexander øvre	NCAA	Participant (legal affairs)
Snorre Steen	NCAA	Participant (Statistical advisor)
John Lim	BAA	Participant (airside operations)
Keith Burridge	BAA	Participant (airside operations)
Arne Ribe	NAS	Participant (pilot)
Mark Eddowes	AEA Technology	Participant (aviation risk)
Anne MacInnes	AEA Technology	Participant (aviation risk)
Roel Berensden	AEA Technology	Participant (aviation risk)

In order to identify the safety risks in a systematic manner, the aerodrome operations were broken down into the following operational phases (or “nodes”):

- Take-off roll
- Reject take-off
- Take-off wheels-off (0 to 35′)
- Take-off climb out
- Circling
- (Precision instrument) approach
- Missed approach[a]
- Balked landing
- Landing[b]

[a] The missed approach phase is defined as from the missed approach point to the missed approach hold point.
[b] For precision approaches the landing phase was defined as from the missed-approach point to the end of landing roll. For non-precision approaches the landing phase was defined as from the visual decent point to the end of landing roll.

(Due to time constraints, taxiing operations were not assessed during the workshop. However, AEA Technology has previously undertaken extensive FHA for taxiing operations and the findings of these studies are summarised in Section A4.5.)

Each of the above operational phases was considered in turn. Causal (and compounding) factors that can potentially impact on the safety of the aircraft operation were then identified for each operational phase. In order to identify the causal factors in a systematic and comprehensive manner, a set of keyword prompts were used. These keywords ensured consideration of the following influencing factors:

- equipment;
- communications;
- weather/visibility;
- movement;
- airside traffic;
- other traffic;
- human factors;
- procedures;
- aircraft characteristics;
- trajectory;
- surface conditions;
- runway/taxiway intersections.

Each of these keywords had a subset of more detailed guidewords; the full list of keywords and guidewords is provided in Annex A4.1. By consideration of each keyword/guideword, a comprehensive set of causal factors was identified for each operational phase.

Regardless of the initiating causal event, the safety of aircraft operations is ultimately compromised by either:

- deviation of the aircraft from its intended path; or
- obstruction of the intended path (and potential collision).

Generally, deviation of the aircraft from its intended path could include catastrophic aircraft failure, for example following a major onboard explosion. However, within the context of aerodrome design rules, only those impacts against which the design rules may provide some protection are of specific interest. As such, during the FHA workshop only limited attention was paid to catastrophic failures.

In order to make use of the identified risks for the development of aerodrome rules, the aerodrome features that play a role in reducing the different risks need to be identified. To achieve this each risk was associated with one or more different incident types, where the incident types were defined as either a specific type of aircraft deviation or a collision. The range of different incident types was assessed by the workshop team for each operational phase and these are summarised in Table A4-2.

Table A4-2 Incident Types by Operational Phase

Operational Phase	Associated Incident Types
Take-off roll	Veer-off, Over-rotation, Under-rotation, Overrun, Collision
Rejected take-off	Veer-off, Overrun, Collision
Wheels-off	Veer-off, Over-rotation, Under-rotation, Overrun, Collision
Take-off climb out	Veer-off, under-rotation, Over-rotation, Collision
Circling	Collision
(Precision instrument) approach	Veer-off, Under approach point, Collision
Missed approach	Veer-off, Under-height, Collision
Balked landing	Veer-off, Under-height, Overrun, Collision
Landing	Land-short, Land-long, Land-offset, Veer-off, Overrun, Hard-landing, Collision

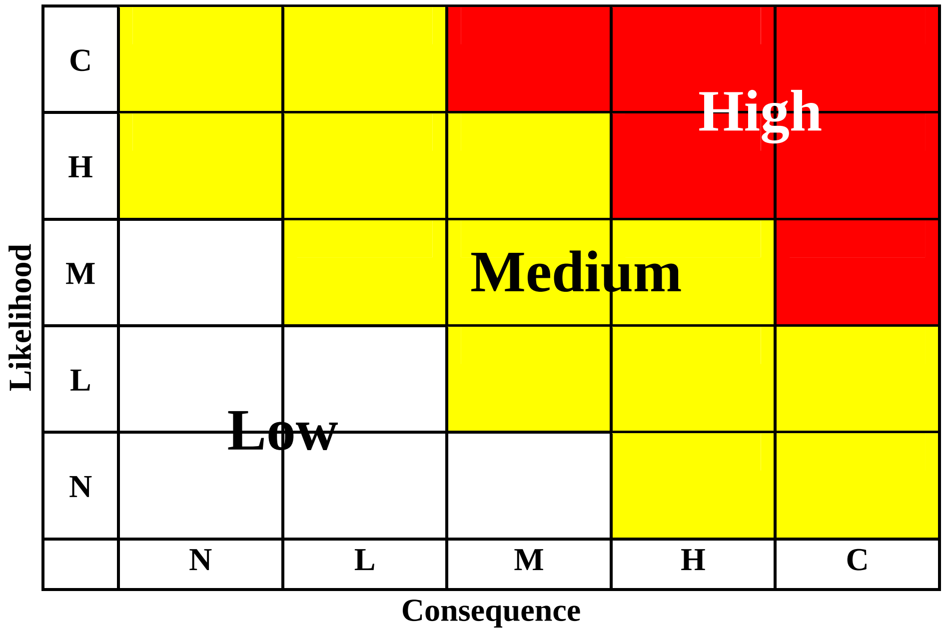
Finally, once the causal factors within each operational phase had been identified, these risks were qualitatively assessed in terms of their likelihood of occurrence and the severity of their consequence if realised. Both the likelihood and consequence severity were assessed on five point scales of Negligible (N), Low (L), Medium (M), High (H) and Certain/Catastrophic (C). The calibration of the five-point scales used in the workshop is based on JAR25 and is presented in Table A4-3.

Table A4-3 Risk Ranking Calibration

Band	Likelihood		Consequence
C	Frequent	10^{-3} to 1	• Loss of aircraft • Multiple fatalities
H	Reasonably probable	10^{-5} to 10^{-3}	• Large reduction in safety margins • Flight crew cannot perform tasks accurately/completely
M	Remote	10^{-7} to 10^{-5}	• Significant reduction in safety margins • Flight crew cannot perform tasks in adverse conditions • Injury to occupants
L	Extremely remote	10^{-9} to 10^{-7}	• Nuisance • Operating limitations
N	Extremely improbable	$< 10^{-9}$	• No significant effects

The overall risk associated with each causal factor can then be assessed through consideration of the likelihood-consequence matrix. Given the uncertainties inherent in the qualitative assessment process, the risks are assessed within three broad bands: High, Medium and Low. The elements of the risk matrix that fall within these bands are shown below in Figure A4.1.

Figure A4.1: Risk Matrix



A4.4 OUTPUT FROM THE FHA WORKSHOPS

A4.4.1 Risk Register

The identification and qualitative assessment of the risks associated with each operational phase was recorded on a “Risk Register” using an Excel-based in-house AEA Technology software tool. The completed risk register is presented in Annex A4.2.

A4.4.2 Identification of Key Risks

Analysis of the risk register enables the identified hazards to be ranked as being of either high, medium or low risk according to the qualitative assessment procedure defined in Section A4.3. The causal risk factors have been prioritised for each operational mode and the high risk factors for each mode are presented in Annex A4.3. A summary of the generic types of causal factors of most significance for the different operational modes are summarised in Table A4-4.

Table A4-4 Key Generic Causal Factor by Operational Mode

Operational Modes	Key Generic Causal Factors	
Take-off roll	• Communications • Visibility • Surface conditions • High/low velocity/momentum	• Winds • Aircraft performance characteristics • Vortex shedding • Other vehicles
Rejected take-off	• Aircraft performance characteristics • Winds • Visibility	• Crew competency • Other vehicles
Wheels-off	• Icing (wings/engines) • Winds	• Vortex shedding
Take-off climb-out	• Icing (wings/engines) • Aircraft performance characteristics • Bird strike	• Winds • Vortex shedding • High/low velocity/momentum
Circling	• Loss of lights	• Loss of visual reference
Approach	• Communications • Aircraft performance characteristics • Winds	• Icing of wings/engines • High/low velocity/momentum
Missed Approach	• Faulty equipment (altimeter) • High/low velocity/momentum	• winds • Icing of wings/engines
Balked landing	• Vortex shedding • Winds • Crew experience/competency • Visibility	• Icing of wings/engines • High/low velocity/momentum • Aircraft performance characteristics • Other vehicles
Landing	• High/low velocity/momentum • Aircraft performance characteristics • Communications	• Surface conditions • Equipment failure (flaps)

One point of interest from the above assessment is that engine failure has not been highlighted as a high risk causal factor. The reason for this is that the likelihood of engine failure is low and further that the loss of a single engine is, to a large extent, allowed for in the aircraft performance characteristics and the airline flight procedures. As noted earlier, catastrophic engine loss (*e.g.* all engines) leading to total loss of flight control is beyond the scope of the current study and so has not been included in the risk register. Nonetheless, it is noted that the combination of engine failure with other adverse operating conditions (*e.g.* strong cross-winds) may be significant. Also, a number of external factors (*e.g.* various weather conditions and vortex) are identified as significant and will therefore deserve consideration during the subsequent risk assessment. Similarly, various less uncommon non-catastrophic system failures have been identified that may be of particular relevance.

It was considered that, once an aircraft has begun to deviate from its intended path, high momentum aircraft (which will, of course, typically be associated with larger aircraft) are likely to deviate further before corrective action can be taken. On the other hand, it was also noted that lower momentum aircraft are more prone to being deviated from their path in the first instance in certain adverse operating conditions, such as strong winds or when encountering vortices.

In addition to identifying the risk factors, it is important that those aerodrome/aircraft features that may play a role in their mitigation are also identified. The identification of such features for each risk factor was undertaken following the FHA workshop. This identification process was achieved through consideration of the operational phase and type(s) of deviation of the aircraft from its intended pathway (see Table A4-2) that may result and assessment of the aerodrome safety features that will be relevant to the control of these risks. The aerodrome/aircraft safety features considered in this context are as follows:

- Declared distances:
  - Take-off distance required (TODR);
  - Accelerate/stop distance required (ASDR);
  - Landing distance required (LDR);
  - Take-off run available (TORA);
  - Take-off distance available (TODA);
  - Accelerate/stop distance available (ASDA);
  - Landing distance available (LDA).
- Runway strip:
  - Width;
  - Length.
- Runway End Safety Area (RESA).
- Runway-Taxiway separation distances.
- Obstacle limitation surfaces:
  - Outer horizontal surface (OHS);
  - Conical Surface (CS);
  - Inner horizontal surface (HIS);
  - Approach surface (AS);
  - Inner approach surface (IAS);
  - Transitional surface (TS);
  - Inner transitional surface (ITS);
  - Balked landing surface (BLS);
  - Take-off climb surface (TCS).

The relevant aerodrome/aircraft features have been identified for all the risk factors identified on the risk register. The features associated with the high priority risk factors are presented in Annex A4.3.

A4.5 TAXIING OPERATIONS

A number of studies have been previously undertaken to assess the deviation of aircraft in taxiing operations. Studies of measured taxiing deviations at Heathrow and Schiphol in the late 1980’s and early 1990’s have struggled to identify any significant causal factors behind aircraft deviation. On the other hand, review of historical incident data by AEA Technology has suggested that a number of factors may influence such deviation, including: human error, mechanical failure and extreme weather conditions (most notably poor visibility in heavy rain/snow). In order to better understand the key causal and compounding factors affecting aircraft deviation during taxiing operations, AEA Technology has previously undertaken FHAs of this operational mode and the findings of these studies are summarised below.

The first step in the FHA process has been to identify all the different aircraft activities of interest and to break these down into separate operational modes for which the potential causes of deviation may be different. For the purposes of the FHA, taxiing operations have been divided into the follow sub-phases:

- Taxiing on straight sections;
- Taxiing on curved sections; and
- Holding.

The most significant causal risk factors identified in the FHA for each of the above operational modes are presented in Table A4-5 below.

Table A4-5 Identified Causal Factors for Taxiway Deviation

Mode	Cause	Comment
Straight Taxiing	Pilot workload	Punctuality pushing more workload to taxiing
Curved Taxiing	Pilot workload	As above
	Pilot displacement	Longitudinal displacement will vary between aircraft more than lateral
	Change of centreline	*i.e.* 'kinks' in taxiway
	Judgmental over-steer	Tied to pilot displacement
Holding short of runway	Unguided movement	Planned deviation to achieve marshalling
	Judging distance in turning	Made harder by longer wheel base

Of the above factors, unguided movement when aircraft are holding short of the runway, *e.g.* while waiting to cross the runway, was identified as posing a particularly significant risk. It was considered that during such operations, there is potential for aircraft deviation of around 20m or more. Pilot workload was identified as a potential cause of moderate deviation during taxiing operations. It was felt by the groups involved in the previous FHAs that this situation has worsened over recent years where increased pressure for punctuality has led to more of the workload of routine pre-take off testing being performed after pushback, thus increasing the potential for pilot error on steering.

In addition to highlighting those factors with the greatest expected impact on aircraft deviation, it is also useful to identify those factors that may lead to the greatest level of deviation regardless of the likelihood of occurrence. For normal taxiing, the following factors have been identified as having the potential to lead to deviation in the region of about 5m:

- Poor visibility, *e.g.* during heavy rain/snowfall
- Obscuring of centreline by diminished surface condition, *e.g.* snow
- Meandering due to pilot confusion/poor guidance

It is noted that the problem of poor visibility in certain weather conditions is possibly worse for New Generation Larger Aircraft (NGLA) due to the increased height of the cabin above the runway. The identification of the influence on deviation of adverse weather through reduced visibility and diminished surface conditions is somewhat inconsistent with the findings of previous deviation measurement studies at Heathrow. However, this may be due to the general lack of really *extreme* weather conditions during the measurement survey period at Heathrow. It is noted that review of historical data also indicate the potential role that weather conditions may play in aircraft taxiing deviation.

Review of historical data also suggests that the level of deviation from centreline due to pilot confusion and/or poor guidance can be very large. However, extreme deviation of this type is probably due to deliberate, but erroneous, mis-routing of aircraft down an unauthorised taxi lane as opposed to what one might call ‘genuine’ deviation around the designated taxiway centreline. Gross deviation of this nature is considered separately as, in essence, taxiway separation distances cannot mitigate against them. As such, only smaller-scale ‘meandering’ deviation due to pilot confusion is of interest in this respect and hence the level of deviation has been assessed as a few metres (as opposed to tens of metres).

Finally, it was concluded that the aircraft momentum is not necessarily a significant contributing to gross deviations. Intuitively, it might be considered that, once deviation has occurred, heavier aircraft (*e.g.* NGLA) would deviate further before corrective action can be taken due to their generally higher momentum. However, discussions within the previous FHA’s and review of historical data suggest that this may not be the case. In particular, it is likely that physical controls on larger aircraft, especially new generation aircraft, enable pilots to actually have greater steering control of such aircraft. This is in contrast to other operational modes (see Section A4.4), where the aircraft momentum has been identified as an important factor in the scale of aircraft deviation.

A4.6 REQUIREMENTS FOR RISK ASSESSMENT MODELLING

On the basis of the review of risks provided by the functional hazard analysis, a number of risk modelling requirements can be identified, essentially relating to deviation of aircraft about the preferred path. In summary, the different elements of operation for which such displacement is to be considered may be listed systematically as follows:

- Operations at ground level:
  - Lateral displacement from the runway during take-off operations;
  - Lateral displacement from the runway during landing operations;
  - Lateral displacement from the taxiway during ground manoeuvres;
  - Longitudinal displacement before the runway end on landing (undershoot);
  - Longitudinal displacement beyond the runway end on landing (landing overrun);
  - Longitudinal displacement beyond the runway end on take-off (take-off overrun);
- Operations of airborne aircraft:
  - Lateral and vertical displacement during take-off/climb out;
  - Lateral and vertical displacement during non-instrument approach;
  - Lateral and vertical displacement during non-precision approach;

- Lateral and vertical displacement during precision approach;
- Lateral and vertical displacement during missed approach;
- Lateral and vertical displacement during balked landing;
- General positioning during circling.

Each of these elements has been considered during the risk assessment phase of the project. In undertaking these assessments, we identify the general need to take account of aircraft positioning both during normal operation and during relevant fault sequences, with reference to the potential causal factors identified by the functional hazard analysis.

A4.7 CONCLUDING REMARKS

The Functional Hazard Analysis has enabled identification and prioritisation of the causal factors that may result in aerodrome safety margins being challenged. Furthermore, those aerodrome/aircraft features that may play a role in the mitigation of the key risks have also been identified through consideration of the types of aircraft displacement from the preferred path during the different operational modes.

The output from the FHA provides an understanding of the key processes and factors that can lead to incidents that challenge aerodrome safety margins. Supported by this understanding the (semi-)empirical risk models described elsewhere in this report have been developed. However, it should be noted the extent to which the identified causal factors can be fully accounted for in the risk models is dependent upon the amount and quality of data that is available.

Annex A4.1 FHA Workshop Keywords

Casual Factors	
Keyword	**Guideword**
Equipment	complete failure partial failure incorrect setting
Communications (verbal)	complete loss partial loss mistakes/misunderstandings alternatives
Communication (hand)	complete loss partial loss mistakes/misunderstandings alternatives
Visibility	loss of visibility diminished operation in darkness dusk/gloom bright sun rain fog
Movement	too fast too slow too high too low steering/angle/turning
Airside traffic	traffic movement and traffic lanes types of traffic speed training loss of control
Other aircraft	parked taxiing stacking congestion
Weather	ice snow rain fog hail heat bright sun radio interference wind

Annex A4.2 Completed Risk Register

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
1		**Take-off roll**	V veer-off, OR over-rotation, U under-rotation, OV overrun, C collision			
1	1	Loss of runway lights	V, OV, C	L	H	Similar risk to rejected take-off
1	2	Engine Failure(s)	U, V, OV, C	L	H	
1	3	Loss of aircraft primary flight instruments	U, V, OV, OR, C	N	H	Problems will occur during climb out. However partial loss is more probable than total loss. May lead to a rejected take-off.
1	4	Landing gear failure	V, OV	M	H	eg tyre blowout
1	5	Failure of flight controls	U, V, OV, OR, C	L	C	
1	6	Communication misunderstanding (flight crew/ATC)	C	M	C	May lead to total disaster in combination with low visibility - ref . Tenerife
1	7	Communication misunderstanding (within flight crew)	OR, U, OV	M	C	
1	8	Fog or Snow & darkness	V	C	M	Blinded by own lights. Turned off as soon as airborne.
1	9	Bright sunlight	U, V, OV, OR, C	C	M	Reflection off surface & windscreen glare
1	10	Bird strike	U, V, OV, C	M	H	Consequences as engine failure
1	11	Heavy rain	V, OV, C	H	M	Mainly a problem combined with strong crosswinds
1	12	Snow	V, OV, C	C	M	
1	13	Fog	V, C	C	M	
1	14	Wildlife	C	M	H	
1	15	Airside vehicles	C	L	C	Collision may be disastrous for the aircraft
1	16	FOD	V, OV, C	L	C	
1	17	Winter contaminants	U, V, OV, OR, C	C	M	
1	18	Request from ATC to take-off before aircraft ready	OV	H	M	Can lead to rejected take-off
1	19	Too fast for abort	OV	M	C	
1	20	Miscalculation of take-off weight & CofG leading to take-off roll too slow	U, OR	L	H	Calculation undertaken by ground staff. C of G critical during initial lift off.
1	21	Loss of take-off roll speed due to runway surface conditions	U, OV	H	M	Reduced margin for obstacle clearace.
1	22	Cross wind leading to deviation of take-off roll	V	C	M	If crosswind leads to a veer-off ending outside the runway, the result is at least significant
1	23	Vehicle breakdown	C	L	H	
1	24	Take-off with unknown aircraft exterior damage	V, OR, U, OV	L	H	Consider degrees of potential damage
1	25	Use of wrong runway/ intersection	C, OV, U	L	H	
1	26	Airside driver competence	C	M	H	
1	27	Taxi movements across runways	C	H	H	eg helicopters

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
1	28	Improper use of ground signals and signage	C	H	H	Taxiways intersecting runways
1	29	Time lag between aircraft undergoing de-icing and actual take-off	U	M	C	Distance between de-icing station and runway or congestion
1	30	Variable wind direction and speed	V	C	M	
1	31	Cross and tail winds	V, U	C	M	Can cause engine cut out at rotation. Environmental pressures on preferrential runway usage versus safety considerations (eg Schiphol)
1	32	Inaccurate or misunderstood declared distances	OV, C, U	M	H	
1	33	Performance characteristics of aircraft	OV, V, U	C	M	Consequences of large aircraft entering a fault situation with insufficient safety margins around runway
1	34	Sequencing of light aircraft movements after large aircraft (vortex shedding)	V	H	H	Could lead to a crash if differential size between aircraft large.
1	35	Runway undulations	U, V, OV, OR, C	M	H	Could lead to premature lift-off. Structural damage to aircraft. Impact not immediate but could effect subsequent operations
1	36	Temporary surfaces during WIP	U, V, OV, OR, C	M	H	As above
1	37	Loss of friction	OV, V	C	M	Winter contaminants, drainage of water
1	38	Quality of runway material	OV, V	H	M	
1	39	Newly resurfaced runway (oil from bitumen)	OV, V	M	M	
1	40	Contamination from de-icer	OV, V	H	M	
1	41	Different surface material along runway	OV, V	H	M	
2		**Rejected take-off**	V veer-off, OV overrun, C collision			
2	1	Reverse thrust relatively less effective than prop	OV, V	C	M	Should be taken into account in aircraft performance graphs. For jet aircraft available margins at airfield will be not much greater than required by regs. Veer off in conjunction with engine failure and subsequent asymmetric power. Surface conditions. For fire situation reverse thrust may lead to fanning of fire.
2	2	Impaired or brake failure	OV, V	L	C	
2	3	Loss of runway lights	V, OV, C	L	H	Can be initiating event and also a compounding issue leading to veer off.

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
2	4	Engine Failure(s)	V, OV, C	M	H	Initiating event. Problem of perceived engine failure.
2	5	Landing gear failure	V, OV	M	H	eg tyre blow-out, initiating event
2	6	Loss of hydraulic power	OV, V	L	C	Initiating event
2	7	Loss of aircraft electrical power	OV, V	L	H	Initiating event
2	8	Inability to communicate to ATC failure to lift off	C	L	H	Combined with low visibility
2	9	Fog or Snow & darkness	V	C	M	Blinded by own lights
2	10	Bright sunlight	V	C	M	Reflection off surface & windscreen glare
2	11	Bird strike close to V1	V	M	H	Initiating event
2	12	Heavy rain	V, OV	H	M	May be a problem combined with strong crosswind
2	13	Snow	V, OV	C	M	
2	14	Wildlife	V	M	H	Initiating event
2	15	Airside vehicles	V, C	L	H	Initiating event. Consequence can be high depending on the combination of vehicle & aircraft eg distance.
2	16	Too fast for reject	OV, V	M	C	
2	17	Cross wind leading to deviation of take-off roll	V	C	M	Initiating event. Covered under take-off. Can cause engine cut out at rotation. Environmental pressures on preferential runway usage versus safety considerations (eg Schiphol)
2	18	Notification from ATC of aircraft exterior damage	V, OV	L	H	Initiating event. Impact will be dependent on the extent of the damage.
2	19	Parked aircraft infringing runway clearance including aircraft at stand	C	C	M	Only an issue in a veer off situation, more significant for landing.
2	20	Inadequate crew competency	V, OV	H	H	
2	21	Inaccurate or misunderstood declared distances	OV, C	M	H	
2	22	Surface contaminants/ reduced friction	V, OV	C	H	Also condition of surrounding surfaces, eg RESA.
2	23	High momentum/kinetic energy	V, OV	C	M	Performance tables take into account aircraft size, mass etc.Veer worse for high momentum, more stable less prone to cross winds, longer to correct, potential for overrun greater
2	24	Low momentum/kinetic energy	V	C	M	Easier to correct but more prone to cross winds etc
2	25	Larger wingspan	V	C	M	Less safety margin from obstacles
3		**Wheels-off (0 to 35')**	V veer-off, OR over-rotation, U under-rotation, OV overrun, C collision			
3	1	Engine Failure(s)	U, V, OV, C	L	H	
3	2	Loss of aircraft primary flight instruments	U, V, OV, OR, C	L	H	Problems will occur during climb out. Partial failure is more probable than total loss

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
3	3	Failure of flight controls	U, V, OV, OR, C	L	C	
3	4	Miscalculation of take-off weight & CofG leading to take-off roll too slow	U, OR	L	H	Calculation undertaken by ground staff. C of G critical during initial lift off.
3	5	Loss of take-off roll speed due to runway surface conditions	U, OV	H	M	Reduced margin for obstacle clearace.
3	6	Cross wind leading to deviation of take-off roll	V	C	L	
3	7	Take-off with unknown aircraft exterior damage	V, OR, U, OV	L	H	Consider degrees of potential damage
3	8	Use of wrong runway/ intersection	C, OV, U	L	H	May lead to reduced obstacle margins, if any
3	9	Parked aircraft infringing runway clearance including aircraft at stand	C	H	M	Only an issue in a veer off situation, more significant for landing. Will be dependent on position of actual take-off point on runway and relative position of apron areas, airport infrastructures and taxiways.
3	10	Movable obstacles (oil rig/cranes)	C	H	M	
3	11	Time lag between aircraft undergoing de-icing and actual take-off	U	M	C	Distance between de-icing station and runway or congestion
3	12	Variable wind direction and speed	V	C	M	
3	13	Cross and tail winds	V, U	C	M	Can cause engine cut out at rotation. Environmental pressures on preferrential runway usage versus safety considerations (eg Schiphol)
3	14	Inaccurate or misunderstood declared distances	OV, C, U	M	H	
3	15	Sequencing of light aircraft movements after large aircraft (vortex shedding)	V	H	H	Could lead to a crash if differential size between aircraft large.
3	16	Runway undulations	U, V, OV, OR, C	M	H	Could lead to premature lift-off. Structural damage to aircraft. Impact not immediate but could effect subsequent operations
4		**Take-off climb out**	V - Veer Off, U - under rotate, C - obstacle collision			
4	1	Failure of de-icing equipment (engine)	V, U	H	H	
4	2	Failure of de-icing equipment (wings)	V, U	H	M	Turboprop more exposed to icing than jets
4	3	Loss of lift (reduced climb) due to aerodynamic problems	U	M	C	
4	4	Engine Failure(s)	V, U	M	H	Post take-off, when airborne
4	5	Loss of aircraft primary flight instruments	V, U	L	H	Likelihood changed for consistency

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
4	6	Landing gear fail to retract	U	L	L	If combined with engine failure, impact on safety - C
4	7	Failure of flight controls	V, U	L	H	
4	8	Loss of navigational aids	V	L	H	
4	9	Failure of lighting on obstacles	C	L	M	
4	10	Communication misunderstanding (flight crew/ATC)	V	M	L	After balked landing impact on safety - M.
4	11	Communication misunderstanding (within flight crew)	V	M	L	
4	12	Fog or Snow & darkness		C	L	In general not a problem unless combined with loss of primary systems
4	13	Bird strike	V, U	H	H	Consequences as engine failure
4	14	Heavy rain leading to flame out		L	C	
4	15	Miscalculation of take-off weight & CofG leading to take-off climb too slow	U	M	H	Calculation undertaken by ground staff. C of G is of key importance at this stage.
4	16	Cross wind	V	C	M	
4	17	Take-off with unknown aircraft exterior damage	V, U	M	H	Retraction of flaps normally takes place around 400 ft. Damage to pressure cabin.
4	18	Damage from faulty airfield equipment	V, U	M	H	eg lighting.
4	19	Movable obstacles (oil rig/cranes)	C	M	H	Problem if not notified and impinges on safeguarded surfaces.
4	20	Inaccurate or lack of obstacle charts	C	C	H	Critical when combined with an engine failure.
4	21	Wind shear	U	C	H	
4	22	Variable wind direction and speed	V, U	C	L	
4	23	Cross and tail winds	V, U	C	M	Can cause engine cut out at rotation. Environmental pressures on preferrential runway usage versus safety considerations (eg Schiphol)
4	24	Combinations of weather conditions	V, U	C	M	Equivalent to cross/tail winds but potential for enhanced effects
4	25	High momentum/kinetic energy	V, U	C	M	Height loss and veer worse for high momentum, more stable less prone to cross winds, longer to correct
4	26	Low momentum/kinetic energy	V, U	C	M	Easier to correct but more prone to wind shear etc
4	27	Larger wingspan	V	C	M	Less safety margin from obstacles.
4	28	Stall speed	U	C	M	Higher stall speed increased height loss. Altimeter inaccuracy not relevant for this scenario.
4	29	Sequencing of light aircraft movements after large aircraft (vortex shedding)	U, V	H	H	Will be dependent on volume of traffic.

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
5		**Circling**	Collision			
5	1	Failure of circling lights	C	M	H	
5	2	Lack of or inadequate circling lights	C	C	M	
5	3	Engine failure	C	L	H	Worst case is when aircraft is turning towards the aerodrome.
5	4	Loss of visual references during circling	C	C	M	Worst case is when aircraft is turning towards the aerodrome.
6		**Precision instrument approach**	V- veer, U - under approach point, C - collision			
6	1	Failure of ILS	V, U	L	M	Worst case is a false signal
6	2	Failure of runway approach lights	V	L	M	Mainly lateral guidance
6	3	Failure of aircraft primary instruments	V, U	L	H	Partly failure is more probable than total failure of primary flight instruments
6	4	General onboard failure	V, U	L	H	
6	5	Failure of marker beacon or equivalent equipment	U	M	L	Differences in failure modes of equipment (hard/soft). Only hazardous if combined with failure of electronic glideslope.
6	6	Failure of altimeter	U	H	L	Worst case is a false high reading
6	7	Failure of aerodrome power supplies	V	L	H	
6	8	Misunderstanding of the QNH	U	H	H	May result into controlled flight into terrain during approach
6	9	Loss of primary communication between ATC and aircraft	C	M	M	Potential for balked landing
6	10	Airspeed too high	U	C	M	Aircrew reaction speed compromised for missed approach and subsequent potential obstacle clearance. ATC pressure to keep airspeed high for airport efficiency.
6	11	Steep glide angle leading to too high airspeed	U	C	M	Consequences as above
6	12	Vortex shedding	U	M	M	
6	13	Failure of radar system	C	M	M	Smaller aircraft (<5700kg) do not have anti-collision equipment
6	14	Cross winds	V	C	M	
6	15	Wind shear	U	H	M	
6	16	Variable wind direction and speed	V, U	C	L	
6	17	Inaccurate or failure of met. reporting	V, U	C	L	
6	18	Icing of engines and wings	V, U	C	M	
6	19	Fatigue or lack of concentration leading to inaccurate positioning	V, U, C	H	M	
6	20	Lack of familiarity with aerodrome	V, U, C	H	M	
6	21	Aircraft characteristics	V,U	C	M	

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
7		**Missed approach**	V - veer-off, U - under height			
7	1	Failure of aircraft primary instruments	V, U	L	H	Partial failure is more probable than total failure of primary flight instruments
7	2	General onboard failure	V, U	M	H	
7	3	Failure of navigation aids	V	M	H	
7	4	Failure or incorrect setting of altimeter	U	H	H	Worst case is a false high reading
7	5	Failure of aerodrome power supplies	V	L	H	Will result in loss of lights, nav. aids and communication. Potential initiating event for missed approach.
7	6	Airspeed too high	U	C	M	Aircrew reaction speed compromised for missed approach and subsequent potential obstacle clearance. ATC pressure to keep airspeed high for airport efficiency. Tend to be prop aircraft asked to fly faster, have better speed reduction capabilities than jets.
7	7	Vortex shedding	U	M	M	Could be higher for smaller aircraft. More likely during take-off.
7	8	Failure of radar system	C	M	M	If using for reduced separation could lead to multiple missed approaches. Smaller aircraft (<5700kg) do not have anti-collision equipment. Safety impact will be dependent on volume of traffic.
7	9	Cross winds	V	C	M	
7	10	Wind shear	U	H	M	
7	11	Variable wind direction and speed	V, U	C	L	
7	12	Inaccurate or failure of met. reporting	V, U	C	L	Potential initiating event for missed approach
7	13	Icing of engines and wings	V, U	C	M	
7	14	Fatigue or lack of concentration leading to inaccurate positioning	V, U, C	H	M	Potential initiating event for missed approach
7	15	Late decision to carry out missed approach	U	H	M	
7	16	Lack of familiarity with aerodrome	V, U, C	H	M	
7	17	Loss of lift (reduced climb) due to aerodynamic problems	U	H	L	Probability based on pilot error on flap control. Safety impact higher if combined with an engine failure.
7	18	Engine Failure(s)	V, U	L	H	Likelihood Changed for consistency
7	19	Failure of flight controls	V, U	L	C	
7	20	Failure of lighting on obstacles	C	M	N	
7	21	Bird strike	V, U	M	M	Consequences as engine failure

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
7	22	Heavy rain leading to flame out		L	H	Could lead to a flame out
7	23	Aircraft took-off with unknown aircraft exterior damage	V, U	N	C	
7	24	Movable obstacles (oil rig/cranes)	C	N	C	
7	25	Combinations of weather conditions	V, U	C	L	Potential initiating event
7	26	Started short of missed approach point	V	H	N	Tendency to be at a higher altitude
7	27	Started beyond missed approach point	U	H	H	Reduced terrain separation
7	28	Too steep at missed approach point	U	H	M	
7	29	Offset from missed approach point	V	H	M	Potential initiating event
7	30	Offset and incorrect heading from missed approach point	V	M	H	
7	31	High momentum/kinetic energy	V, U	C	M	Different safety margins for different aircraft type - ie categorisation. Height loss and veer worse for high momentum, more stable less prone to cross winds, longer to correct
7	32	Low momentum/kinetic energy	V, U	C	M	Different safety margins for different aircraft type - ie categorisation. Easier to correct but more prone to wind shear etc
7	33	Larger wingspan.	V	C	M	Less safety margin from obstacles (3D).
7	34	Stall speed	U	C	M	Different safety margins for different aircraft type - ie categorisation. Higher stall speed increased height loss
8		**Balked landing**	V - veer-off, U - under height, O - overrun, C - collision			
8	1	Failure of aircraft primary instruments	V, U	L	H	Importance dependent on met. conditions. Partial failure more probable than total failure of primary flight instruments.
8	2	General onboard failure	V, U	M	H	
8	3	Failure of runway edge lights	V	L	M	
8	4	Failure of navigation aids	V	M	L	During pull-out phase. Importance dependent on met. conditions. Likelihood changed for consistency
8	5	Failure or incorrect setting of altimeter	U	H	L	Worst case is a false high reading, less important if using visual reference
8	6	Total failure of aerodrome power supplies	V	L	M	

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
8	7	Airspeed too high	U	M	M	Aircrew reaction speed compromised for balked landing and subsequent potential obstacle clearance.
8	8	Vortex shedding	U	H	H	Particularly important if caught in vortex from aircraft taking-off.
8	9	Failure of radar system	C	M	L	Importance during pull-out phase
8	10	High cross winds	V	C	M	Efficiency rating will depend on strength - could lead to closure
8	11	Wind shear	U	C	H	
8	12	Variable wind direction and speed	V, U	C	M	
8	13	Inaccurate or failure of met. reporting	V, U	C	L	Initiating factor of a balked landing
8	14	Icing of engines and wings	V, U	C	M	Landing preferable
8	15	Fatigue or lack of concentration leading to inaccurate positioning	V, U, C	M	H	
8	16	Pilot inexperience of balked landing procedure	V, U, O	C	M	
8	17	Late decision to carry out balked landing	U	C	M	
8	18	Loss of lift (reduced climb) due to aerodynamic problems	U	M	H	
8	19	Engine Failure(s)	V, U	L	H	Post take-off, when airborne
8	20	Failure of flight controls	V, U	L	C	
8	21	Failure of lighting on obstacles	C	L	M	Will also be outside of safety margins
8	22	Fog or Snow & darkness	V, U	C	M	In general not a problem unless combined with loss of primary systems
8	23	Bird strike	V, U	H	M	Consequences as engine failure
8	24	Heavy rain leading to flame out	V, U	L	H	Could lead to a flame out. Significant differences between aircraft
8	25	Combinations of weather conditions	V, U	C	H	Potential initiating event for balked landing
8	26	Too steep at missed approach point	U	M	M	Potential initiating event for balked landing
8	27	Offset from runway centre line	V	H	M	Potential initiating event for balked landing
8	28	Offset and incorrect heading from runway centre line	V	M	H	
8	29	High momentum/kinetic energy	V, U	C	M	Height loss and veer worse for high momentum, more stable less prone to cross winds, longer to correct
8	30	Low momentum/kinetic energy	V, U	C	M	Easier to correct but more prone to wind shear etc
8	31	Larger wingspan	V	C	M	Less safety margin from obstacles (3D).

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
8	32	Stall speed	U	C	M	Higher stall speed increased height loss. Altimeter inaccuracy not relevant for this scenario.
8	33	Type of aircraft landing or parked, taxiing, on hold may result in a loss of clearance	C, V	C	H	
8	34	Obstruction on runway	V	M	H	Potential initiating event for balked landing
9		**Landing**	S - Landing short, L - landing long, O - landing offset, V- veer off during landing roll, OR - overrun, H - hard landing, HO - hit obstacle on final approach.			
9	1	High momentum/kinetic energy	L, OR, V, H	C	M	Relative to normal approach speed and landing mass for each aircraft type
9	2	Low momentum/kinetic energy	S, V	C	M	Inverse of above
9	3	Larger wingspan	V, HO	C	M	Less safety margin from obstacles (3D).
9	4	Stall speed	S	C	M	Higher stall speed increased height loss
9	5	Incorrect flaring (leading to aircraft damage)	S, L, H	M	H	
9	6	Failure/maintenance of visual glide slope indication	S, L	L	M	Worse case is incorrect indication.
9	7	Failure of ILS	S, L	L	L	Safety impact based on loss of ILS after missed approach point.
9	8	Wind shear	S, L, H	C	H	
9	9	Optical illusion	H	H	C	Has resulted in controlled flight into terrain during visual conditions
9	10	Loss of aircraft flaps	OR	H	H	Approx 1 in 20,000 movements.
9	11	Aircraft without reverse thrust	OR	C	M	Combined with loss of friction on runway
9	12	Partial loss of brakes	V, OR	M	H	
9	13	Total loss of brakes	OR	L	C	
9	14	Failure of undercarriage on landing	V	L	C	Could be a consequence of hard landing
9	15	Failure of undercarriage to operate	V	M	H	
9	16	Accuracy of promulagated information from ATC	O, S, L, V, H	C	H	Safety impact will depend on aircraft type
9	17	Landing in darkness with runway lighting failure	O, S, L, V	L	M	
9	18	Bright sunlight with wet runway	H	H	L	See optical illusion.
9	19	Visibility impaired by snow/rain	O	C	M	
9	20	Night time confusion with other lit routes	O	M	H	Airport familiarity important. Gatwick - taxiway lights are switched so that they can not be seen by landing aircraft (after Air Malta/BIA incidents).

Task	Threat	Description/ Consequence of Issue	Consequence type	Likelihood	Impact	Comments
9	21	Too fast for landing	OR, L, H	H	M	Caused by misjudgement, unexpected tail wind, steep approach
9	22	Too slow for landing	S	M	C	Caused by misjudgement, unexpected head wind
9	23	Location of RETS leading to potential aborted landing for following aircraft	HO	L	C	Could also lead to aborted landing
9	24	Snow, ice, rain leading to reduced runway friction	V, OR	C	H	
9	25	Snow and fog leading to disorientation	O	H	M	
9	26	Icing of control surfaces	S, L, O, V, OR, H, HO	C	M	
9	27	Cross winds	O, V	C	M	
9	28	Tail winds	L, OR	C	L	Should be accounted for in performance calcs. More common when can only make ILS approach from one direction. Upto 5knts frequent - large effort to redirect traffic to opposite end of runway. Safety impact on 5 knot tailwind, see also "too high speed".
9	29	Variable wind direction and speed	S, L, O, V, OR, H, HO	C	M	
9	30	Reverse thrust leading to disorientation on snow covered runways	V	M	M	Jets use reverse thrust at high speed - therefore snow likely to be behind aircraft. More of a problem for helicopters.

Appendix A4.3 Prioritised Risk Factors and Associated Aerodrome Safety Features

Task	Threat	Description/ Consequence of Issue	Associated Safety Feature
1	**Take-Off Roll**		
1	6	Communication misunderstanding (flight crew/ATC)	Other[1]
1	7	Communication misunderstanding (within flight crew)	TODR, ASDR, TORA, TODA, Length, RESA, TCS, Other
1	8	Fog or Snow & darkness	Width, Separation, TS, ITS
1	9	Bright sunlight	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS, TCS, Other
1	12	Snow	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS, Other
1	13	Fog	Width, Separation, TS, ITS, Other
1	17	Winter contaminants	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS, TCS, Other
1	19	Too fast for abort	TODR, ASDR, TORA, TODA, Length, RESA,
1	22	Cross wind leading to deviation of take-off roll	Width, Separation, TS, ITS
1	27	Taxi movements across runways	Other
1	28	Improper use of ground signals and signage	Other
1	29	Time lag between aircraft undergoing de-icing and actual take-off	TCS
1	30	Variable wind direction and speed	Width, Separation, TS, ITS
1	31	Cross and tail winds	Width, Separation, TS, ITS, TCS
1	33	Performance characteristics of aircraft	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS, TCS
1	34	Sequencing of light aircraft movements after large aircraft (vortex shedding)	Width, Separation, TS, ITS
1	37	Loss of friction	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	**Rejected Take-Off**		
2	1	Reverse thrust relatively less effective than prop	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	9	Fog or Snow & darkness	Width, Separation, TS, ITS
2	10	Bright sunlight	Width, Separation, TS, ITS
2	13	Snow	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	16	Too fast for reject	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	17	Cross wind leading to deviation of take-off roll	Width, Separation, TS, ITS
2	19	Parked aircraft infringing runway clearance including aircraft at stand	Other
2	20	Inadequate crew competency	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	22	Surface contaminants/ reduced friction	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	23	High momentum/kinetic energy	TODR, ASDR, TORA, TODA, Width, Length, RESA, Separation, TS, ITS
2	24	Low momentum/kinetic energy	Width, Separation, TS, ITS
2	25	Larger wingspan	Width, Separation, TS, ITS

[1] “Other” means safeguard other than aerodrome physical characteristic

Task	Threat	Description/ Consequence of Issue	Associated Safety Feature
3	**Wheels-Off**		
3	11	Time lag between aircraft undergoing de-icing and actual take-off	TCS
3	12	Variable wind direction and speed	Width, Separation, TS, ITS, TCS
3	13	Cross and tail winds	Width, Separation, TS, ITS, TCS
3	15	Sequencing of light aircraft movements after large aircraft (vortex shedding)	Width, Separation, TS, ITS, TCS
4	**Take-Off Climb Out**		
4	1	Failure of de-icing equipment (engine)	HIS, TS, ITS, TCS
4	3	Loss of lift (reduced climb) due to aerodynamic problems	TCS
4	13	Bird strike	HIS, TS, ITS, TCS
4	16	Cross wind	HIS, TS, ITS, TCS
4	20	Inaccurate or lack of obstacle charts	
4	21	Wind shear	TCS
4	23	Cross and tail winds	HIS, TS, ITS, TCS
4	24	Combinations of weather conditions	HIS, TS, ITS, TCS
4	25	High momentum/kinetic energy	HIS, TS, ITS, TCS
4	26	Low momentum/kinetic energy	HIS, TS, ITS, TCS
4	27	Larger wingspan	HIS, TS, ITS, TCS
4	28	Stall speed	TCS
4	29	Sequencing of light aircraft movements after large aircraft (vortex shedding)	HIS, TS, ITS, TCS
5	**Circling**		
5	2	Lack of or inadequate circling lights	Other
5	4	Loss of visual references during circling	Other
6	**Precision Instrument Approach**		
6	8	Misunderstanding of the QNH	AS
6	10	Airspeed too high	AS
6	11	Steep glide angle leading to too high airspeed	AS
6	14	Cross winds	CS, AS
6	18	Icing of engines and wings	CS, AS
6	21	Aircraft characteristics	CS, AS
7	**Missed Approach**		
7	4	Failure or incorrect setting of altimeter	CS, AS
7	6	Airspeed too high	CS, AS
7	9	Cross winds	CS, AS
7	13	Icing of engines and wings	CS, AS
7	27	Started beyond missed approach point	CS, AS
7	31	High momentum/kinetic energy	CS, AS
7	32	Low momentum/kinetic energy	CS, AS
7	33	Larger wingspan.	CS, AS
7	34	Stall speed	CS, AS

Task	Threat	Description/ Consequence of Issue	Associated Safety Feature
8	**Balked Landing**		
8	8	Vortex shedding	IAS, BLS
8	10	High cross winds	HIS, IAS, TS, ITS, BLS
8	11	Wind shear	IAS, BLS
8	12	Variable wind direction and speed	HIS, IAS, TS, ITS, BLS
8	14	Icing of engines and wings	HIS, IAS, TS, ITS, BLS
8	16	Pilot inexperience of balked landing procedure	HIS, IAS, TS, ITS, BLS
8	17	Late decision to carry out balked landing	IAS, BLS
8	22	Fog or Snow & darkness	HIS, IAS, TS, ITS, BLS
8	25	Combinations of weather conditions	HIS, IAS, TS, ITS, BLS
8	29	High momentum/kinetic energy	HIS, IAS, TS, ITS, BLS
8	30	Low momentum/kinetic energy	HIS, IAS, TS, ITS, BLS
8	31	Larger wingspan	HIS, IAS, TS, ITS, BLS
8	32	Stall speed	IAS, BLS
8	33	Type of aircraft landing or parked, taxiing, on hold may result in a loss of clearance	HIS, IAS, TS, ITS, BLS, Other
9	**Landing**		
9	1	High momentum/kinetic energy	ASDR, LDR, ASDA, LDA, Width, Length, RESA, Separation, TS, ITS, Other
9	2	Low momentum/kinetic energy	Width, Length, RESA, Separation, IAS, TS, ITS
9	3	Larger wingspan	Width, Separation, IAS, TS, ITS, Other
9	4	Stall speed	Length, RESA, IAS
9	8	Wind shear	ASDR, LDR, ASDA, LDA, Length, RESA, IAS, Other
9	9	Optical illusion	Other
9	10	Loss of aircraft flaps	ASDR, LDR, ASDA, LDA, Length, RESA
9	11	Aircraft without reverse thrust	ASDR, LDR, ASDA, LDA, Length, RESA
9	16	Accuracy of promulagated information from ATC	ASDR, LDR, ASDA, LDA, Width, Length, RESA, Separation, IAS, TS, ITS, Other
9	19	Visibility impaired by snow/rain	Width, Separation, TS, ITS
9	22	Too slow for landing	Length, RESA, IAS
9	26	Snow, ice, rain leading to reduced runway friction	ASDR, LDR, ASDA, LDA, Width, Length, RESA, Separation, TS, ITS
9	28	Icing of control surfaces	ASDR, LDR, ASDA, LDA, Width, Length, RESA, Separation, IAS, TS, ITS, Other
9	29	Cross winds	Width, Separation, TS, ITS
9	31	Variable wind direction and speed	ASDR, LDR, ASDA, LDA, Width, Length, RESA, Separation, IAS, TS, ITS, Other

Appendix 5
Aerodrome Ground Operations Risk Assessment

Appendix 5: Aerodrome Ground Operations Risk Assessment

A5.1 INTRODUCTION

This appendix provides an account of the risk analysis undertaken into hazard scenarios associated with aerodrome operations at ground level, as distinct from those in which the aircraft is airborne and for which the obstacle limitation surfaces provide the basis for the available safety margin. In this respect, four incident types have been assessed:

- overrun incidents on take-off and landing;
- undershoot incidents on landing;
- lateral veer-off incidents on take-off and landing; and
- lateral deviation during taxiing operations.

The material presented is based on a series of working papers (working papers 2 [1], 3 [2], 5 [3], 7 [4] and 11 [5]) developed during the course of the risk analysis. The outline approach to the development of the risk model is described in Section A5.2 and a detailed assessment of each of the four incident types is given in the following sections.

A5.2 OUTLINE MODELLING APPROACH

The modelling approach adopted for the quantitative assessment of the risks associated with runway operations is based on the evaluation of:

- the likelihood of the incident occurring; and
- the consequences of such an incident.

Each of the four incident types of interest may essentially be considered in terms of the deviation of the aircraft from its intended path. The definition of the deviation for each incident type may be summarised as follows:

- For overrun incidents the “deviation” is described by the longitudinal distance travelled beyond the expected accelerate stop distance (for take-off events) and beyond the expected landing distance required (for landing events).
- For undershoot incidents the deviation is described by the longitudinal distance by which the aircraft undershoots the intended runway threshold.
- For veer-off incidents the deviation is described by the lateral distance of the aircraft from the runway centreline.
- For taxiing deviation incidents the deviation is described by the lateral distance of aircraft from the taxiway centreline.

In the risk modelling approach adopted here the deviation of the aircraft for each incident type is described by a probability density function (PDF) and hence an associated complementary cumulative probability distribution (CCPD). The PDFs are based on empirical data for landing and take-off incidents. The frequency per movement with which incidents lead to aircraft deviation beyond a certain distance is then calculated by the product of the frequency per movement of an event occurring and the CCPD.

The frequencies with which each of the different types of incident occur are based on review of incident data. Typically, the incident records have been reviewed for the period from 1978 to 2001 in the present study. It is noted that improvements in aviation accident rates have been made over this period through, *inter alia*, improvements in safety related equipment on newer aircraft. Approximate six-year rolling averages of fatal aircraft accident rates per million departures for world-wide[1] schedule operations based on ICAO graphical data are presented in [6]. Review of this data shows that the fatal accident rate has reduced by a factor of around two over the last two decades (this data is broadly in line with accidents statistics presented [7]). This suggests that accident frequency rates estimated from data over this period may overestimate the present frequency rates by less than a factor of two. It is noted that this level of overestimate is within the general bounds of uncertainty within which the assessments in the current study have been undertaken and that the accident data from the period 1978 to 2001 may be reasonably used to estimate current accident frequency rates.

A5.3 OVERRUN RISK ASSESSMENT

A5.3.1 Introduction

Within the context of the current risk analysis of aerodrome design rules, overrun risk is identified as a relevant consideration in determining design requirements for the runway end strip and runway end safety area provision.

The model is based on empirical data derived from historical overrun incidents and enables the quantitative determination of:

- the likelihood of an overrun accident occurring on either take-off or landing;
- the likely distance travelled in the event that either a take-off or landing overrun occurs.
- the extent of “excess” runway available beyond the specified accelerate stop distance or landing distance required.

In addition, dependence on other parameters characterising operations has been evaluated, *e.g.*: whether or not precision approach aids are available; and aircraft type.

Through application of the risk model, the residual risk associated with any given length of RESA can be estimated. For the current purposes, estimates have been made of the risk associated with the following:

- The residual risk for a clear area extending 150 m from the runway end, comprising the current ICAO standard of 90 m RESA plus 60 m of runway end strip (except for visual code 1 runways where the strip length is 30 m only).

[1] Data excludes data from CIS/former USSR states.

- The residual risk for a clear area extending 300 m from the runway end, comprising the current ICAO recommendation for runway codes 3 and 4 of 240 m RESA plus 60 m of runway end strip.
- The length of RESA required to provide a residual risk of 10^{-7} serious incidents[1] per movement.

Estimates have been made using "best-estimate", "lower bound" and "upper bound" values for both incident frequency and overrun distance distribution functions.

A5.3.2 Outline Modelling Approach

The proposed model for quantitative assessment of the overrun risk is based on the quantitative determination of:

- the likelihood of an overrun accident occurring on either take-off or landing;
- the likely distance travelled in the event that either a take-off or landing overrun occurs.

This basic risk model will provide a quantitative estimate of the likelihood of an overrun accident reaching a defined distance beyond the runway end. Given the potential for travel beyond the runway end safety area to result in collision with an obstacle, giving rise to a potentially catastrophic consequence, this model will provide a basis for defining the length of RESA required to achieve a given risk level, *i.e.* the frequency of occurrence of a (potentially) catastrophic consequence. The proposed approach is based on empirical data from overrun incidents.

The provisional model proposed that the overrun accident location distribution (overrun distance beyond the runway end) be described separately for take-off and landing incidents by exponential functions. The fraction, $N(x)$ of overruns reaching a given distance x is given by a function of the following form:

$$N(x) = exp(- a\, x^n)$$

The accident rates derived are based on historical incident rates for overrun which typically are in the range 0.1 to 1 per million movements, according to the type of aircraft and movement.

It is to be emphasised that these are average rates observed for operations of aircraft with a wide range of performance characteristics at a wide range of aerodromes. It appears from review of the CAA and FAA data sets that overrun incidents are far more frequent at shorter runways than at longer runways. Using the extended data set, specific consideration has therefore been given to possible modelling approaches to take account of the influence of the amount of "excess runway" for a given movement on the probability of occurrence of an

[1] By "serious incident" we mean an incident in which the aircraft travels beyond the limits of the available RESA into a region where it may encounter rough terrain or obstacles sufficient for serious injuries or fatalities to occupants to occur. It is recognised that the area beyond the specified RESA may, at some aerodromes, continue to present an obstacle free environment. The cautious assumption made here is that an obstacle free environment cannot be guaranteed beyond the specified RESA and all incidents travelling beyond the limits of the RESA are therefore assumed to be potentially serious.

overrun incident. Other factors considered include the type and operating characteristics of the aircraft.

A wide variety of external factors that may contribute to overrun risk have been identified in guidance issued by the UK CAA [8]. These include, for example:

- runway contamination and/or runway friction characteristics;
- obstructions beyond the RESA (which could turn an overrun into an accident);
- the lack of approach aids, particularly precision instrument systems;
- the non-use of public transport performance safety factors by flights when the runway length is critical and adverse weather prevails;
- problems encountered close to decision speed (V_1) on take-off;
- a malfunction of an aeroplane system;
- the type and/or operating characteristics of aeroplanes using the runway; and,
- failure to adhere to approved operating techniques, and other inappropriate action by flight crew.

Some of these factors may be more or less specific to certain airports and certain types of operations. In developing the model, it will therefore be appropriate to consider the possibility of incorporating at least some of these factors into the model, taking account also of the output of the functional hazard analysis (see Appendix 4). In particular, specific consideration has been given to the possible influence of the type and operating characteristics of the aeroplane using the runway be taken into account, having regard to the available runway length. A number of the identified factors are basic causes (e.g. aircraft malfunction, problems encountered close to decision speed and inappropriate crew action) and will inherently be factored into the incident frequency. The presence of obstructions beyond the runway, i.e. the required RESA provision will similarly be addressed directly by the model, since this is the critical design feature which it is intended to evaluate. It is assumed that public transport safety factors will apply for the operations relevant to the current study and the influence of this factor will not need to be included in the risk model.

This leaves two factors which may deserve further attention: runway contamination and friction characteristics; and the lack of approach aids. Consideration has therefore been given to the correlation between incident frequency and the lack of approach aids which can be identified as a specific characteristic of an aerodrome. As regards runway condition, this may be regarded as a causal or at least contributory factor which will inherently be included in the risk model. This and other causal/contributory factors have been reviewed but no convenient approach to accounting explicitly for runway surface conditions in the risk model has been identified.

A5.3.3 Data Availability

Initial modelling was based on two data sets:

- a list of overrun incidents in the UK between 1976 and 1996 by civilian-registered, fixed-wing aircraft over 5700 kg MTWA, compiled [8] by the UK CAA.

- data provided by a US Federal Aviation Administration (FAA) report [9] into the location of commercial aircraft accidents relative to runways.

A more recent research effort [10] has sought to develop a more comprehensive data set of overrun incidents world-wide. Although this data set is regarded as being the intellectual property of the research organisation (Loughborough University) responsible for its compilation, AEA Technology has been able to purchase the rights to use it for the purposes of the current project. Drawing on these three data sources, a combined data set has been complied that comprises a total of 224 overrun incidents that occurred between 1976 and 1998. Within this data set there are 118 landing overrun incidents and 39 take-off incidents for which overrun distances are recorded.

In addition, a number of studies that have been carried out in recent years addressing the assessment of risk from aircraft accidents in the vicinity of airports (so-called “airport-related accidents”) provide useful additional data. These include the study [11] and supporting risk modelling [12] commissioned by the Department of the Environment, Transport and the Regions (DETR) into the third party risk near airports in the context of its review of public safety zone policy. This study collates data on aircraft accident rates during take-off and landing and their locations. Although these studies were not undertaken with the assessment of overrun risks specifically in mind, they represent useful further sources of data to support this analysis.

A5.3.4 Overview of Incident Types

Summary information concerning the incidents and their identified causes is provided in the data set obtained from Loughborough University. Although this information is limited, it does nevertheless provide a basis for characterising incidents in a manner that may support risk assessment and risk management decision making. Key features of take-off and landing overrun incidents are summarised separately below. Further consideration of the relevance of these features to the risk model is given in the subsequent sections.

A5.3.4.1 Summary of Take-off Incidents

There are 32 take-off incidents in the data set for which an indication of cause is given. In 17 cases it is explicitly stated that a rejected take-off was involved and it would appear from the information given that several other incidents involved a conventional rejected take-off. A variety of initiators for the rejected take-off were identified, including engine problems (four cases), landing gear faults (five cases), bird strike (two cases), false warnings (two cases) and pitot fault (two cases). Use of the wrong runway was identified as the cause of the incident in three cases. Faulty or incorrect setting of control surfaces was identified in several instances and in one case, miscalculation of aircraft weight is identified.

In three cases, a wet runway was identified as contributing to the overrun and in two cases braking problems were identified.

Within the above types of incident, a number of more typical scenarios can be identified (e.g. the conventional rejected take-off). It will be important that any design rules developed on the basis of the proposed risk model take appropriate account of these incident types. In addition, we can identify a limited number of what might be considered more gross failures or errors (e.g. selection of the wrong runway) which may not be so readily protected against by (dimensional) aerodrome design features.

A5.3.4.2 Summary of Landing Incidents

For landing incidents, the data set includes 93 incidents for which an indication of cause is given. A wide variety of causal factors contributing to the overrun are identified, and in many cases multiple factors are identified. Factors identified include the following:

- Landing long;
- Excess speed;
- Poor approach;
- Tailwinds;
- Adverse crosswinds;
- Wet or icy runway;
- Brake system failure;
- More general aircraft systems failure;
- Landing on the wrong runway;
- Visibility.

Wet or icy runways are identified in 38 incidents but in only nine of these cases is this the only causal factor identified. Landing long, a poor approach and excess speed (or combination of these factors) are identified as relevant factors in 46 cases. Aircraft faults are identified in 21 incidents, including 16 cases of brake system faults, one case of landing gear faults and four cases of more general aircraft system failure (fuel starvation, power plant failure, electrical system failure). Selection of the wrong runway was identified in six cases. As for the take-off incidents, a number of more typical scenarios can be identified that any design rules developed on the basis of the proposed risk model should address. Again, we can identify a limited number of what might be considered more gross failures or errors (*e.g.* selection of the wrong runway) which may not be so readily protected against by (dimensional) aerodrome design features.

A5.3.4.3 Conclusions

A variety of landing and take-off overrun incident types and factors contributing to them can be identified. Although it has been suggested [13] in the CAA draft working paper that risk assessment of specific aerodromes might take account of certain causal factors, on the basis of available data we do not consider that such factors can reliably be taken into account in the estimation of overrun rate. In the case of adverse weather or contaminated runway conditions, for example, whereas we have some information on the number of incidents for which these factors are identified as contributory, there is no comprehensive information concerning the proportion of incidents subject to these risk factors. Accordingly, there is no basis for estimating relative risks associated with these factors. In addition, we note that, for landing incidents in particular, multiple factors are identified and the relative importance of these different factors cannot be separated.

However, we note that different overrun incident types may exhibit different characteristic consequences, i.e. the overrun distance travelled may be greater for certain incident types. As indicated above, it may be appropriate to focus risk-based design rules on certain incident types for which design can provide effective mitigation, and accept that the risk for other gross errors or failures cannot be readily addressed by aerodrome design. Further specific consideration of the risk characteristics of the different overrun incident types and their significance to aerodrome design is therefore given below in Section A5.3.6.

A5.3.5 Overrun Incident Rate

This section considers first the average rate of occurrence of overrun incidents for a number of generic classes of aircraft types to be employed in the overrun risk model, which is based on historical incident statistics. It then evaluates the extent to which this average value varies according to operating conditions, in particular with the presence or absence of precision approach aids and with the available runway length compared with requirements determined by aircraft performance characteristics (e.g. landing distance required, take-off distance required, accelerate stop distance required).

A5.3.5.1 Average Overrun Incident Rate

Average overrun incident rates were derived based on both UK and wider international incident statistics. More precise statistics are available for both movements and incidents in the UK but the data set is comparatively small and the rates are therefore likely to be subject to potentially significant statistical uncertainty. On the other hand, although a considerable amount of relevant data is available from international experience, fully comprehensive movement and incident statistics have not been compiled and there is therefore some uncertainty in the data. Taken together, the UK and international data provide consistent estimates of incident rates.

UK Overrun Incident Rate Data

Based on the total number of overrun incidents in the UK in the period 1975-1996 and the total number of movements, involving commercial transport movements for aircraft greater than 5.7 tonne MTWA, an overrun incident rate of 1.02×10^{-6} overrun incidents per movement has been calculated and presented by the CAA in its draft working paper [13] on overrun risk.

It is evident from the available data sets that overrun incidents are more frequent on landing than on take-off, although the CAA draft working paper did not consider this issue. The relative rates over the 22 year period 1975-1996 are 20 landing overruns to 6 take-off overruns[1]. On this basis we can derive the following overrun rates for landing and take-off respectively:

[1] The subsequent CAA paper on overrun risk [8] identified 21 landing overrun incidents and 5 take-off incidents in the period 1976-1996. The take-off overrun data set excludes the Dunsfold incident in 1975 in which an aircraft suffered bird strike immediately after take-off and attempted to land back on the runway, finally coming

- 1.57 x 10^{-6} overruns per landing movement;
- 0.47 x 10^{-6} overruns per take-off movement.

The CAA working paper provides a breakdown of overrun rate according to aircraft type, as follows:

- corporate jets: 18.8 x 10^{-6} overrun incidents per movement;
- turboprops: 0.95 x 10^{-6} overrun incidents per movement;
- narrow-bodied jets: 0.61 x 10^{-6} overrun incidents per movement;
- wide-bodied jets: 0.56 x 10^{-6} overrun incidents per movement.

International Overrun Incident Rate Data

In addition to considering the available UK overrun incident statistics, readily available compilations of accident and movement statistics have been reviewed, in particular drawing on generic “First World” movement statistics. This is intended to assess the extent to which the UK statistics may be representative of broader experience in international aviation.

The DETR report [11] provides a summary of aircraft accident rates according to aircraft type. These give the accident rates per million movements, derived from aircraft accident (total losses) and movement statistics in the period 1979 to 1995. These rates are averages for “First World” operations and are summarised in Table A5-1. To derive the total loss overrun rates for take-off and landing, reference has been made to the proportion of these incidents making up the total data set. The DETR report records that 8% of these “total loss” accidents in the data set are take-off overruns and 20% are landing overruns. Multiplying the overall accident rates by these factors provides the take-off and landing overrun accident rates for total losses, as summarised in the Table A5-2.

Given that the accident data is based on total losses only and does not take account of overrun incidents which do not lead to such severe consequences, the total loss rates presented in Table A5-1 will be lower than the total overrun accident rates. For the purposes of comparison with the above UK overrun incident rates, it is necessary to take account of the proportion of overrun accidents not giving rise to major losses. Broadly speaking, review of accident reports indicates that the likelihood of major loss in an overrun incident is dependent on the presence of obstacles in the path of the overrunning aircraft. In the majority of cases, such collisions are avoided. An adjustment to the incident rate to take account of this factor is therefore required and the required adjustment factor can be estimated by reference to the UK CAA data set. This estimate is based on the following observations and analysis:

- The ratio of 2.5:1 for landing to take-off overruns in the DETR data set compares with a ratio of 4:1 in the CAA’s data set for UK overrun incidents. The difference may not be statistically significant, bearing in mind the small UK data set. However, it may be worth noting that such a difference would be consistent with a higher proportion of take-off overruns ending in total hull losses than that for landing overruns. Given that take-off

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to rest 435 m from the runway end. In many respects, this incident might best not be regarded as an overrun. A ratio of 21 to 5 landing to take-off overruns might therefore have been assumed and would give rates of 1.65 and 0.39 overruns per million landing and take-off movements, respectively, but this does not significantly influence the overall conclusions.

overruns are typically associated with travel for longer distances from the runway end, this observation would not be unexpected.

- Review of accidents in the DETR study data set [11] and the recent UK overrun accidents reveals that, of the 21 UK landing overrun accidents identified by the CAA occurring in the period 1976 to 1996, five are classified as being “serious”. Of the 14 landing overruns occurring during the period 1979 to 1995, four resulted in major losses and are included in the DETR study data set. Similarly, review reveals that, of the five UK take-off overrun accidents identified by the CAA occurring in the period 1976 to 1996, one is classified as being “serious”. Of the four take-off overruns occurring during the period 1979 to 1995, one resulted in a major loss and is included in the DETR study data set. While bearing in mind the limited data set and the potential for statistical error, the data suggests that the landing overrun incident rate is of the order of 3.5 to 4.2 times higher than the total loss rate from landing overruns. Similarly, the data suggests that the take-off overrun incident rate is of the order of 4 to 5 times higher than the total loss rate from take-off overruns. (This ratio of overrun incident to total loss rate for the take-off overrun, compared with landing overrun, might appear to be inconsistent with the first bullet point where it is stated that consequences are considered more likely to be serious for the take-off and landing overrun. However, it should be noted that we are dealing with a small data set that is likely to be subject to some statistical uncertainty. The purpose of the current analysis is to provide a more accurate estimate of incident rates by reference to a larger data set.)

Take-off and landing overrun incident rates, taking account of this factor, are summarised in Table A5-3. With the exception of the estimates for “executive jets”, these rates are broadly consistent with those identified earlier from UK incident statistics.

Further analysis has been undertaken making reference to overrun data set. Relevant statistics derived from the enlarged data set are set out in Table A5-4 and Table A5-5.

Based on the data presented in Table A5-4, the following observations can be made concerning the relative rates of landing and take-off overrun incidents:

- The relative rates of landing and take-off overruns are essentially identical for jet and turboprop aircraft.
- The observed relative rate of 3.05:1 for landing/take-off overruns is consistent with the values of 4:1 and 2.5:1 obtained using the CAA and DETR data sets.
- Given that the relative rate of 4:1 is based on a comparatively small data set and that the relative rate of 2.5:1 is based on “total loss” incidents only, it seems likely that the observed rate of 3.05:1 will represent a more realistic estimate than these two earlier estimates.

From review of the data presented in Table A5-5, the following observations can be made concerning the relative rates of overrun incidents involving jet and turboprop aircraft:

- The relative rates of incidents involving jet and turboprop aircraft are found to be essentially the same for landing and take-off movements.
- The observed relative rate (jets 72% and turboprops 28%) is consistent with the relative proportions of these generic aircraft types in the world-wide fleet (jets 73% and

turboprops 27%) and with the relative rates of movements of these generic aircraft types, as recorded in the DETR study (jets 69% and turboprops 31%).

- For the purposes of the current risk modelling exercise these data indicate that it should be possible to adopt the same basic incident rate parameters for turboprop and jet aircraft.

Overrun incidents broken down by consequence level are presented in Table A5-6. The data on the extent of damage sustained in the event of an overrun was evaluated with the aim of determining the proportion of take-off and landing overruns that result in total losses. It is, however, subject to some uncertainty since the consequences are unknown for a significant number of incidents and it is unclear what proportion of incidents where the damage is reported as “substantial” represent “total losses”. It is likely that, for a significant proportion of incidents where the consequences are “unknown”, the consequences were relatively minor and not reported. Assuming this to be the case the above data suggest that the take-off overrun rate for all incidents would be between 2 to 5 times higher than the take-off overrun total loss rate, according to the proportion of incidents for which “substantial” damage was reported that resulted in total losses. Similarly, the data suggest that the landing overrun rate for all incidents would be between 2.1 and 9.3 times higher than the landing overrun total loss rate. Using these factors and recognising the uncertainty in the data upon which they are based, lower and upper estimates for the total take-off and landing overrun rates have been derived and these are presented in Table A5-7.

Discussion and Recommendations

The various approaches to overrun incident rate estimation have produced generally consistent results though there is clearly some variation in the precise values obtained. We require now to identify the most appropriate values for use in the subsequent risk modelling.

The enlarged overrun incident data set provides the most extensive set of data but, on its own, can provide only relative incident rates. Given the size of the data set, it is likely to provide the most reliable estimates for relative rates and it is therefore proposed that these are selected as best estimate values. On this basis, it is recommended first that jet and turboprop aircraft are assumed to have essentially identical overrun incident rates. We believe the available data adequately supports the adoption of this assumption but note also that it will simplify the subsequent development of design rules. In making this recommendation, we note that the rates derived from the CAA data set for these two generic classes of aircraft type are quite similar and that the approach to estimating overrun rates from total loss accident data in DETR study is subject to some uncertainty. Second, it is recommended that the relative rates for take-off to landing overrun incidents be assumed to be 1:3.05.

As regards the absolute rates, the estimate derived from the UK data set is towards the upper end of the range of values obtained. We note that a significant proportion of incidents in that data set involved corporate jets (8 out of 26 or 31%), although these represent a much lower proportion of total movements, and corporate jets exhibit a significantly higher incident rate per movement than other generic aircraft classes. (This very much higher incident rate for corporate jets compared with passenger movements is understood to result from the use of lower safety factors in the higher risk operations. If this higher risk is of specific concern to the NCAA it might be more effectively addressed by changes to operating practices rather than the development of aerodrome design rules requiring potentially excessive provision of runway end safety areas.) By removal of this corporate jet incident data from the CAA data set employed for estimation of incident rates, we derive revised estimates of approximately 0.3 and 1 overrun incident per million movements, for take-off and landing respectively, which we suggest are more realistic values for use in respect of public transport movements. The estimates derived from the DETR study suggest a slightly lower risk. However, taking account of the uncertainty in the data supporting these estimates, it is hard to justify the adoption of values below 0.15 and 0.5 per million movements, for take-off and landing respectively.

On this basis, we propose the use of the following overrun rates:

- Best estimate average landing overrun rate: 1 per million movement;
- Best estimate average take-off overrun rate: 0.33 per million movements;
- Lower bound average landing overrun rate: 0.5 per million movement;
- Lower bound average take-off overrun rate: 0.167 per million movement

A5.3.5.2 Dependence on Precision Approach Aids

Clearly, the presence or absence of precision approach aids for landing is a potentially important factor which may influence the likelihood of occurrence of an overrun incident on landing. A previous study [14] analysed the correlation between the incidence of accidents on landing and a number of “airport-related risk factors” including the presence or absence of precision approach landing aids. This study found that accidents were significantly more likely at aerodromes which lack such aids. In general, the risk of an accident was found to be of the order of five times higher at aerodromes without precision landing aids. The accident data set evaluated in that study included a variety of other accident types of which 10.6% were overrun incidents.

Whereas the possibility of direct dependence between overrun incident likelihood and the presence of precision approach aids can be identified, for many of these accident types no simple basis for such a dependency can be identified. The enlarged data set has been evaluated to determine the extent to which a correlation can be observed specifically for overrun incidents.

Of 168 landing overrun incidents in the enlarged data set, 57 are identified as involving a precision approach (55 ILS and two precision approach radar (PAR)). Of the remainder, 48 are identified as involving a visual/non-precision approach but for 12 of these, some glide slope indication instrumentation was available (visual approach slope indicator (VASI) or precision approach slope indicator (PAPI)). For the remaining 63, the nature of the approach is not specified. Review of the data indicates that the incidents where the approach is not specified took place at a wide range of aerodromes, many of which have precision approach aids available. There is no indication that the lack of reporting is associated with operation at smaller aerodromes lacking precision approach aids and these data have therefore been discarded from further analysis.

The previous study [14] indicated a ratio of nine precision approach movements to one non-precision or visual approach movement in North America between 1984 and 1993. This movement data set is generally representative of the overrun incident data set, which contains predominantly incidents in the USA and Canada between 1976 and 1998. Taking account of the above relative proportion of movements and overrun incidents for precision and non-precision/visual approaches, the following relative incident rates have been estimated:

Precision approach relative overrun rate = 0.60

Non-precision/visual approach relative overrun rate = 4.68

Clearly, the data indicate that overrun incidents are very much more likely for non-precision/visual approaches than for precision approaches. The relative rate for overruns is slightly more than a factor of 7.8, compared with a factor of 5 for all incident types indicated by the previous study. This is perhaps not surprising, given the non-relevant incident types included in the previous analysis. It is concluded that it will be appropriate to include this factor in the risk model. However, it should be stressed that the correlation does not necessarily indicate a direct dependence between the presence or absence of precision approach aids and the overrun rate. There may be another factor associated with non-precision/visual approach operations that is responsible for the correlation, for example the standard of the operators involved or the typical amount of excess runway available for operations at smaller aerodromes where the majority of non-precision/visual approaches occur. Some caution must therefore be exercised in interpreting the data.

Based on the observed correlation and the average landing overrun rates, as presented in the previous section, the estimates for overrun rates for precision and non-precision/visual approach movements are as follows:

- Best estimate precision approach landing overrun rate: 0.6 per million movement;
- Best estimate non-precision/visual approach landing overrun rate: 4.68 per million movements;
- Lower bound precision approach landing overrun rate: 0.3 per million movement;
- Lower bound non-precision/visual approach landing overrun rate: 2.34 per million movement.

When applying these relative rates to the Norwegian case, it is noted that all code 1 and 2 runways in Norway are non-precision. However, most of the code 3 and 4 runways are equipped with ILS.

A5.3.5.3 Relative Rates According to Available Excess Runway

Introduction

It is evident from review of the data that overrun incidents are far more frequent at shorter runways than at longer runways. Movement statistics for UK airports were reviewed to determine the proportion of movements taking place on runways of different lengths. Data for 1997 is provided on the CAA web-site [15] and this showed that over 50% of UK air transport movements took place at the airports with the four longest runways, Heathrow (3658/3902 m), Gatwick (3159 m), Manchester (3048 m) and Stansted (3048 m). One out of the twenty-six overruns recorded in the CAA guidance document [8] in the twenty year period

1976-1996 was found to have occurred at one of these runways. Several overrun incidents were found to have taken place at runways of the order of 2300 m in length, these being at Leeds/Bradford (2250 m), East Midlands (2280 m), Liverpool (2286 m) and Newcastle (2332 m). None are reported for the larger Scottish Airports with runways in excess of 2500m. These include Glasgow (2658 m) and Edinburgh (2560m) which represent the 5th and 7th busiest UK airports in terms of commercial (fixed-wing) air transport movements, and Prestwick (2987 m).

Review of the types of aircraft using these airports with longer runway indicates that the majority of movements will not be runway length critical. The observation of a much lower overrun incident rate at these airports appears to correlate with this increase in the safety factor provided by the longer runway.

On this basis, it appears that, for the typical movements in the UK, runway length may become a significant factor in determining the likelihood of overrun accidents when the runway length is below 2500 m. On the basis of 1990 movement statistics [16], derived from CAA published data, movements on runways less than 2500 m in length represent 33% of the total. This analysis indicates that overrun rates are 2.5 to 3 times higher for movements at shorter runways, less than 2500 m in length. This relatively simple approach has previously provided a mechanism for factoring this increased rate of incidents into risk estimates during risk management studies of aerodromes with shorter runways.

Available runway length compared with runway length required would therefore appear to be a key factor in determining the overrun incident rate and should ideally be included more systematically into the overrun risk model. In their 1997 draft working paper [13] on overrun risk, the CAA proposed an approach to the estimation of the relative rate of overrun incident occurrence, according to the “excess runway” available (*i.e.* the length of available runway in addition to the runway length required.) Their analysis indicated a relative overrun rate of 10 (*i.e.* 1.02×10^{-5} per movement) where the “excess runway” length is zero. The mean excess runway length for the UK data set is 650 m (*i.e.* the relative rate where the “excess runway length is 650 m is 1). The proposed relationship between “excess runway” and relative overrun rate is logarithmic and so, for an “excess runway” length of 2000 m, the relative rate is 0.01.

In principle, the approach outlined in the CAA working paper provides a method for calculating overrun rates for specific movement types at runways of a given length. However, as currently implemented, it appears to have some potential deficiencies, as follows:

- it is based on a limited data set, in particular as far as take-off overruns are concerned;
- it does not differentiate between take-off and landing overruns, for which the relationship between “excess runway” and incident rate may be quite different.

While recognising these limitations, it is concluded that this approach could nevertheless offer a practical means of deriving reasonable estimates of overrun incident frequency. This issue is of particular importance for the Norwegian case where a relatively high proportion of movements occur with limited excess runway available. Accordingly, specific consideration has been given to the possibility of factoring runway length requirement characteristics into the risk model, making use of the enlarged data set. Analysis of this data has sought to determine whether there is any significant correlation between the number of recorded incidents and the amount of excess runway available.

Take-off Incidents Data Analysis

In the case of take-off incidents, the key required distance in relation to overrun incidents is expected to be the accelerate stop distance required (ASDR). Initial analysis has therefore sought to establish whether there is any correlation between incident probability and the length of excess runway, where excess runway is defined as the accelerate stop distance available (ASDA) less that required:

$$\text{excess runway, } x_s = \text{ASDA} - \text{ASDR}.$$

In the first instance, the analysis has involved plotting a complementary cumulative probability distribution (CCPD) for incidents with a given excess runway length available: *i.e.* the fraction of incidents for which there is a given excess runway length or more as function of that given distance (see Figure A5-1). In addition, the excess runway function normalised with respect to the ASDR has been considered, as follows:

$$\text{normalised excess runway, } x_{sn} = (\text{ASDA} - \text{ASDR})/\text{ASDR}.$$

The plot of the fraction of overrun events with a normalised excess runway greater than a specified value is presented in Figure A5-2.

These excess runway and normalised excess runway plots show that the number of incidents decreases progressively with increasing excess runway until the excess runway distance is of the order of 750 m, or the normalised excess runway is of the order of 0.5. There are very few incidents with excess runway available greater than these amounts. Logarithmic plots of the data give a good linear correlation. We will return to consider how this apparent correlation might be factored in to the risk model following some further data analysis.

A second possible functional correlation that has been investigated is that between the probability of an event and the total distance travelled in excess of the required distance (i.e. the ASDA plus the distance travelled beyond runway end less the ASDR). This appears to be the approach taken in the CAA draft working paper but the description in that document of the analysis performed is not clear. A plot of the fraction of take-off events that overrun (beyond the ASDR) in excess of a specified distance (*i.e.* the CCPD) is shown in Figure A5-3. It can also be seen from this figure that the CCPD can be reasonably well modelled by a probability function of the form $\exp(-a\,x)$ (the form of this function is further discussed in Section A5.3.6).

Plots of the fraction of incidents travelling a given excess distance beyond the identified ASDR or the excess distance normalised with respect to the ASDR again fit an exponential function with a significant statistical correlation.

We now consider the derivation of relative overrun rates from these plots. The first set of plots represents the relative frequencies with which overrun incidents are observed, according to the available excess runway. However, we are interested in the relative probability of occurrence of an incident for a movement according to the given available excess runway.

Although related to the observed relative frequency, this is a distinct parameter. The observed relative rate will be dependent not only on the relative probability but also the relative number of movements for which there is a given excess runway available. If there are more movements with one rather than another excess runway available, we would expect proportionately more incidents:

observed relative rate = relative probability per movement x relative movement frequency.

At present, we do not have specific information on the relative frequency of movements that take place at runways with different amounts of excess runway available. For simplicity, if we assume that there is an equal probability of movements with any given excess runway available between 0m and 1200m (this is the maximum excess distance for which any overrun events were identified), the relative probability per movement can be readily derived from observed relative rate. We derive the following:

relative overrun rate = 2.28 exp (-0.0019 x_s)

where x_s is the excess runway distance in metres. This would indicate a rate of 2.28 times the observed average where there is an excess runway distance of 0 metres and that the average rate would be observed where there is an excess runway distance of 434 metres. A factor of ten change in rate is indicated for a change of 1215 m in the available excess runway. For the normalised data we derive the following:

relative rate = 2.62 exp (-3.05 x_{sn})

where x_{sn} is the normalised excess runway distance. This would indicate a relative rate of 2.62 times the observed average where there is an excess runway distance of 0 metres and that the average rate would be observed where there is a normalised excess runway distance of 0.316. A factor of ten change in rate is indicated for a change of 0.754 in the available normalised excess runway.

In practice, one might expect that the number of movements with a given excess runway available will increase progressively with increasing excess runway, reach a peak and then decline progressively. In that case, the relative probability of incidents with lower excess runway distances available would be under estimated by the above analysis. Even assuming a uniform probability distribution of events for excess distances, the above methods for estimating the relative rates scales linearly with the maximum excess distance for which it is assumed overruns exist. Hence considerable uncertainty in the above relative rates is likely.

Alternatively, the relative rates may be assessed through consideration of the frequency of incidents travelling a given total excess distance beyond the ASDR. Assessment of this frequency has been based on reported incidents. However, in addition to these incidents, we can expect that there will be a set of events in which the ASDR was exceeded but, because the available excess runway was greater than the total excess distance travelled, no overrun incident was recorded. The data set for observed incidents cannot therefore be taken to be representative of the probability of incidents in which the aircraft travels a given total excess distance beyond the ASDR. We would expect that the number of unreported events where the ASDR is exceeded should decrease with an increasing amount of excess runway available. (The more the ASDR is exceeded the more likely it is that the available runway length will be exceeded and the event become a true overrun.) This would suggest that an analysis based on this data set would indicate a lower relative proportion of incidents for movements with a comparatively small excess runway distance than the actual relative probability: *i.e.* it will under estimate the relative probability for movements with lower excess runway distances available.

The *actual* frequency with which a overrun of x metres (beyond the ASDR) occurs, $F(x)$, is given by:

$$F(x)\,D(x) = f\,N(x)$$

where f is the observed frequency with which overrun events occur (see Section A5.3.5.2);

$N(x)$ is the observed fraction of overrun events that travel a distance x;

$D(x)$ is the probability that the excess distance x_s is less than x (*i.e.* the probability that a movement takes place with an excess distance x_s less than x).

It may be noted that $N(x)$ is essentially the differential of the CCPD of the overrun distance shown in Figure A5-3. Assuming that the CCPD is described by a function of the form exp(-$a\,x$) (see Section A5.3.6 for a further discussion), then $N(x)$ has the form a exp(-$a\,x$).

Exact information on the probability of movements occurring with a particular excess runway distance is not known. However, as noted earlier, the available data suggest that the probability, P, is broadly uniform between minimum excess distance (x_{smin}) and maximum excess distance (x_{smax}). In this case, $D(x)$ is given by:

$$D(x) = \begin{cases} \text{Invalid} & x \le x_{s\,\min} \\ p \cdot (x - x_{s\,\min}) & x_{s\,\min} < x < x_{s\,\max} \\ 1 & x \ge x_{s\,\max} \end{cases}$$

Again assuming that there is an equal probability of movements with any given excess runway available between 0m and 1200m, *i.e.* $P = 8.3 \times 10^{-4}$, the frequency with which a overrun of x metres (beyond the ASDR) occurs, $F(x)$ can be calculated. Similarly, by integrating $F(x)$, we can derive the frequency with which an overrun of greater than x metres occurs. This enables us to assess the frequency with which an overrun occurs for an excess runway length of x metres. This function is plotted in FigureA5-4 normalised by the occurrence frequency f.

It can be seen from FigureA5-4 that the relative risk of an overrun derived from this latter methodology increases sharply where the excess runway is reduced below around 150m and that the relative risks may be around an order of magnitude above the average risk when the excess runway is close to zero.

In summary, the two approaches to data analysis provide generally consistent estimates of the dependence of the relative probability of overrun on the available excess runway distance, though the latter methods suggests that the risks may rise more sharply in the region where the excess runway reduces below around 150m. We conclude that movements with no excess runway available will have a probability of overrun of at least 3 times the observed average rate, and possibly up to around 10 times higher. Furthermore, we conclude that the average probability will be observed where the excess runway available is of the order of 500 to 600 metres.

Landing Incidents Data Analysis

The landing overrun data has been analysed in a similar manner to the take-off events above, except that:

- the overrun distance has been expressed in terms of the overrun distance beyond the Landing Distance Required (LDR); and
- the excess runway distance is expressed in terms of the Landing Distance Available (LDA) minus the LDR.

The CCPD for the overrun distance for landing events is shown in Figure A5-5. It can be seen that the landing overrun data can be reasonably fitted to a function of the form $\exp(-a\,x)$ (see Section A5.3.6 for further discussion).

As with the take-off events, it is liable that a certain fraction of landing overrun events will not be reported as incidents will occur where the aircraft overruns beyond the LDR, but where there is sufficient excess runway to contain the aircraft within the runway. In order to assess the actual landing overrun frequency (defining overruns events as those events where the aircraft runs beyond the LDR rather than LDA), information regarding the distribution of landing operations as a function of excess runway is necessary. Such data is not available for the operations over which the accident data has been collected. However, data has been supplied regarding the number of movements of different aircraft type at each of the Norwegian aerodromes. By making assumptions regarding the LDR for the different aircraft and taking the LDA at each aerodrome from the Norwegian Aerodrome Information Publication (AIP), the distribution of landing operations with given excess runway distances can be estimated. Review of this data suggests that the distribution is uniform between excess distances of 0m and 2500m (the probability of operations with excess distances greater than 2500m is zero).

The *actual* frequency with which a landing overrun of x metres (beyond the LDR) occurs, $F(x)$, can then be derived in a similar manner to that described above for take-off overrun events. Similarly, by integrating $F(x)$, we can derive the frequency with which a landing overrun of greater than x metres occurs. This enables us to assess the frequency with which a landing overrun occurs for an excess runway length of x metres. This function is plotted in Figure A5-6 normalised by the occurrence frequency.

It can be seen from Figure A5-6 that the relative risk of a landing overrun derived from this methodology increases sharply where the excess runway is reduced below around 100m and that the relative risks may be over an order of magnitude above the average risk when the excess runway is close to zero.

Summary

In summary, the available data indicates a dependence of overrun rates on a number of key operational parameters:

- whether the movements is a take-off or landing;
- whether or not precision approach aids are available;
- the extent of “excess” runway available beyond the specified accelerate stop distance or landing distance required.

On the basis of the above analysis, quantitative estimates of the rates and their dependencies on these relevant operating characteristics can be made for use in subsequent risk modelling studies.

A5.3.6 Overrun Accident Location Distribution

A5.3.6.1 Introduction

In the context of the current analysis, the distance travelled beyond the runway end only is being assessed. It is recognised that, in some instances at least, the extent of deviation laterally from the runway centre-line may be a relevant factor in determining the risk and this is addressed elsewhere in this working paper.

Initially, an overrun accident location distribution was derived, based on overrun location data sets provided by the CAA guidance document [8] and the FAA report on commercial aircraft accident locations relative to runways [9]. No significant correlation between overrun distance and runway length or between overrun distance and aircraft weight could be identified from that data. Take-off and landing overruns were analysed separately and a clear distinction between the distribution of take-off and landing overruns was evident, with take-off overruns travelling further on average. Based on these data sets, exponential functions were derived for the overrun distance distribution (distance travelled beyond the runway end), excluding data for wide-body jets and incidents at particularly short runways have been employed. (This data set was judged to be reasonably representative of more typical conditions.) The fraction, $N_t(x)$ of take-off overruns reaching a given distance x is given by:

$$N_t(x) = exp(-0.0065x)$$

The fraction, $N_l(x)$ of landing overruns reaching a given distance x is given by:

$$N_l(x) = exp(-0.0037x^{1.22})$$

For a given runway at which 50% of movements are take-offs and 50% are landings, the overall distribution of overruns, taking account of both take-off and landing incidents, will be determined by the sum of the above exponential functions, factored by the relative rates of take-off and landing overrun incidents, according to:

$$N(x) = (v_t exp(-0.0065x) + v_l exp(0.0037x^{1.22}))/(v_t + v_l)$$

where *N(x)* is the fraction of total overruns reaching the given distance *x*, and v_t and v_l are the rates of take-off and landing incidents respectively.

Using an enlarged data, further analysis of the overrun distance distribution function was carried out. The possible dependence of the distribution function on various incident characteristics was further evaluated and revised exponential functions have been developed.

A5.3.6.2 Analysis of Correlation with Operational Characteristics

It has been established by the previous studies that take-off and landing incidents exhibit distinct overrun distance characteristics and it has therefore been concluded that these incident types should be assessed separately. Attempts have also been made to determine the extent to which the overrun distance travelled may be dependent upon other parameters characterising an incident. Earlier preliminary studies based on the limited CAA and FAA data sets investigated the potential dependence upon aircraft size and upon runway length but failed to identify any significant correlation. Further assessment has been carried out employing the enlarged data set. Take-off and landing incidents have been evaluated separately.

In the first instance the relationship between the overrun distance and excess runway available (available runway less the distance required for the operation in question) has been evaluated. In principle, we might anticipate a greater overrun distance the less excess runway that is available. In practice, no significant correlation is observed for either take-off or landing incidents.

Second, the relationship between overrun distance and the size of aircraft (characterised in terms of the maximum take-off or landing weight) has been evaluated and again, no significant correlation is observed for either take-off or landing incidents.

It has therefore been concluded that these parameters cannot be factored simply into the overrun risk model. Some further evaluation of the dependence of the overrun distance distribution function on aircraft type has been undertaken in the context of the analysis described in the following section but again no significant correlation that might be included in the overrun risk model has been found. This analysis is described further in the following section.

A5.3.6.3 Analysis of Take-off Overrun Distance Distribution

Analysis of All Take-off Incident Types

The overrun distance distribution for the enlarged data set has been evaluated, as before, by plotting the fraction of incidents for which a given distance or more is reached against that distance. The line of best fit, assuming a simple exponential function, has a correlation coefficient of 0.9734 and is given by:

$$N_t(x) = exp\ (-0.0058\ x)$$

Sub-sets of the data have been evaluated to determine whether correlation with any specific parameters might be identified. In the first instance, the sub-set of data for aircraft below a selected maximum take-off weight of 50,000 lbs has been compared with the corresponding sub-set for aircraft above that weight. The line of best fit for the sub-set of data with higher weight corresponds well with that for the complete data set ($N_t(x) = exp(-0.006\ x)$). However, that for the sub-set of data with weight below 50,000 lbs appears to indicate a somewhat slower decrease in the fraction of incidents reaching a given distance with that overrun distance ($N_t(x) = exp(-0.0039\ x)$).

Second, sub-sets of data representing incidents with lower and higher amounts of excess runway available were analysed (those above and below a normalised excess runway of 0.2, a division which split the data set into two roughly equal parts). The sub-set of data with the lower amount of excess runway available exhibits a good exponential fit, with a relatively rapid decrease in the distance travelled ($N_t(x)) = exp(-0.008\ x)$). The sub-set of data with the higher amount of excess runway available did not exhibit a good exponential fit.

The potential difference between turboprop and jet incidents was not investigated since the sub-set of data for turboprop take-off overrun incidents is relatively small.

Analysis of Dependence on Take-off Incident Type

As discussed earlier in Section A5.3.5, many of the identified incident types fall into a fairly coherent group of rejected take-off events. Others may be identified as being gross failures or errors which may not be so readily protected against by aerodrome design rules. In this respect we identify in particular the incidents in which the wrong runway was selected. Of the three incidents where the wrong runway was selected, the overrun distance travelled is available for two cases. The distances travelled in these two cases were relatively long: 1200 m and 437 m. It is appropriate to consider the form of the distribution function with these points eliminated. The incident where a problem was encountered after the aircraft had become airborne might similarly be eliminated as not relevant to the primary incident type for which the RESA is intended to provide risk mitigation. We note again that a fairly long overrun distance of 355 m was encountered in this case.

An analysis has been undertaken using selected data including only those incidents for which an essentially conventional rejected take-off was specifically identified to have been involved. In this case the exponential best-fit curve obtained for the location distribution was found to be $N_t(x) = exp(-0.0047\ x)$. This curve falls off less rapidly with distance than that obtained above using the data set for all accident types (with the outlying point at 1200 m removed). Thus, although inspection of data suggests that the incidents with larger overrun distances are associated with more gross errors or failure, analysis of the data for more typical accident types has not demonstrated a more rapid fall off in the fraction travelling a given overrun distance for these incident types. The difference between the two distribution functions is relatively small and, given the limited size of the data set, no firm conclusions can be drawn from it.

On the basis of this analysis of sub-sets of data, we conclude that the incident types of primary relevance to the current study are adequately described by the take-off overrun distance distribution function identified earlier from the analysis of the complete data set.

A5.3.6.4 Analysis of Landing Overrun Distance Distribution

Analysis of All Landing Incident Types

The landing data set was analysed in a similar manner to that for the take-off incidents described in the preceding section. In addition jet and turboprop aircraft data were analysed separately. The line of best fit, assuming a simple exponential function, has a correlation coefficient of 0.9861 and is given by (see Figure A5-5):

$N_l (x) = exp (-0.0081 x)$

Sub-sets of data for different aircraft landing weights (above 100,000 lbs and below 50,000 lbs) and jet and turboprop aircraft gave very similar results (exponential coefficient between -0.0075 and -0.0084).

As for take-off incidents, sub-sets of data representing incidents with lower and higher amounts of excess runway available were analysed (those above and below a normalised excess runway of 0.5, a division which split the data set into two roughly equal parts). Both sub-sets of data exhibit a good exponential fit. That with the lower amount of excess runway available provides a relatively rapid decrease in the distance travelled ($N_l (x) = exp(-0.0101 x)$ compared with $N_l (x) = exp(-0.0081 x)$ and $N_l (x)) = exp(-0.068 x)$ for the complete and higher excess runway data sets respectively).

Overall, it is not possible to identify any specific relationship between these factors and the overrun distance travelled that might be factored into the overrun risk model. However, the variation observed between the different sub-sets of data give an indication of the level of variation that might be encountered and which may need to be taken into account in sensitivity studies.

Analysis of Dependence on Landing Incident Type

The review of incidents summarised in Section A5.3.4, identified a number of potentially relevant incident types. For landings at the wrong runway, which might be considered a more gross error not necessarily to be mitigated by RESA provision, the observed overrun distances were 65, 137, 206, 220 and 274. The analysis of all incident types presented above indicates that 50% of incidents travel up to approximately 80 m. These more gross errors can be seen to exhibit overrun distances typically above this median value. For major system failures, the observed overrun distances are 107 and 478 m, again above this median.

A selected data set where landing long, excess speed and/or poor approach is identified as the primary cause has been analysed. The majority of incidents (all but one) are contained within just over 200 m and the point beyond that is at 400m. The data set gives an exponential best fit for the overrun distance distribution of $N_l (x) = exp (-0.0101 x)$. In general then, the selected data set indicates a relatively sharp fall off in the overrun distance distribution function.

Similarly, a selected data set where brake failure is identified as the primary cause has been analysed. Excluding the outlying point at 1159 m, an exponential best fit for the overrun distance distribution of $N_l(x) = exp(-0.0046\,x)$ is obtained. This indicates that brake failure incidents are typically associated with longer overrun distances.

Finally, a selected data set where contaminated runway conditions are encountered has been analysed and gives an exponential best fit for the overrun distance distribution function of $N_l(x) = exp(-0.0088\,x)$, which is generally consistent with the value obtained for the complete data set.

The data set combining the incidents where brake problems were encountered and where landing long, excessive speed and/or poor approach is identified as a causal factor, an exponential best fit for the overrun distance distribution function of $N_l(x) = exp(-0.0082\,x)$ is obtained, which again is generally consistent with the value obtained for the complete data set.

On the basis of this analysis of sub-sets of data, we conclude that the incident types of primary relevance to the current study are adequately described by the landing overrun distance distribution function identified earlier from the analysis of the complete data set.

A5.3.6.5 Discussion and Recommendations

On the basis of the above analysis, we recommend the use of the following exponential functions as best estimates for the take-off and landing incident overrun distribution:

$$N_t(x) = exp(-0.0058\,x)$$

and

$$N_l(x) = exp(-0.0081\,x)$$

To take account of the uncertainty, we recommend that sensitivity studies be undertaken employing other distribution functions. For the more "optimistic" case (lower bound risk), for which the function falls off most rapidly with distance therefore indicates a smaller RESA length to achieve a given residual risk level, we recommend the use of the following functions:

$$N_t(x) = exp(-0.0065\,x)$$

and

$$N_l(x) = exp(-0.0101\,x)$$

For the more "pessimistic" case (upper bound risk), for which the function falls off least rapidly with distance and therefore indicates the greatest RESA length to achieve a given risk level, we recommend the following:

$N_t(x) = exp(-0.004\,x)$

and

$N_l(x) = exp(-0.0068\,x)$

In proposing these different values of “best-estimate”, “lower bound” and “upper bound”, we recognise that there is some uncertainty in the data set most applicable to Norwegian operational conditions. We have not been able to characterise the function in terms of specific parameters determining the distance travelled and identify how such parameters might apply to the Norwegian case. Formal and systematic uncertainty analysis in respect of such parameters is therefore not practical. The “best-estimate” represents the value obtained using the largest available data set. Given the relatively large size of that data set we consider it to be a good representation of the historical average behaviour for the identified overrun incidents which were predominantly in the UK and North America. However, although we identify Norwegians operations to be broadly consistent with those in the UK and North America these data may not be fully representative of the Norwegian case. By evaluating different selected data sets, for different types of operation, we have sought to provide some indication of the uncertainty and the various functions obtained for the various data sets are used as a basis for indicating the scale of uncertainty, in terms of the proposed “lower” and “upper” bounds. Our observation is that the different data sets give generally consistent results and we therefore have no indication that we should expect significantly different risk functions to apply to Norwegian operations.

A5.3.7 Risk Assessment of RESA Provision

Applying the incident rates and overrun distance distribution functions derived in the previous two sections, the residual risk associated with any given length of RESA can be estimated. For the current purposes, estimates are presented here of the risk associated with the following:

- The residual risk for a clear area extending 150 m from the runway end, comprising the current ICAO standard of 90 m RESA plus 60 m of runway end strip.
- The residual risk for a clear area extending 300 m from the runway end, comprising the current ICAO standard of 240 m RESA plus 60 m of runway end strip.
- The length of RESA required to provide a residual risk of 10^{-7} serious incidents per movement.

(More comprehensive tabulations of residual risk as a function of distance are provided in Table A5-14 which also presents data on undershoot residual risk derived in accordance with the model described below in Section A5.4.)

Estimates have been made using “best-estimate”, “lower bound” and “upper bound” values for both incident frequency and overrun distance distribution functions. As indicated earlier, the nature of the model does not allow formal and systematic uncertainty analysis to be undertaken and these values represent our judgement concerning the likely level of uncertainty, taken account of the uncertainty in the empirical data that supports the model and its relevance to the Norwegian situation.

Contributions from take-off and landing incidents have been identified separately and "mean" values (for a runway at which 50% of movements are take-offs and 50% are landings) are also presented. Separate estimates are presented for "average" movements, comprising a mixture of precision, non-precision and visual approaches, for precision approach movements and for non-precision/visual approach movements. It is noted that the risk factors provided below take no account of excess runway factoring and are based on the risks averaged over movements with a wide range of excess runway available. The overruns risks associated with runway length limited operations (*i.e.* movements with limited excess runway) are of the order of tens times higher than those quoted in the table below; it is noted that such runway length limited operations are relatively common at many of the small-to-medium sized Norwegian aerodromes.

Overall average (precision/non-precision/visual, no excess runway factoring)			
	Lower bound	Best-estimate	Upper bound
Residual risk at 150 m: Mean	0.086×10^{-6}	0.217×10^{-6}	0.271×10^{-6}
Residual risk at 150 m: Take-off	0.063×10^{-6}	0.138×10^{-6}	0.181×10^{-6}
Residual risk at 150 m: Landing	0.110×10^{-6}	0.297×10^{-6}	0.361×10^{-6}
Residual risk at 300 m: Mean	0.024×10^{-6}	0.073×10^{-6}	0.115×10^{-6}
Residual risk at 300 m: Take-off	0.024×10^{-6}	0.058×10^{-6}	0.099×10^{-6}
Residual risk at 300 m: Landing	0.024×10^{-6}	0.088×10^{-6}	0.130×10^{-6}
Required length for TLS of 10^{-7}: Mean	135 m	255 m	325 m
Required length for TLS of 10^{-7}: Take-off	80 m	205 m	300 m
Required length for TLS of 10^{-7}: Landing	160 m	285 m	340 m

Precision average (precision approach, no excess runway factoring)			
	Lower bound	Best-estimate	Upper bound
Residual risk at 150 m: Mean	0.064×10^{-6}	0.158×10^{-6}	0.199×10^{-6}
Residual risk at 150 m: Take-off	0.063×10^{-6}	0.138×10^{-6}	0.181×10^{-6}
Residual risk at 150 m: Landing	0.066×10^{-6}	0.178×10^{-6}	0.216×10^{-6}
Residual risk at 300 m: Mean	0.019×10^{-6}	0.055×10^{-6}	0.089×10^{-6}
Residual risk at 300 m: Take-off	0.024×10^{-6}	0.058×10^{-6}	0.099×10^{-6}
Residual risk at 300 m: Landing	0.014×10^{-6}	0.053×10^{-6}	0.078×10^{-6}
Required length for TLS of 10^{-7}: Mean	100 m	215 m	280 m
Required length for TLS of 10^{-7}: Take-off	80 m	210 m	300 m
Required length for TLS of 10^{-7}: Landing	110 m	220 m	260 m

Non-precision/visual average (non-precision/visual, no excess runway factoring)			
	Lower bound	Best-estimate	Upper bound
Residual risk at 150 m: Total	0.289×10^{-6}	0.763×10^{-6}	0.934×10^{-6}
Residual risk at 150 m: Take-off	0.063×10^{-6}	0.138×10^{-6}	0.181×10^{-6}
Residual risk at 150 m: Landing	0.514×10^{-6}	1.389×10^{-6}	1.688×10^{-6}
Residual risk at 300 m: Total	0.068×10^{-6}	0.235×10^{-6}	0.354×10^{-6}
Residual risk at 300 m: Take-off	0.024×10^{-6}	0.058×10^{-6}	0.099×10^{-6}
Residual risk at 300 m: Landing	0.113×10^{-6}	0.412×10^{-6}	0.609×10^{-6}
Required length for TLS of 10^{-7}: Mean	260 m	410 m	500 m
Required length for TLS of 10^{-7}: Take-off	80 m	210 m	300 m
Required length for TLS of 10^{-7}: Landing	310 m	475 m	565 m

The assessment provides an indication of the potential level of uncertainty in the risk for given types of operation and the range of risk levels to which different types of operation are subject. We should note also the higher risk to which operations with no available “excess” runway are expected to be subject, possibly up to a factor of ten higher than those presented in the above tables.

A5.3.8 Conclusions

We conclude that the overrun risk model and the assessment of the relationship between residual risk and RESA length provides a sound basis for establishing risk-based design rules for RESA provision. However, given the range of risk levels identified for different types of operation, it will be necessary to consider in some further detail the risk management objectives for aerodrome design. In particular we note that, as regards appropriate TLS standards, the possible need to distinguish between the risk applicable to average movements or to those movements most at risk has previously been recognised. The assessment provides an estimate of the range of risks which may need to be accommodated. Other issues that may need to be considered include the use of measures other than aerodrome design to mitigate against overrun risk and the relative effectiveness in reducing risk of RESA provision compared with these other measures. In this context we identify provision of precision approach aids and the use of stricter safety factoring in relation to runway length requirements as possible measures to address movements at higher risk.

A5.4 UNDERSHOOT RISK ASSESSMENT

A5.4.1 Risk Assessment Approach

The approach adopted for the assessment of landing undershoots is based on the quantitative assessment of:

- the likelihood of an undershoot accident occurring on landing; and
- the probability distribution of the distance by which the aircraft undershoots the touchdown threshold should such an undershoot event occur.

The above assessments are made through review and analysis of incident data. For the assessment of undershoots, the main sources of data utilised are as follows:

- the FAA Incident Database System (FIDS) [17];
- the US National Transport Safety Board (NTSB) accident and incident database [18];
- the ICAO Accident/Incident Reporting database (ADREP) [19];
- the CAA Mandatory Occurrence Reporting System (newMORS) incident database.

In addition to the above main reference data sources, more limited data was also used from the Norwegian CAA, Flight International, an FAA report of accident locations [9] and the UK Air Accident Investigation Bulletin (AAIB) [20].

A5.4.2 Undershoot Incident Rate

A5.4.2.1 Average Incident Rate

The undershoot incident rate may be estimated from incident/accident databases provided that there is sufficient confidence in the comprehensiveness of reporting and that the operations covered by the database reporting is known. Generally, of the data sources identified above, only the FIDS/NTSB and the CAA/AAIB data sources may be considered to fulfil these criteria with any great confidence.

For the estimation of undershoot incident rates, the main source of data proved to be the FIDS/NTSB databases. These associated databases may be searched on-line via the FAA web site. Following review of these databases, a comprehensive search criterion was produced in order to generate a complete set of the available undershoot incident and accident reports. The number of undershoot incidents identified is presented in TableA5- 8, broken down by type of operation. Movement data is also available for the commercial carriers and air taxis whose operations are covered by the FIDS and NTSB databases for a range of years from 1975 through to 2000 [21] and these are presented in Table A5-9.

The undershoot incidents identified in the FIDS database occurred over the period of 1978 to 2000 and it can be seen that the total number of reported incidents for commercial carriers over this period is 18. From the data presented in Table A5-9 (and using linear interpolation to obtain the annual number of landing operations for the intervening years between 1975 and 1980, between 1980 and 1985 and between 1985 and 1990 respectively), it is estimated that the number of commercial carrier landing operations between 1978 and 2000 is around 1.5×10^8. The undershoot incident rate for such operations is therefore assessed to be approximately 10^{-7} incidents per landing operation.

Total air taxi/commuter landing data is available for the period 1990 to 1994 and extrapolating the growth trend over 1978 to 2000, provides an estimated total number of landing movements within the 23 year period of approximately 1×10^8 landings. The number of identified undershoot incidents in this period is 46 for air taxi/commuter operations and hence the undershoot incident frequency for such operations is estimated as around 5×10^{-7} incidents per landing. By similar argument, the undershoot incident frequency over combined commercial and air taxi/commuter operations is estimated to be around 2.5×10^{-7} incidents per landing.

It is also noted that the relative frequency of undershoots to landing overruns found from analysis of accident and incident reports held with the ADREP database is approximately a ratio of 1:5. Additionally, it may be noted that the landing overrun frequency is estimated as 1.57×10^{-6} per landing (see Section A5.3) and hence an assumed undershoot frequency of 2.5 $\times 10^{-7}$ is broadly consistent with a relative frequency of 1 to 5.

A5.4.2.2 Relative Incident Rates

In addition to the overall undershoot frequency, the accident/incident data has also been assessed to determine the relative undershoot rates for:

- jets compared to turboprops;

- precision approach compared to non-precision/visual approach.

In total, for commercial carrier and air taxi operations, 47 undershoot incidents were identified for which the undershoot distance was recorded. The breakdown of these incidents by the propulsion mechanism of the aircraft involved is provided in Table A5-10. The percentage of undershoot incidents involving jets is 64%. This is broadly consistent with the relative proportions of these generic aircraft types in the world wide fleet (jets 73% and turboprops 27%) and with the relative rates of movements of these generic aircraft types (jets 69% and turboprops 31%) as presented in a DETR study [11]. It is thus concluded that it is unlikely that turboprop aircraft are significantly more likely to undershoot than jets per landing movement.

As with landing overrun incidents, the type of approach aids utilised for landing has been identified as a potentially important factor which influences the likelihood of occurrence of an undershoot incident. Details of the approach aids used in undershoot incidents have been recorded in a total of 44 incident reports (for commercial carrier and air taxi operations). These incidents were almost exclusively in the US. The breakdown of these incidents by approach aid type is presented in Table A5-11. It is estimated that the ratio of precision to non-precision approaches is 14.5 to 1 for landing movements in North America (based on landing data for the period 1984 to 1993 at the 120 busiest North American airports [14]). Similarly the ratio of precision approach movements to combined non-precision/visual approach movements for these airports is 10.2 to 1. Given that these movement figures are based on the larger North American aerodromes, it is more appropriate to compare the undershoot frequency for the commercial carrier data only as significant air taxi movements will occur at the smaller aerodromes without precision approach aids. The ratio of undershoot incidents for commercial carriers between precision approach and non-precision/visual approach is about 1.6 to 1 (see Table A5-11). The relative rates of undershoot occurrence (relative to the average frequency) are thus estimated as:

Precision approach relative undershoot rate = 0.68

Non-precision/visual approach relative undershoot rate = 4.3

However, it should be stressed that the correlation between the presence or absence of precision approach aids and the overrun rate does not necessarily indicate a direct dependence. There may be another factor associated with non-precision/visual approach operations that is responsible for the correlation, for example the standard of the operators involved at smaller aerodromes where the majority of non-precision/visual approaches occur. Some caution must therefore be exercised in interpreting the data.

A5.4.2.3 Extrapolation to the Norwegian Case

In the Functional Hazard Analysis (FHA), a number of causal and influencing factors for undershoots were identified. Of specific interest to the assessment of Norwegian aerodromes, were certain meteorological related factors:

- icing of controls;
- restricted visibility (*e.g.* due to precipitation or fog);
- strong, variable winds.

These factors are of interest because of their relatively high prevalence in Norway, particularly icing. It is therefore appropriate to consider these factors when extrapolating general world-wide aviation risks to the specific case of Norwegian aerodromes. Insufficient data is available on the relative frequency with which these meteorological conditions occur in the countries over which the incident data has been collected compared to Norway to enable a detailed quantitative assessment. Nonetheless, review of the causal and influencing factors of the available incident reports does enable qualitative judgements to be made regarding the application of the general aviation risks to the Norwegian aerodromes.

With this in mind, the incident records available from the FIDS/NTSD databases were reviewed to identify those incidents for which investigation by the relevant authorities found that adverse meteorological conditions had contributed to the incident. A summary of the review is presented in Table A5-12. Review of this data finds that adverse weather conditions do not contribute to most (62%) of the undershoot incidents. Icing of controls was found to be a contributing factor in around 8% of undershoot incidents. Given the prevalence of icing conditions in Norway, the undershoot risks may be higher for Norway than in the countries for which incidents have been analysed. However, the small percentage of incidents for which icing was identified as a contributing factor suggests that the overall increase in undershoot risks is likely to be relatively small.

Furthermore, in all the identified icing related incidents, investigators concluded that while icing was a contributing factor, pilot and procedural error, generally in relation to prevention of icing of controls, were the key causal factors. It is to be expected that pilot and operator experience of icing conditions will be greater in Norway (at least for domestic operations) and hence the increased risk for the Norwegian case is likely to be partially mitigated. Overall, it is concluded that, while some increase in the rate of occurrence of undershoot events may be anticipated when the generic risks are extrapolated to Norway, this increase is likely to be relatively small and so the generic risks assessment may be reasonably applied to support the development of design rules for Norwegian aerodromes.

A5.4.2.4 Consequences of Undershoots

The consequences of undershoot incidents have been assessed through review of accident and incident records. The main source of data on the scale of consequences was found to be the FIDS and NTSB databases. In total 64 undershoot incidents involving commercial carriers and air taxis were reviewed and the consequences were assessed in terms of damage sustained to the aircraft (described on a four point scale of “destroyed”, “substantial”, “minor” or “none”) and the incidence of different degrees of human injury (classified in terms of “fatal”, “serious”, “minor” or “none”). The numbers of incidents within each consequence category are shown in Table A5-13.

Comparison of the expected resultant damage from undershoot incidents with overruns (see Table A5-6) shows that total aircraft loss is much more unlikely for undershoots (around 3% of incidents) than is the case for overruns (about 18% of incidents). Similarly, substantial aircraft damage is also relatively less likely for undershoot incidents (38% *cf* 65% for overruns incidents). The lower likelihood of severe damage may arise from either the increased likelihood that the undershoot be contained within the RESA or runway end strip, thereby avoiding impact with unfavourable terrain, or some other feature of undershoots compared with overruns.

A5.4.2.5 Recommendations

It is recommended that the undershoot incident frequency of 2.5 x 10^{-7} per landing derived from the combined commercial carrier and air taxi/commuter operations is used as the best estimate frequency for development of aerodrome design rules. Nonetheless, the estimated frequency for the commercial carriers (*i.e.* 1 x 10^{-7} undershoots per landing movement) may provide a useful lower bound.

A5.4.3 Undershoot Location Distribution

In total 115 undershoot incidents were identified for which the distance by which the aircraft undershot the runway threshold was reported. From this data, the fraction of events undershooting the runway by more than a specified distance can be estimated, *i.e.* a Complementary Cumulative Probability Distribution (CCPD) of the undershoot distance can be derived. When multiplied by the frequency of occurrence of an undershoot event (per movement), the overall frequency with which landings result in undershoots in excess of specific distances can be derived in the form of a Complementary Cumulative Frequency Distribution (CCFD). The CCFD can then be used to set the length of the runway end safety area required to meet the undershoot TLS.

The main sources of undershoot distance data were the FIDS/NTSB databases and ICAO ADREP database. In total 115 undershoot incidents were identified covering all types of aviation operations. Of these 73 incidents involved commercial operations (*i.e.* commercial carrier and air taxi/commuter operations) of which 47 related to aircraft >5.7 te. The CCPD plots are presented in Figure A5-7 for the complete dataset and the subset of commercial operations, both for all aircraft and the subset of aircraft in excess of 5.7 te. It can be seen that these plots are almost identical except in the region of the most extreme data points where the CCPD is sensitive to a small number of data points and is hence somewhat uncertain. This suggests that, although the frequency with which undershoot events occur may vary between different types of operation, the distribution of the undershoot distances is similar across all different types of operation. Furthermore, the data suggests that the mass of the aircraft appears to have little bearing on the extent of the undershoot. To further investigate the relationship between aircraft mass and undershoot distance, the sample Pearson correlation coefficient, ρ, between mass and distance was estimated for the commercial operation events. A value for ρ of around 0.1 was found from the data, further indicating that no strong correlation exists.

In line with our general approach, the risk assessment is largely focused on the risks associated with commercial operations with aircraft in excess of 5.7 te. Nonetheless, comfort may be drawn from the above analysis that the aerodrome design rules developed from the assessment of such operations will also provide similar levels of safeguarding for general aviation operations. In particular, the absence of a strong link between the undershoot distance and mass ensures that the risk assessment will be broadly appropriate to the smaller aircraft of interest to the Norwegian aerodromes, such as the Beech 200, which falls just below the 5.7 te weight category.

The CCPD for the undershoot distances can be described by a function of the form:

Fraction of events undershooting by a distance > x = $\exp(-a\, x^{b})$

For commercial operations with aircraft > 5.7 te, the fitted function constants take the values a = 0.0769 and b =0.593. The coefficient of determination (R^2) for the fitted function is 0.91, thus demonstrating a reasonable fit to the data. This function is shown in Figure A5-8.

A5.4.4 Risk Assessment

Assuming an undershoot frequency of 2.5×10^{-7} per landing operation, the frequency per landing movement with which aircraft undershoot by a distance in excess of x m, $f(x)$, (*i.e.* the CCFD) is given by:

$$f(x) = 2.5 \times 10^{-7} \exp(-0.0769\, x^{0.593})$$

This CCFD is presented in Figure A5-9.

Assuming that the approximately 10% of undershoots incidents that lead to either fatalities or serious injury (see Table A5-13) are those that occur beyond the RESA, the frequency of such consequences from undershoot events is derived directly from the CCFD.

From review of the CCFD it can be seen that provision of the following combined RESA and strip end lengths will reduce the undershoot risks as follows:

RESA/strip length	Frequency of Fatality/Serious Injury
60m	1×10^{-7}
180m	4.7×10^{-8}
300m	2.6×10^{-8}
560m	1×10^{-8}
1340m	1×10^{-9}

The current ICAO recommendations provide a combined RESA/runway end length of 180m for Code 1 (instrument) and 2 aerodromes and 300m for code 3 and 4 aerodrome. Applying the average undershoot frequencies at these distances finds that the frequency of undershoot events is less than 10^{-8} events per landing movements for all aerodrome codes meeting the ICAO recommendations. A more comprehensive tabulation of residual risk as a function of distance is provided in Table A5-14 which also presents data on overrun residual risk derived in accordance with the model described earlier in Section A5.3.)

A5.5 RUNWAY VEER-OFF RISK ASSESSMENT

A5.5.1 Risk Assessment Approach

The modelling approach for the quantitative assessment of the risks associated with lateral deviation during runway operations comprises four elements:

- a risk model to inform the design rules defining the runway width requirements;
- a risk model to inform the design rules for the width of the graded portion of the runway strip;
- a risk model to inform the design rules defining runway strip requirements[1]; and
- a risk model to inform the design rules for runway-taxiway separation distances.

As regards the last aspect, consideration is requires of the lateral deviation during taxiing operations which is considered in Section A5.7, below.

Both the runway width and the runway strip risk models require:

- the evaluation of the frequency of veer-off events occurring (per landing or take-off operation);
- the probability distribution of the extent of the aircraft deviation from the runway centreline should a veer-off incident occur (described in the form of a Complementary Cumulative Probability Distribution (CCPD)).

Both the frequency with which veer-off events occur and the probability distribution of the level of deviation (*i.e.* the CCPD) are evaluated through review and analysis of accident and incident data. For the assessment of veer-off incidents, the main sources of data utilised are as follows:

- the Loughborough University Overrun Database (which also contains veer-off distances);
- the FAA Incident Database System (FIDS) [17];
- the US National Transport Safety Board (NTSB) accident and incident database [18];
- the CAA Mandatory Occurrence Reporting System (newMORS) incident database; and
- the UK Air Accident Investigation Bulletin (AAIB) [20].

The frequency of veer-off incidents occurring can be combined with the CCPD of the lateral deviation to describe the frequency per movement with which the aircraft deviate laterally beyond a distance *x*. By describing this frequency mathematically as a function of the deviation distance, the widths of the runway, runway strip and runway strip graded area respectively required to meet defined Target Levels of Safety can be defined.

[1] The runway strip provides protection to both veering aircraft during landing/take-off roll and also during missed approach and initial take-off (where wheels-off occurs before the end of the runway). These latter two issues will be dealt with in risk assessment studies described in Appendix 6.

The assessment has been undertaken separately for landing and take-off operations. The assessment of the frequency with which veer-off events occur is described in Section A5.5.2 and the development of the veer-off deviation distribution is discussed in Section A5.5.3. Finally, the risk assessment of veer-off incidents is represented in Section A5.5.4.

A5.5.2 Veer-Off Incident Rate

The main sources of veer-off incident and accident records were the FIDS and NTSB databases for which incidents were searched over the period 1978 to 2000. The number of veer-off incidents identified in this period are presented in Table A5-15 as a function of type of operation. From this table it can be seen that a total of 66 veer-off incidents involving commercial carrier operations have been identified in this period. From data presented in Table A5-9, it is estimated that the number of commercial carrier operations in the US over the same period is of the order of 1.5×10^8 landing operations and hence 3×10^8 landing and take-off operations. The combined frequency with which veer-off incidents occur during landing and take-off operations is thus estimated to be around 4.4×10^{-7} per movement.

Review of the incident records reveals that 25% of these incidents occur on take-off and so the frequency with which such events occur during commercial carrier take-off operations is estimated to be 1.1×10^{-7} events per take-off operation. Similarly, the frequency of veer-off incidents during commercial carrier landing operations is estimated as 3.3×10^{-7} per landing movement.

Total air taxi/commuter landing data is also available for 1990 to 1994 and extrapolating the growth trend over 1978 to 2000, provides an estimated total number of air taxi/commuter landing operations of approximately 1×10^8 within this 23 year period. Combining this with the commercial carrier operations, provides an estimated total number of landings of 2.5×10^8 between 1978 and 2000. The total number of identified commercial operation veer-off incidents is 185 (see Table A5-15). Assuming the same split between landing and take-off incidents as above, the frequency with which veer-off events (though not necessarily total hull loss or fatal events) occur over all commercial operations is estimated to be:

Frequency of veer-off events per take-off operation = 1.9×10^{-7}

Frequency of veer-off events per landing operation = 5.6×10^{-7}

For those landing veer-off events identified in the Loughborough database, information is recorded on the type of approach utilised. Of the 34 landing veer-off events reported, 19 were precision approaches, 13 were non-precision or visual and the approach type was not recorded for two events. Hence, 59% of the events for which the approach type is known occurred during precision approach and 41% during non-precision or visual approach. As noted earlier the ratio of precision approach movements to non-precision/visual in North America is approximately 10.2 to 1. Therefore the relative rates of veer-off events occurring (relative to the average frequency) for precision and non-precision/visual approaches is:

Precision approach relative veer-off rate = 0.65

Non-precision/visual approach relative veer-off rate = 4.6

It may be noted that these relative rates are similar to those identified for both undershoot and overrun events.

The consequences of veer-off incidents have been assessed through review of accident and incident records. The fraction of the take-off and landing events utilised in the location distribution assessment (see below) that led to total aircraft loss is summarised in Table A5-16. From this data it is estimated that around 36% of veer-off incidents during take-off lead to total aircraft loss. For landing incidents, the percentage of total loss incidents is somewhat lower at about 17%. However, the fraction of events for which the level of damage is not reported is high (about 42%) for the landing incidents. If it is assumed that total aircraft loss would always be reported and, hence that the incidents where the level of damage is unreported are, in fact non-total losses then the percentage of total loss incidents for landing reduces to just 10%.

A5.5.3 Veer-Off Deviation Distribution

A5.5.3.1 Landing Operations

In total 35 landing operation veer-off events were identified for which the distance by which the aircraft deviated from the runway centreline was reported. Of these, 22 incidents related to commercial operation aircraft in excess of 5.7 te. From this data, the fraction of landing veer-off events which deviate more than a specified distance from the runway centreline can be estimated; *i.e.* the Complementary Cumulative Probability Distribution (CCPD) of the veer-off distance can be derived.

The CCPD plots for the complete data set and the subset of data relating to commercial operations are presented in Figure A5-10. The CCPD for the landing veer-off distances can be described by a function of the form:

Fraction of events with a veer-off distance > $x = \exp(-a\,x)$

For commercial landing operations with aircraft >5.7 te, the constant in the fitted function takes the value of $a = -0.0236$. The coefficient of determination for the fitted function is 0.91, thus demonstrating a reasonable fit to the data. This function is also shown on Figure A5-10. It should be noted that the available data for smaller-scale veer-off incidents is likely to be limited due to the nature of incident reporting and hence the derived model is somewhat uncertain, particularly for such veer-off distances.

It can be seen from Figure A5-10 that the CCPD is similar for the full data set and the subset of commercial operations, suggesting that the extent of the veer-off deviation is similar across the different types of operation.

Veer-off data held in the Loughborough database also contained information on a range of parameters, including:

- aircraft mass;
- crosswind strength; and
- visibility.

The influence of these parameters on the extent of the lateral deviation during veer-off incidents was then examined through the estimation of the sample Pearson correlation coefficient, ρ. No significant correlations between either the aircraft mass or visibility and the deviation distance were identified. However, a moderate correlation with crosswind strength ($\rho \approx 0.3$) was identified and hence some consideration of the relative frequency of strong cross winds at the Norwegian aerodromes may need to be considered. (One of the key causal factors for veer-off incidents identified in the FHA was the runway surface condition. Unfortunately information on runway surface condition was not available and hence its influence on the extent of deviation could not be formally assessed.)

Finally, the correlations between the lateral veer-off distance and aircraft wheel track, wingspan and reference field length were also assessed and no significant correlation was identified. This suggests that the deviation of the aircraft centreline is independent of the aircraft width and field length and hence the safety margins required for the different code letters and numbers will vary only according to the increase in the wheel track and wingspan.

A5.5.3.2 Take-Off Operations

For take-off operations a total of 15 incidents records were identified for which the lateral distance from the runway centreline was reported. 13 of these events related to commercial operations. The fraction of take-off veer-off events for which the lateral deviation from the runway centreline exceeds a specified distance (*i.e.* the CCPD) is shown in Figure A5-11. The CCPD for these events can be fitted to an exponential function as follows:

Fraction of events with a veer-off distance > $x = \exp(-a\,x)$

For take-off veer-off events the constant a takes the value of 0.0158, with a coefficient of determination of 0.98, demonstrating a good fit to the incident record data. Nonetheless, as with landing veer-off, the derived model is somewhat uncertain, particularly for small-scale veer-off distances, due to the limitations inherent in incident reporting.

As with landing veer-off, incidents the influence of a range of factors on the lateral extent of the veer-off during take-off operations were statistically assessed. For take-off incidents, no significant correlations with most of the assessed factors, including crosswind strength, were identified. A moderate correlation with the aircraft reference was identified (Pearson correlation coefficient of around 0.5), but the data set is too small to provide statistical significance to this apparent correlation. Nonetheless, the possibility that the safety margins required to protect against veer-off during take-off roll may need to be developed as a function of runway code number.

A5.5.4 Risk Assessment

Review of the CCPD plots for landing and take-off veer-off events (see Figure A5-10 and Figure A5-11 respectively), shows that the CCPD for landing operations declines more rapidly than for take-off. In other words, the veer-off incidents have a higher probability of deviating to larger distances from the runway centreline for take-off than for landing. This is consistent with the lower rate of total aircraft loss identified for landing veer-off events noted in Section A5.5.2.

Combining the CCPD functions with the frequency of occurrence factors identified in Section A5.5.2, the frequencies with which veer-off events occur in excess of a set distance x are given by:

Frequency of veer-off in excess of x m for precision approach = $3.46 \times 10^{-7} \exp(-0.0236\, x)$

Frequency of veer-off in excess of x m for non-precision/visual approach =
$2.58 \times 10^{-6} \exp(-0.0236\, x)$

Frequency of veer-off in excess of x m for take-off = $1.9 \times 10^{-7} \exp(-0.0158\, x)$

The risk-based development of design rules for runway widths is based on the frequency with which the aircraft main gear deviates beyond the edge of the runway[1]. The frequency per landing or take-off operation with which this would occur for the existing ICAO runway standards based on the above risk models are presented below for a range of aerodrome reference codes:

Gear Deviation from Runway			Frequency per movement		
Code	Runway width (m)	Max. wheel span	Precision landing	Non-precision/visual landing	Take-off
A3	30	4.5	2.69×10^{-7}	1.91×10^{-6}	1.55×10^{-7}
B3	30	6	2.7407	1.94×10^{-6}	1.57×10^{-7}
C4	45	9	2.38×10^{-7}	1.68×10^{-6}	1.43×10^{-7}
D4	45	14	2.52×10^{-7}	1.79×10^{-6}	1.49×10^{-7}
E4	45	14	2.52×10^{-7}	1.79×10^{-6}	1.49×10^{-7}

Similarly, the frequency with which the outer main gear would deviate beyond the edge of the graded portion of the runway strip are estimated for a range of runway code numbers, and for selected assumed aircraft codes:

Gear Deviation from Graded Area			Frequency per movement		
Code[a]	Graded area width (m)	Max. wheel span	Precision landing	Non-precision/visual landing	Take-off
C1	40	9	2.52×10^{-7}	1.79×10^{-6}	1.49×10^{-7}
C2	40	9	2.52×10^{-7}	1.79×10^{-6}	1.49×10^{-7}
E3	75	14	1.77×10^{-7}	1.25×10^{-6}	1.17×10^{-7}
E4	75	14	1.77×10^{-7}	1.25×10^{-6}	1.17×10^{-7}

[a] Graded area widths are specified as a function code letter, code widths are provided here to illustrate the range in the risks associated with different aircraft widths.

The risks associated with deviation beyond the runway strip are assessed in terms of the risk of the outer edge of the aircraft wingtip protruding beyond the runway strip. The frequency per landing or take-off operation with which this would occur for the existing ICAO runway

[1] It is noted that other aspects such as practical issues regarding aircraft manoeuvres and protection against FOD ingestion are also relevant to the design of runway widths.

strip standards based on the above risk models are presented below for a range of aerodrome reference codes:

Wingtip Deviation Beyond Strip			Frequency per movement		
Code[a]	Strip width (m)	Max. wingspan	Precision landing	Non-precision/visual landing	Take-off
C2 (precision)	75	36	2.30×10^{-7}		1.40×10^{-7}
C2 (visual)	40	36		2.46×10^{-6}	1.84×10^{-7}
E3 (precision)	150	65	1.34×10^{-7}		9.71×10^{-8}
E3 (non-precision)	75	65	3.23×10^{-7}	2.29×10^{-6}	1.76×10^{-7}

[a] Strip widths are specified as a function code letter and approach type, code widths are provided here to illustrate the range in the risks associated with different aircraft widths.

The frequency with which aircraft veer beyond set runway/strip widths is also summarised in Table A5-17.

The following general conclusions are drawn from review of the incident frequencies estimated above:

- Veer-off risks are higher for non-precision and visual approach than for precision approach. This appears to be at particular odds with the runway strip width recommendations of ICAO which require greater strip widths for precision approaches than for visual. However, it is noted the additional extent of the Obstacle Free Zone (OFZ) provided by ICAO for precision approach runways may also be considered to provide protection for the ILS equipment. Additionally, the strip width also provides protection against veer-off during missed precision approach; the protection against this type of incident is the subject of a separate risk assessment studies, as described in further detail in Appendix 6.
- For precision approach and take-off movements, the current ICAO standards provide a safety level of approximately 10^{-7} per movement in respect of the more catastrophic risk associated with veer-off beyond the runway strip.
- For visual approaches, the frequency of veer-off beyond the runway strip is of the order of 2×10^{-6} per landing movement. This is significant in comparison to other risks, such as those associated with overruns.
- Veer-off risks are generally greater for landing than for take-off operations.
- The ICAO recommendations for runway strip width and the width of the graded strip area are defined as a function of the aircraft reference field length and not the aircraft wingspan or wheel track. The analysis presented here suggests that the dependence on the aircraft width dimensions may usefully be incorporated in the runway strip and graded area design rules. Evidence for the need for the width dimensions to be scaled as a function of aircraft field length is limited, though the data suggest that this may be the case for take-off roll.

A5.6 ASSESSMENT OF VEER-OFF DURING OVERRUNS

Data on the aircraft locations following overrun and veer-off incidents is provided in the Loughborough database. This data was analysed to assess whether any correlation existed between the distance of overrun and the extent of the lateral veer-off distance. Separate assessments were undertaken for landing and take-off incidents.

For take-off incidents, no significant correlation was found between the extent of the overrun (measured from the end of the required distance) and the lateral extent of the veer-off. However, a moderate correlation (Pearson correlation coefficient value of about 0.4) was found when the overrun distance beyond the required was normalised by the required distance (see also Figure A5-12). This suggests that any increase in the overrun safety margins for landing operations, should be reflected by a coincidental increase in the veer-off safety margins. In other words, if the length of the RESA is increased to reduce the risk of overruns, then consideration should also be given to increasing the width of the RESA to protect against veer-off risks.

No significant correlation was identified between overrun distance and veer-off distance for landing operations.

ICAO recommendation is for a RESA width equal to that of the graded portion of the associated runway strip but not to the full width of the runway strip. That is to say that there is less protection against lateral veer-off beyond the runway end than there is alongside the runway itself. However, our risk analysis suggests that a significant number of overrun incidents involve veer-off beyond the width of the graded area and that a RESA width equal to that of the full width of the runway strip would be required to achieve a safety level of around 10^{-7} per movement.

A5.7 TAXIWAY DEVIATION MODEL

A5.7.1 Introduction

Taxiing deviation is identified as a relevant consideration in determining design requirements in two respects:

- the width of taxiway, in relation to the risk of aircraft excursion from the taxiway;
- the separation distances between parallel taxiways and between taxiways and physical obstacles, in relation to the risk of collision.

Outline models for the assessment of the above risks have been developed and the results of the implementation of these models are described here, together with preliminary recommendations for the development of risk-based design rules for taxiway physical dimensions.

The risks associated with lateral deviation during both runway operations (*i.e.* landing take-off roll) and taxiing operations have also been identified as relevant with respect to runway-taxiway separation distances. An assessment of the required taxiway-to-runway separation distances to meet the target level of safety for the combined risks of taxiing and runway operation veer-off deviation is presented in this appendix.

A5.8.2 Outline Modelling Approach

The developed model for the quantitative assessment of taxiing (and runway operation) deviation risks can be considered in four elements:

- a risk model to inform the design rules for taxiway strip width provision;
- a risk model to inform the design rules for taxiway-to-object separation distances;
- a risk model to inform the design rules for taxiway-to-taxiway separation distances; and
- a risk model to inform the design rules for taxiway-to-runway separation distances.

These models are based on the development of Complementary Cumulative Probability Distributions (CCPD) from empirical data. For the taxiway width model, the risks are assessed in terms of the frequency per movement with which the aircraft wheels depart the graded area. Similarly, for the taxiway-to-object separation distances the risks are assessed in terms of the frequency with which the aircraft deviates such that the outer wingtip extends beyond the separation distance.

For the assessment of the taxiway-to-taxiway and taxiway-to-runway separation distances, the model is more complex and requires consideration of the frequency with which two aircraft pass one another (on parallel taxiways/runways) such that their combined deviation towards one-another is sufficient to lead to a collision.

For all the above operations, the deviation risk model is based on empirical monitoring data of taxiing aircraft, rather than on historical incident history. One limitation of this approach is that it is difficult to allow for pilot avoidance behaviour, *i.e.* pilot actions to avoid collisions by corrective steering before the collision occurs, and also the phenomena whereby pilots will tend to adhere more accurately to taxiway centrelines when in close proximity to objects and other taxiing aircraft. By not accounting for these features, it may be seen that the model may be considered to provide cautious estimates of the collision risks.

For all aspects of the taxiway risk model, a complication occurs in the integration of the deviation risks over entire taxiway routes and over the entire aerodrome. The difficulty in developing generic aerodrome design rules here is that the TLS is based on the incident frequency per movement, but that the length of relevant taxiway sections will vary strongly between different aerodromes and, furthermore, the actual length and nature of the taxiway used at a particular aerodrome will vary from movement to movement. Resolution of this issue is thus aerodrome specific and requires detailed knowledge of the taxiway routes and the frequency with which they are used. Also, the exact method of integration is complex. One method of assessment is to breakdown the taxiway system into a series of sections such that:

- the risk of deviation at a single point is representative of the risk over the section (taking account the probable taxiing path to ensure against double-counting); and
- the overall risk is a summation of the risks within each section.

Additionally, for the collision risks, either between aircraft passing on two parallel taxiways/runways or between a taxiing aircraft and an object, the overall risk per movement requires knowledge of the taxiway occupancy rates. The occupancy rates are also aerodrome and movement specific and, further, will vary with operational changes, such as increases in aerodrome movement numbers.

In order to develop generic rules for taxiway design, it is therefore required that the rules are defined to allow for these factors, for example through definition as functions of taxiway route length and frequency of use. For taxiway-taxiway separations, the rules would need to be more complex and defined as a function of the length of the parallel elements and frequency with which aircraft pass one-another. Alternatively, a simpler design rules system could be developed by the use of cautious generic values for the taxiway lengths and frequency of use. However, this latter approach may lead to unnecessarily cautious rules for the majority of aerodrome/taxiway routes, while potentially providing insufficient protection to high risk (*e.g.* high occupancy) aerodromes/taxiways.

The difficulties that these issues present to the basis for suitable target levels and the generation of generic rules are discussed further in the following sections.

A5.7.3 Development of Risk Targets

A general discussion of the basic approach to the development of target levels of safety has been provided in Appendix 2. Here we consider more specifically risk levels and targets relevant to taxiway movement incidents.

The criteria set out in JAR 25 were established to facilitate the assessment and evaluation of aircraft safety in respect of the certification of new aircraft. Given the specific application for which the above risk tolerability criteria were established, it would not necessarily be appropriate to apply them directly in this case. However, the process adopted for establishment of the criteria, by making reference to historic rates and recognising that we should like at least to match if not better the historic safety performance, is considered to be a pragmatic and valid approach, employed not only in the aviation industry but in many other risk management situations. It is therefore appropriate to consider the risk from ground collisions within this general context. Two basic reference points can be identified that provide a basis for development of appropriate risk management criteria in this instance, as follows:

- the historic ground collision incident data reviewed earlier; and
- broader data on airport related accidents.

In this context, it is proposed that the incident frequency per movement may serve as an appropriate primary measure of the risk level. This provides the most convenient measure for comparison with historic data. The annual risk at a given airport can, of course, be related to this measure, by reference to the annual number of movements.

A recent study conducted by the DETR in the context of third party safety management found a frequency of airport related accidents with catastrophic consequences (total hull losses) for modern jet aircraft of 0.148 per million movements [11]. This establishes an initial pragmatic risk standard which, in general terms, we would seek always to improve upon, where practicable. It is to be recognised that a single incident scenario should make only a small contribution to the overall frequency of incidents with catastrophic consequences. On this basis, the likelihood of a taxiway collision that leads to a total hull loss should be considerably less than 0.148 per million movements, say perhaps 1 in a thousand million (10^{-9}). (Taking account of the length of a typical flight, this is broadly equivalent to the 10^{-9} per flight hour identified in JAR 25.)

However, turning more specifically to ground collision incidents, it has already been noted that the incident frequency for taxiway collisions is of the order of 0.87 per million movements. The majority of incidents give rise to minor consequences only. The likelihood of catastrophic consequences resulting from a ground collision is judged to be less than 1 in 500 (and probably very much lower). On this basis, the frequency of taxiway collisions giving rise to catastrophic consequences is judged to be less than 0.87 per five hundred million movements, or 1.74×10^{-9} per movement. This value is broadly consistent with the 10^{-9} per movement total loss criterion derived earlier. Put another way, achieving a total taxiway collision rate of no more than 0.5 per million movements should ensure that the target frequency for incidents giving rise to catastrophic consequences of less than 10^{-9} per movement would be met.

Similarly, in relation to the risks of aircraft landing gear departing from the graded portion of the taxiway strip, it should be noted that the consequences of such incidents will be relatively minor. It is therefore suggested that the acceptable frequency of such incidents may be higher than for taxiing collision rates.

Finally, as noted earlier, the development of TLS in terms of incidents per movement is problematic for taxiing operations as the risks for any taxiing operation will be strongly dependent on the exact nature and length of the particular taxiway route used. To overcome such problems, the TLS will need to be met for each taxiway route.

A5.7.4 Data Availability and Analysis

The taxiing deviation CCPDs are based on monitoring data collected from taxiing aircraft. Previous monitoring data studies have been undertaken at Heathrow (BAA, 1987 [22]) and Schiphol (Boeing 1995 [23]) respectively. Although these studies provide much useful general information, they have largely focused on the taxiing performance of New Generation Larger Aircraft (NGLA), and the Boeing 747 in particular. As such these studies are of only limited relevance for the development of design rules for a comprehensive range of aircraft.

In addition to these previous studies, ongoing monitoring studies are now also being undertaken at a number of airports, including JFK (FAA/Boeing), Anchorage (FAA/Boeing) and Heathrow (BAA). Although these new studies are being undertaken separately, the organisations involved are co-ordinating their efforts and working towards a consistent and unified approach. To date, as part of these studies, taxiing deviation monitoring data has been collected at the JFK and Anchorage airports. Further data collection exercises will start shortly and at the end of these exercises, a large data bank will have been assembled for statistical analysis.

The timescales for the completion of these studies is, unfortunately, beyond the Norwegian Aerodrome Design Rule Project timeframe. Nonetheless, useful information on monitored taxiway deviations is now becoming available and the FAA recently presented some initial findings of the Anchorage and JFK airport studies at a recent Airbus380/NGLA conference [24]. More importantly, raw monitoring data from the initial stages of the Anchorage study have been made available by the FAA. This data has therefore been used as the basis for the development the CCPDs. However, it is important to note certain limitation in the data and its analysis within the context of the present study:

- Insufficient information is presently available for the identification and assessment of the causal and influencing factors involved in taxiing deviation. However, such assessments will be undertaken as part of the wider ongoing FAA/BAA studies.
- Because of the inability to assess the causal factors of deviation at this stage, extrapolation of the results to the Norwegian case is uncertain. However, it should be noted that the use of data from Alaska will at least cover many of the extreme weather conditions that may potentially play a role in deviation during taxiing. Nonetheless, it should be recognised that other factors may exist that limit the extent to which this data may be appropriate to Norwegian aerodromes.
- The available dataset from Anchorage covers some 3000 events, with the largest deviation identified being of the order of 4m from taxiway centreline. However, the deviation distances in excess of these distances are required for the risk model, and hence extrapolation beyond the data range is required, particularly in order to assess deviation distances at the 10^{-7} per movement frequency level. Hence the risk models must be based on extrapolation beyond the limits of the available data.

It may be noted that the above issues will be largely resolved for the ongoing FAA/BAA studies. In particular, extrapolation beyond the available data limits can lead to large uncertainties if simple parametric procedures are applied. In order to (partially) overcome these problems, specific sophisticated non-parametric analysis techniques are currently being developed under the FAA program. These techniques will not be available on the timescales of the NCAA project and development of similar techniques are beyond the scope of the study. Therefore, the analysis has been based on the use of simple parametric analysis by the fitting the data to curves of the form:

$$\text{probability of deviation exceeding a distance } x,\ P(x) = \exp\,(a\, x^{b})$$

In order to account for the uncertainties inherent in extrapolation beyond the limit of the available data, a range of curves of the above form were fitted against different ranges within the available data. The bounding curves are shown against the data in Figure A5-13. The parameter values for the bounding curves and a tentative “best estimate” are presented in Table A5-18.

The raw monitoring data provided also enables the main gear wheelspan to be estimated for each recorded event. Analysis of this data has shown that no strong correlation exists between the wheelspan and the level of deviation from the taxiway centreline. It may be noted that this finding is contrary to the underlying principles on which the Annex 14 taxiway dimensions have been based.

Nonetheless, the limitations of the present study are emphasised and it is suggested that the recommended design rules based on this analysis may be best viewed as being preliminary and should be reviewed at a later date in the light of the findings of the more detailed FAA/BAA studies.

As noted earlier, the development of generic risk models require methods for integrating the taxiing risks over the entire aerodrome. One method of assessment is to breakdown the taxiway system into a series of sections such that

- the risk of deviation at a single point is representative of the risk over the section (taking account the probably taxiing path to ensure against double-counting); and
- the overall risk is a summation of the risks within each section.

However, the data currently available does not allow a suitable section length to be defined. A second issue raised earlier relates to the dependence of the taxiing risks per movement on the length of the taxiway route, the frequency of use and, for parallel taxiways, the frequency with which taxiing aircraft pass one-another. Presently available data does not allow resolution of these issues. In the present study, therefore, we present the risks per movement of taxiing aircraft within a taxiway section without integrating over the whole taxiway route and without regard to frequency of use.

However, the ongoing FAA/BAA studies will consider these issues in greater detail and it is suggested that these problems are unlikely to be resolved until these international studies are complete. In the meantime, we present quantitative assessment of individual taxiway sections and provide qualitative consideration of how these risks may be generically integrated over whole aerodrome taxiway systems.

A5.7.5 Development of the Risk Assessment

A5.7.5.1 Taxiway Width Assessment

The key risk considered with regard to taxiway width assessment is deviation of the aircraft such that its wheels depart from the graded portion of the strip, resulting in landing gear damage. Based on the fitted CCPD curves described above, the frequency per movement with which this occurs for a taxiway section afforded with the current Annex 14 recommended graded areas are estimated in Table A5-19. Frequency estimates are presented in this table for both the minimum and the maximum outer main gear wheel span within each aircraft code letter. The highest frequencies (based on the upper bound fitted curve) of deviation of the landing gear beyond the Annex 14 recommended graded portion of the taxiway strip are in excess of 10^{-6} per movement and occur for code letters A and C. This is likely to represent a worst case estimate and it is noted that the “best estimate” CCPD curve provides maximum frequencies less than 10^{-6}.

Given the low level of consequence of the landing gear departing from the graded taxiway surface and allowing for the cautious nature of the upper bound CCPD function this level of frequency may be considered to be acceptable, even allowing for integration over long taxiway sections. It is also noted that the frequency of this type of scenario occurring is generally lower for the larger aircraft types (*i.e.* codes D to F) and, indeed generally less than

10^{-7} per movement. However, the taxiway strips also provide other forms of protection, for example safeguarding against FOD engine ingestion, and so a reduction in the taxiway strip widths is not recommended for these code letters.

It is also noted that the risk bounds for each code letter taxiway strip definition cover a range of around one order of magnitude or less for the upper bound CCPD. It is thus concluded that the present categorisation of taxiway strip widths by code letter provides an appropriately graded scale.

A5.7.5.2 Taxiway-to-Object Separation Assessment

Taxiway-to-object separation distances have been assessed through consideration of the frequency with which a taxiing aircraft deviates such that the outer wing tip extends beyond the taxiway-to-object separation distance. The predicted frequency with which this occurs for a taxiway section provided with the Annex 14 recommended separation distances for the range of aircraft size codes is presented in Table A5-20.

The risks of aircraft deviating such that the outer wingtip displacement from the taxiway centreline is greater than the taxiway to object separation distance are of the order of 3×10^{-6} per movement for code C aircraft (based on the upper bound) and very much lower for larger aircraft.

It is noted that the consequences of a taxiing aircraft striking an object are generally greater than those associated with landing gear deviation beyond the graded surface. Nonetheless, as noted earlier a TLS of the order of 5×10^{-6} per movement may be appropriate, based on the likelihood of such a collision leading to serious consequences. Simple integration over the whole taxiway route may lead to the worst case risks (*i.e.* code C aircraft taxiways) challenging this TLS. However, it should be noted that this risk model is conservative as:

- it is based on the upper bound CCPD rather than the “best estimate”; and
- the risk model assumes that deviation beyond the separation distance will lead to collision with an object – this is obvious not the case as obstacles will not be present up to the minimum separation distance along the entire taxiway route.

Allowing for these factors, it is likely that the TLS will be met by the existing Annex 14 recommended taxiway-object separation distance for all aircraft codes. Indeed, for the larger code aircraft, the recommended taxiway separation distances would appear to provide more than adequate safeguarding.

A5.7.5.3 Taxiway-Taxiway Separation Assessment

The frequency of the combined deviation of two aircraft passing on parallel runways exceeding the Annex 14 recommendation taxiway-to-taxiway separation distances is presented in Table A5-21. These estimates are based on aircraft of the maximum wingspan within each aircraft code and on the assumption that both aircraft are of the same dimensions. For the upper bound CCPD model, the risks for smaller aircraft are in excess of 10^{-7} per movement and, for code C aircraft, challenge the TLS value of 5×10^{-6} per movement.

However, it is noted that the above estimates make no allowance for the frequency with which aircraft pass one-another on parallel taxiways. The passing frequency will be aerodrome dependent. Nonetheless, this frequency will typically be somewhat less than unity. Even cautiously assuming a passing frequency of 10^{-1} events per movement, this would reduce the actual collision rate to well below the TLS. Also, additional risk reductions can be qualitatively argued, particularly with respect to pilot avoidance behaviour and the observed improved adherence to taxiway centrelines during passing manoeuvres.

It is therefore concluded that the existing Annex 14 recommendations for taxiway-to-taxiway separation distances provide adequate safeguarding against aircraft collisions. Indeed, for larger aircraft (codes D to F), the risk analysis suggests that the current Annex 14 recommendations may be excessively cautious.

A5.7.5.4 Taxiway-Runway Separation Assessment

Comparative review of the CCPD of the deviation distances during runway and taxiway operations shows that the exposure to collision risks for the operation of parallel runway-taxiway configurations is largely dominated by the magnitude and frequency of lateral deviation during runway operations. To illustrate this point, the predicted deviation distance encountered at the level of 10^{-7} per movement for taxiing operations using the upper bound CCPD is of the order of 10m. This compares with a veer-off distance of around 70m predicted at the same frequency level for landing operations.

As such, the taxiing deviation may be regarded as a second order effect and it is suggested that the strip width recommendations made from assessment of veer-off during runway operations (and allowing for the safeguarding required for missed approach and balked landings – see Appendix 6) will also provide adequate minimum specifications for the taxiway-to-runway separation distances (with additional allowance the aircraft wingspan).

A5.7.6 Conclusions

Risk models for the deviation of aircraft during taxiing operations have been developed from empirical taxiing monitoring data. This data has been supplied by the FAA and was originally collected as part of an ongoing international study into the development of appropriate design rules for taxiways that includes the FAA and BAA. Some preliminary monitoring data from Anchorage have been supplied by the FAA and this has enabled the development of simple risk models. However, a number of problems with the development of such models at present have identified:

- A lack of information on the causal and influencing factors behind taxiing deviation that makes the construction of detailed model difficult.
- Because of the inability to assess causal factors of deviation, extrapolation of the results to the Norwegian case is uncertain.
- The presently available data set comprises some 3000 events and so extrapolation beyond the data is required to assess the risks at the levels of 10^{-6} to 10^{-7} per movement. Such extrapolation is fraught with uncertainty and the development of sophisticated analysis techniques to address this issue is beyond the scope of the present study.

- In order to assess design rules to meet a TLS framed in terms of the risk per taxiing movement, the taxiing risks need to be integrated over the whole taxiway route and over whole aerodromes. This leads to a number of complications:
  - the model requires knowledge of the length, nature and frequency of use of the taxiways, all of which are aerodrome and taxiway specific, thus making the derivation of generic rules problematic;
  - the precise method of integration requires an improved understanding of the taxiing paths in order to prevent double counting of the overall risk of deviation beyond the taxiway/taxiway separation limits.

Resolution of the above issues is not possible within the constraints of the current project or with the level of data presently available. However, it is noted that the ongoing international studies being undertaken by the FAA and BAA will attempt to address and resolve these problems. Unfortunately the timescales for the completion of these international studies are beyond the timeframe of the Norwegian Aerodrome Rule project. In the meantime, we have presented a simple quantitative assessment of individual taxiway sections in isolation and have provided qualitative consideration of how these risks may be used as the basis for generic design rules.

In particular we have assessed the risks associated with the current Annex 14 recommendations against a defined TLS (as collisions during taxiing are unlikely to lead to catastrophic consequences, a TLS of 5×10^{-6} per movement is suggested). Through consideration of these risks, we conclude that the current Annex 14 recommendations are likely to provide adequate safeguarding for all taxiing operations and that the basis of the current reference system, which defines the taxiway dimensions as a function of aircraft wingspan and wheelspan, is appropriate. Results of the assessment suggest that the risks more closely challenge the TLS for the smaller aircraft (*i.e.* codes A to C), and that the present Annex 14 recommendations are likely to be somewhat cautious for larger aircraft (*i.e.* codes D to F). However, given the uncertainties in the method of assessment and that the taxiway strips provide other forms of protection (*e.g.* safeguarding against FOD engine ingestion) reductions in the taxiway dimensions are not recommended at present.

One important finding from the assessment of the deviation monitoring data is that no strong correlation was found to exist between the aircraft size and the level of deviation from the taxiway centreline. It may be noted that this finding is contrary to the underlying principles on which the Annex 14 taxiway dimensions have been based and this largely explains the higher levels of caution found to exist for taxiways designed for larger aircraft.

Nonetheless, the limitations of the present study are emphasised and it is suggested that the recommended design rules based on this analysis are best viewed as being preliminary and that they should be reviewed at a later date in the light of the findings of the more detailed FAA/BAA studies.

A5.8 SUMMARY AND CONCLUSIONS

A number of key conclusions regarding the development of dimensional design rules for runways, runway strips and RESA have been derived. In particular, with regard to overrun incidents, we conclude that the developed overrun risk model and the assessment of the relationship between residual risk and RESA length provides a sound basis for establishing risk based design rules for RESA provision. However, given the range of risk levels identified for different types of operation, it will be necessary to consider in some further detail the risk management objectives for aerodrome design. In particular we note that, as regards appropriate TLS standards, the possible need to distinguish between the risk applicable to average movements or to those movements most at risk has previously been recognised. The assessment provides an estimate of the range of risks that may need to be accommodated. Other issues which may need to be considered include the use of measures other than aerodrome design to mitigate against overrun risk and the relative effectiveness in reducing risk of RESA provision compared with these other measures. In this context we identify provision of precision approach aids and the use of stricter safety factoring in relation to aircraft runway length requirements as possible measures to address movements at higher risk. These are issues for discussion at part of the project progress review process.

Another point raised by the findings of the risk assessment is the possibility of defining different RESA requirements in respect of mitigation of take-off overrun risk, landing overrun risk and undershoot risk. Residual risks associated with these different incident types for different RESA lengths are summarised in Table A5-14. Landing overrun risk mitigation to a given TLS will typically require a greater length of RESA than take-off overrun risk mitigation to the same level which will in turn require a greater length of RESA than undershoot risk mitigation to that same level.

The current ICAO recommendations provide a combined RESA/runway end length of 180m for Code 1 and 2 aerodromes and 300m for code 3 and 4 aerodrome. Applying the average undershoot frequencies at these distances finds that the frequency of undershoot events is less than 10^{-8} events per landing movements for all aerodrome codes meeting the ICAO recommendations. It is thus concluded that the basis for the longitudinal provision of runway end safety areas is dominated by the overrun risks.

The veer-off risk model has been developed and it has been demonstrated that this model provides a reasonable basis for the development of rules governing the widths of the runway, runway strip and the graded portion of the strip. The following general conclusions are drawn from the risk assessment of veer-off events:

- Veer-off risks are higher for non-precision and visual approach than for precision. This appears to be at particular odds with the runway strip width recommendations of ICAO which require greater strip widths for precision approaches than for visual. However, it is noted the additional extent of the Obstacle Free Zone (OFZ) provided by ICAO for precision approach runways may also be considered to provide protection for the ILS equipment. Additionally, the strip width also provides protection against veer-off during missed precision approach; risk assessment in relation to protection against this type of incident is described in Appendix 6.

- For visual approaches, the frequency of veer-off beyond the runway strip is of the order of 2 x 10^{-6} per landing movement. This is significant in comparison to other risks, such as those associated with overruns.
- Veer-off risks are generally greater for landing than for take-off operations.
- The ICAO recommendations for runway strip width and the width of the graded strip area are defined as a function of the aircraft reference field length and not the aircraft wingspan or wheel track. The analysis presented here suggests that the dependence on the aircraft width dimensions may usefully be incorporated in the runway strip and graded area design rules.

With regard to the definition of the required RESA width, assessment was made of the correlation of veer-off distance with overrun distance. For take-off incidents, no significant correlation was found between the extent of the overrun (measured from the end of the required distance) and the lateral extent of the veer-off. However, a moderate correlation was found when the overrun distance beyond that required was normalised by the required distance. This suggests that any increase in the overrun safety margins for landing operations, should be reflected by a coincidental increase in the veer-off safety margins. In other words, if the length of the RESA is increased to reduce the risk of overruns, then consideration should also be given to increasing the width of the RESA to protect against veer-off risks.

The ICAO recommendation is for a RESA width equal to that of the graded portion of the associated runway strip but not to the full width of the runway strip. That is to say that there is less protection against lateral veer-off beyond the runway end than there is alongside the runway itself. However, our risk analysis suggests that a significant number of overrun incidents involve veer-off beyond the width of the graded area and that a RESA width equal to that of the full width of the runway strip would be required to achieve a safety level of around 10^{-7} per movement.

In summary, the risk models provide a basis for defining risk-based aerodrome design criteria that will achieve a given TLS. The assessment indicates that non-precision/visual movements have an inherently higher risk than precision movements in respect of key accident types and would therefore need greater safety provision from aerodrome design if they are to achieve a given TLS. This is contrary to previous ICAO practice that seems to be developed on the presumption that precision approaches require greater clearances to be provided by aerodrome design. A further key point is that certain higher risk movements would, according to the models, achieve a very much lower level of safety than the average for a given aerodrome design specification. The implications for aerodrome design rule recommendations will be developed further in the subsequent phase of the project.

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Table A5-1 Number of Fatal Accidents per Million Departures (Six-Year Rolling Averages)[a]

Year	Fatal Accidents per Million Departures
1960	5.2
1970	3.5
1980	2.3
1990	1.8
1999	1.3

[a] Data based on world wide schedule operations, excluding CIS/former USSR states.

Table A5-2 "First World" Total Loss Accident and Overrun Rates

	Total loss accident rate		
Aircraft type[a]	Total[b]	Take-off overrun[c]	Landing overrun[d]
Class II-IV Jets	0.15	0.024	0.06
Executive Jets	0.27	0.0432	0.108
Turboprops T1	0.27	0.0432	0.108
Turboprops T2	0.73	0.1168	0.292
Piston-engine	3	0.48	1.2
Miscellaneous	3	0.48	1.2

Notes on Table A5-2.

a. Aircraft types as defined in Reference 11.

b. Total loss accident rate per million movements from Reference 11.

c. Take-off total loss overrun rate per million take-off movements, assuming take-off overruns comprise 8% of total losses, in accordance with Reference 11.

d. Landing total loss overrun rate per million landing movements, assuming landing overruns comprise 20% of total losses, in accordance with Reference 11.

Table A5-3 All Overrun Incident Rates derived from International Accident Rates

Aircraft type[a]	Take-off overrun[b]	Landing overrun[c]
Class II-IV Jets	0.096	0.24
Executive Jets	0.1728	0.432
Turboprops T1	0.1728	0.432
Turboprops T2	0.4672	1.168

Notes on Table A5-3.

a. Aircraft types as defined in Reference 11.

b. Take-off overrun incident rate per million take-off movements, assuming the all overrun incident rate to be 4 times that of overrun total loss rate.

c. Landing overrun incident rate per million take-off movements, assuming the all overrun incident rate to be 4 times that of overrun total loss rate.

Table A5-4 Relative rates for landing and take-off incidents

All Incidents	Landing	Take-off
Number of incidents	168	55
Fraction (%)	75.34	24.66
Relative rate	3.05	1
Jet aircraft incidents	Landing	Take-off
Number of incidents	121	40
Fraction (%)	75.16	24.84
Relative rate	3.03	1
Turboprop incidents	Landing	Take-off
Number of incidents	47	15
Fraction (%)	75.81	24.19
Relative rate	3.13	1

Table A5-5 Relative rates for incidents involving turboprop and jet aircraft

All Incidents	Jet	Turboprop
Number of incidents	161	62
Fraction (%)	72.20	27.80
Relative rate	2.60	1.00
Landing incidents	Jet	Turboprop
Number of incidents	121	47
Fraction (%)	72.02	27.98
Relative rate	2.57	1.00
Take-off incidents	Jet	Turboprop
Number of incidents	40	15
Fraction (%)	72.73	27.27
Relative rate	2.67	1.00

Table A5-6 Extent of damage sustained in overrun incidents

All incidents			
Nature of damage	no.	% of total	% of known
destroyed	29	13.00	17.79
substantial	77	34.53	47.24
minor	31	13.90	19.02
none	26	11.66	15.95
unknown	60	26.91	36.81
Landing incidents			
Nature of damage	no.	% of total	% of known
destroyed	18	10.71	14.63
substantial	61	36.31	49.59
minor	21	12.50	17.07
none	23	13.69	18.70
unknown	45	26.79	36.59
total	168		
Take-off incidents			
Nature of damage	no.	% of total	% of known
destroyed	11	20.00	27.50
substantial	16	29.09	40.00
minor	10	18.18	25.00
none	3	5.45	7.50
unknown	15	27.27	37.50
total	55		

Table A5-7 Lower and upper bounds for Overrun Incident Rates derived from International Accident Rates

Aircraft type	Take-off overrun		Landing overrun	
	lower bound	upper bound	lower bound	upper bound
Class II-IV Jets	0.048	0.12	0.126	0.558
Executive Jets	0.0864	0.216	0.2268	1.0044
Turboprops T1	0.0864	0.216	0.2268	1.0044
Turboprops T2	0.2336	0.584	0.6132	2.7156

TableA5- 8 Numbers of Undershoot Incidents Identified

Database Source	**Total**	**General Aviation/ Other**	**Commercial Carrier (Part 121)**	**Air Taxi/ Commuter (Part 135)**
FIDS	804	767	14	23
NTSB	537	508	4	23
Total	1341	1275	18	46

Table A5-9 Landing Movements by Operation Type under the FAA

	Number of Landing Operations by Type of Operation (Millions)		
Year	**Commercial Carrier[a]**	**Air Taxi[b]**	**Combined**
1975	4.55	-	-
1980	5.16	-	-
1985	5.51	-	-
1990	6.64	4.42	11.1
1991	6.55	4.45	11.0
1992	6.61	4.65	11.3
1993	7.19	4.84	12.0
1994	7.51	5.00	12.5
1995	8.03	-	-
1996	8.20	-	-
1997	8.10	-	-
1998	8.25	-	-
1999	8.47	-	-
2000	8.81	-	-

[a] Data from the US Bureau of Transport statistics
[b] Data from the FAA

Table A5-10 Breakdown of Undershoot Incidents by Aircraft Propulsion Type

Propulsion	No. Incidents	Percentage
Jet	30	64%
Turbo prop	15	32%
Piston	2	45%
Total	47	100%

Table A5-11 Breakdown of Undershoot Incidents by Approach Type

Approach Aid Type	Commercial Carriers and Air Taxi		Commercial Carriers Only	
	Number	**Percentage**	**Number**	**Percentage**
Precision	15	34%	8	62%
Non-precision	2	5%	0	0%
Visual	27	61%	5	38%
Unknown	20	-	5	-
Total	64	100%	18	100%

Table A5-12 Breakdown of Undershoot Incidents by Contributing Meteorological Conditions

Contributing Factor	Number of Incidents	Percentage (of known)
Fog	4	7%
Rain	2	3%
Freezing rain/icing	5	8%
Turbulence	4	7%
Downdrafts	2	3%
Thunderstorm	1	2%
Winds	5	8%
Weather not a factor	37	62%
Unknown	4	-
Total	64	100%

Table A5-13 Breakdown of Undershoot Incident by Consequence

Aircraft Damage			Human Injury		
Category	**Number**	**Percentage**	**Category**	**Number**	**Percentage**
Destroyed	2	3%	Fatal	3	5%
Substantial	24	38%	Serious	3	5%
Minor	25	39%	Minor	2	3%
None	13	20%	None	56	87%
Total	64	100%	Total	64	100%

Table A5-14 Residual Risk Summary for Given RESA length (Risk per million movements for combined runway end strip and RESA length)

Distance	Overrun				Undershoot (Average)
	Take-off	Landing			
		Average	Precision	Non-precision/visual	
0	0.330	1.000	0.600	4.680	0.250
10	0.311	0.922	0.553	4.316	0.185
20	0.294	0.850	0.510	3.980	0.159
30	0.277	0.784	0.471	3.670	0.140
40	0.262	0.723	0.434	3.385	0.126
50	0.247	0.667	0.400	3.121	0.114
60	0.233	0.615	0.369	2.879	0.105
70	0.220	0.567	0.340	2.655	0.096
80	0.207	0.523	0.314	2.448	0.089
90	0.196	0.482	0.289	2.258	0.083
100	0.185	0.445	0.267	2.082	0.077
110	0.174	0.410	0.246	1.920	0.072
120	0.165	0.378	0.227	1.771	0.067
130	0.155	0.349	0.209	1.633	0.063
140	0.147	0.322	0.193	1.506	0.059
150	0.138	0.297	0.178	1.389	0.056
160	0.130	0.274	0.164	1.281	0.053
170	0.123	0.252	0.151	1.181	0.050
180	0.116	0.233	0.140	1.089	0.047
190	0.110	0.215	0.129	1.004	0.044
200	0.103	0.198	0.119	0.926	0.042
210	0.098	0.183	0.110	0.854	0.040
220	0.092	0.168	0.101	0.788	0.038
230	0.087	0.155	0.093	0.726	0.036
240	0.082	0.143	0.086	0.670	0.034
250	0.077	0.132	0.079	0.618	0.033
260	0.073	0.122	0.073	0.570	0.031
270	0.069	0.112	0.067	0.525	0.030
280	0.065	0.104	0.062	0.484	0.028
290	0.061	0.095	0.057	0.447	0.027
300	0.058	0.088	0.053	0.412	0.026
310	0.055	0.081	0.049	0.380	0.025
320	0.052	0.075	0.045	0.350	0.024
330	0.049	0.069	0.041	0.323	0.023
340	0.046	0.064	0.038	0.298	0.022
350	0.043	0.059	0.035	0.275	0.021
360	0.041	0.054	0.032	0.253	0.020
370	0.039	0.050	0.030	0.234	0.019
380	0.036	0.046	0.028	0.216	0.018
390	0.034	0.042	0.025	0.199	0.018
400	0.032	0.039	0.023	0.183	0.017
410	0.031	0.036	0.022	0.169	0.016
420	0.029	0.033	0.020	0.156	0.016
430	0.027	0.031	0.018	0.144	0.015
440	0.026	0.028	0.017	0.133	0.015
450	0.024	0.026	0.016	0.122	0.014

Table A5-15 Number Veer-Off Incidents by Type of Operation

Type of Operation	FIDS	NTSB	Total FIDS/NTSB
All Operations	1161	709	1871
Commercial Carrier	55	11	66
Air Taxi/Commuter	83	36	119
Other	973	659	1632

Table A5-16 Breakdown of Veer-Off Incidents by Consequence Level

Consequence	Take-Off		Landing	
Level	No. of Events	Percentage[a]	No. of Events	Percentage[a]
Destroyed	5	36%	5	17%
Non-destroyed	9	64%	24	83%
Unknown	1	-	21	-
Total	15	100%	50	100%

[a] Percentage of events for which damage level is known

Table A5-17 Residual Risk Summary for Given Runway/Strip Width

Distance	Veer-off			
	Take-off	Landing		
		Average	Precision	Non-precision/visual
30	1.18×10^{-7}	2.76×10^{-7}	1.79×10^{-7}	1.27×10^{-6}
40	1.01×10^{-7}	2.18×10^{-7}	1.42×10^{-7}	1.00×10^{-6}
50	8.62×10^{-8}	1.72×10^{-7}	1.12×10^{-7}	7.92×10^{-7}
60	7.36×10^{-8}	1.36×10^{-7}	8.83×10^{-8}	6.25×10^{-7}
70	6.29×10^{-8}	1.07×10^{-7}	6.98×10^{-8}	4.94×10^{-7}
80	5.37×10^{-8}	8.48×10^{-8}	5.51×10^{-8}	3.90×10^{-7}
90	4.58×10^{-8}	6.69×10^{-8}	4.35×10^{-8}	3.08×10^{-7}
100	3.91×10^{-8}	5.29×10^{-8}	3.44×10^{-8}	2.43×10^{-7}
110	3.34×10^{-8}	4.18×10^{-8}	2.71×10^{-8}	1.92×10^{-7}
120	2.85×10^{-8}	3.30×10^{-8}	2.14×10^{-8}	1.52×10^{-7}
130	2.44×10^{-8}	2.60×10^{-8}	1.69×10^{-8}	1.20×10^{-7}
140	2.08×10^{-8}	2.06×10^{-8}	1.34×10^{-8}	9.46×10^{-8}
150	1.78×10^{-8}	1.62×10^{-8}	1.06×10^{-8}	7.47×10^{-8}
160	1.52×10^{-8}	1.28×10^{-8}	8.34×10^{-9}	5.90×10^{-8}
170	1.29×10^{-8}	1.01×10^{-8}	6.59×10^{-9}	4.66×10^{-8}
180	1.11×10^{-8}	8.00×10^{-9}	5.20×10^{-9}	3.68×10^{-8}
190	9.44×10^{-9}	6.32×10^{-9}	4.11×10^{-9}	2.91×10^{-8}
200	8.06×10^{-9}	4.99×10^{-9}	3.25×10^{-9}	2.30×10^{-8}

Table A5-18 Parameter Values for Fitted CCPD Curves

Fitted curve	Parameter a	Parameter b
Upper bound	-2.17	0.85
Best estimate	-2.17	0.9
Lower bound	-2.17	1.0

Table A5-19 Frequency per Movement of Landing Gear Departing Graded Taxiway Strip

Code/Wheelspan Range		Graded strip width (m)[a]	Frequency deviation beyond graded strip	
			Upper bound curve	Best estimate curve
A	Max wheelspan (<4.5m)	22	1.1×10^{-6}	2.3×10^{-7}
B	Min wheelspan (4.5m)	25	1.5×10^{-7}	2.2×10^{-8}
	Max wheelspan (<6m)	25	4.1×10^{-7}	7.1×10^{-8}
C	Min wheelspan (6m)	25	4.1×10^{-7}	7.1×10^{-8}
	Max wheelspan (<9m)	25	3.0×10^{-6}	7.5×10^{-7}
D	Min wheelspan (9m)	38	7.1×10^{-10}	3.5×10^{-11}
	Max wheelspan (<14m)	38	1.6×10^{-8}	1.5×10^{-9}
E	Min wheelspan (9m)	44	1.8×10^{-11}	4.1×10^{-13}
	Max wheelspan (<14m)	44	3.8×10^{-10}	1.7×10^{-11}
F	Min wheelspan (14m)	60	2.9×10^{-14}	1.4×10^{-16}
	Max wheelspan (<16m)	60	9.1×10^{-14}	6.0×10^{-16}

[a] Annex 14 recommended whole width values

Table A5-20 Frequency per Movement of Wingtip Displacement Beyond Taxiway-Object Separation Distance

Code/Wingspan Range		Separation Distance (m)[a]	Frequency deviation beyond graded strip	
			Upper bound curve	Best estimate curve
A	Max wingspan (<15m)	16.25	1.1×10^{-6}	2.3×10^{-7}
B	Min wingspan (15m)	21.5	1.3×10^{-9}	7.4×10^{-11}
	Max wingspan (<24m)	21.5	4.1×10^{-7}	7.1×10^{-8}
C	Min wingspan (24m)	26	1.3×10^{-9}	7.4×10^{-11}
	Max wingspan (<36m)	26	3.0×10^{-6}	7.5×10^{-7}
D	Min wingspan (36m)	40.5	5.1×10^{-14}	2.9×10^{-16}
	Max wingspan (<52m)	40.5	7.1×10^{-10}	3.5×10^{-11}
E	Min wingspan (52m)	47.5	1.6×10^{-13}	1.2×10^{-15}
	Max wingspan (<65m)	47.5	3.8×10^{-10}	1.7×10^{-11}
F	Min wingspan (65m)	57.5	2.9×10^{-15}	8.4×10^{-18}
	Max wingspan (<80m)	57.5	1.8×10^{-11}	4.1×10^{-13}

[a] Annex 14 recommended values

Table A5-21 Frequency per Movement of Combined Deviation of Aircraft Passing on Parallel Runways Exceeding the Annex 14 Recommended Separation Distance

Code	Maximum Wingspan (m)	Separation Distance (m)	Frequency	
			Upper bound CCPD	Best Estimate CCPD
A	<15	23.75	1.5×10^{-6}	4.1×10^{-7}
B	<24	33.5	5.6×10^{-7}	1.3×10^{-7}
C	<36	44	4.1×10^{-6}	1.4×10^{-6}
D	<52	66.5	1.0×10^{-9}	7.1×10^{-13}
E	<65	80	5.4×10^{-10}	3.4×10^{-11}
F	<80	97.5	2.5×10^{-11}	8.4×10^{-13}

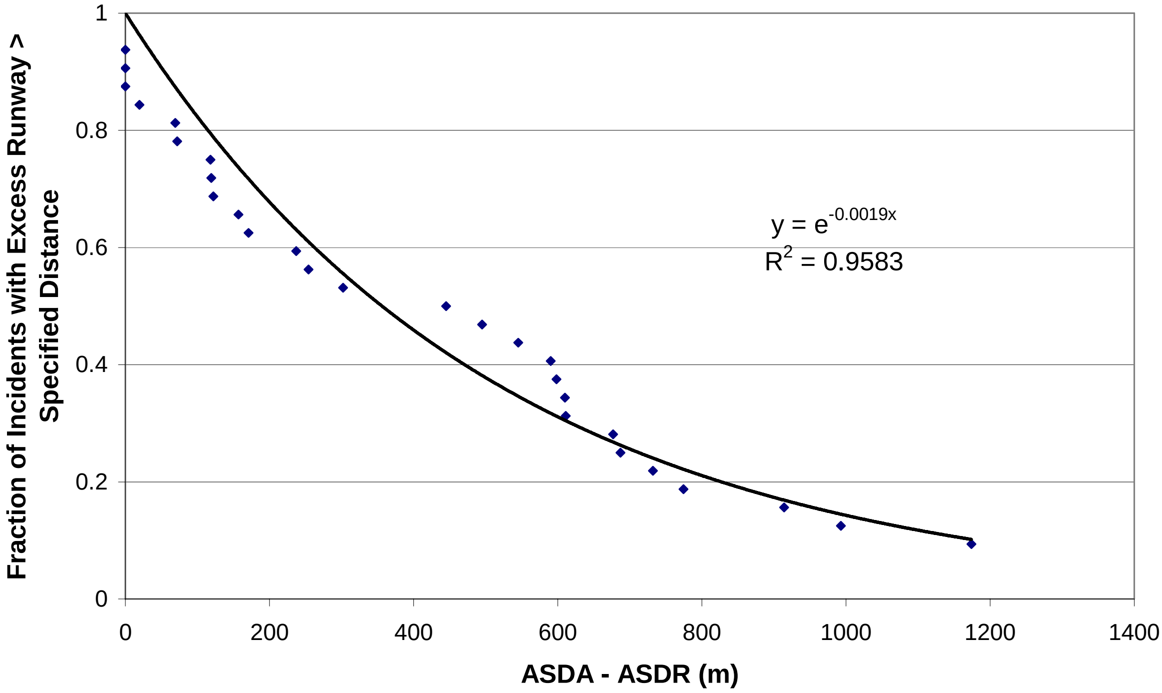


Figure A5-1 Fraction of Take-off Overruns with Excess Runway > Specified Distance

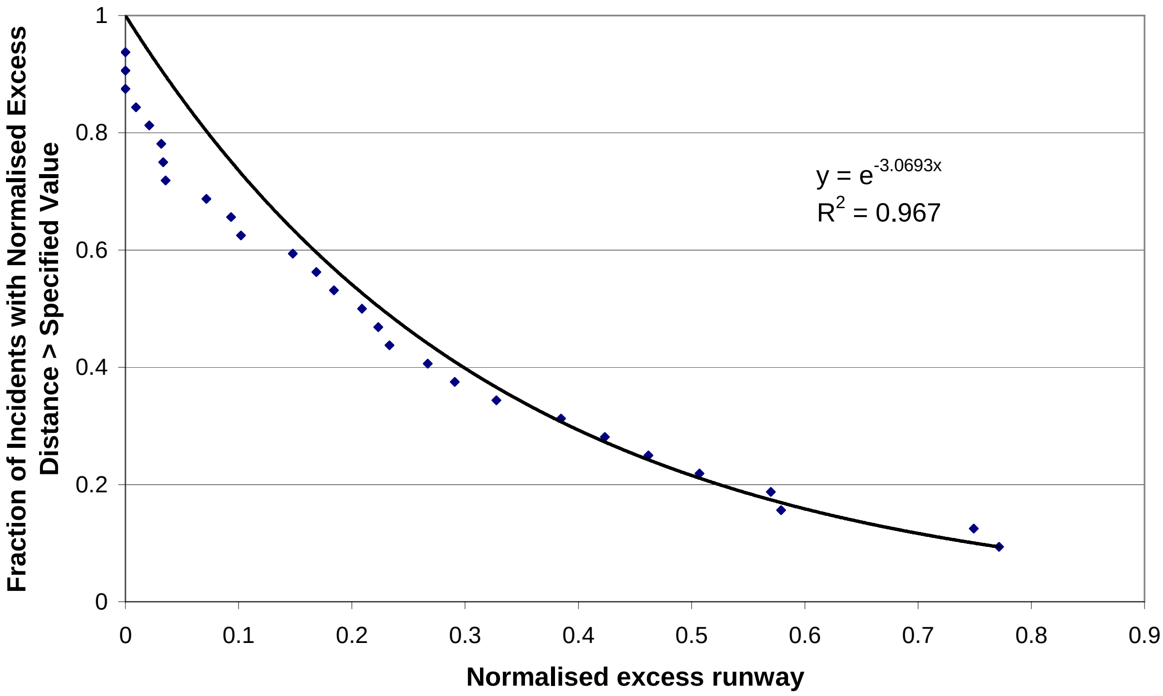


Figure A5-2 Fraction of Take-off Overruns with Normalised Excess Runway > Specified Value

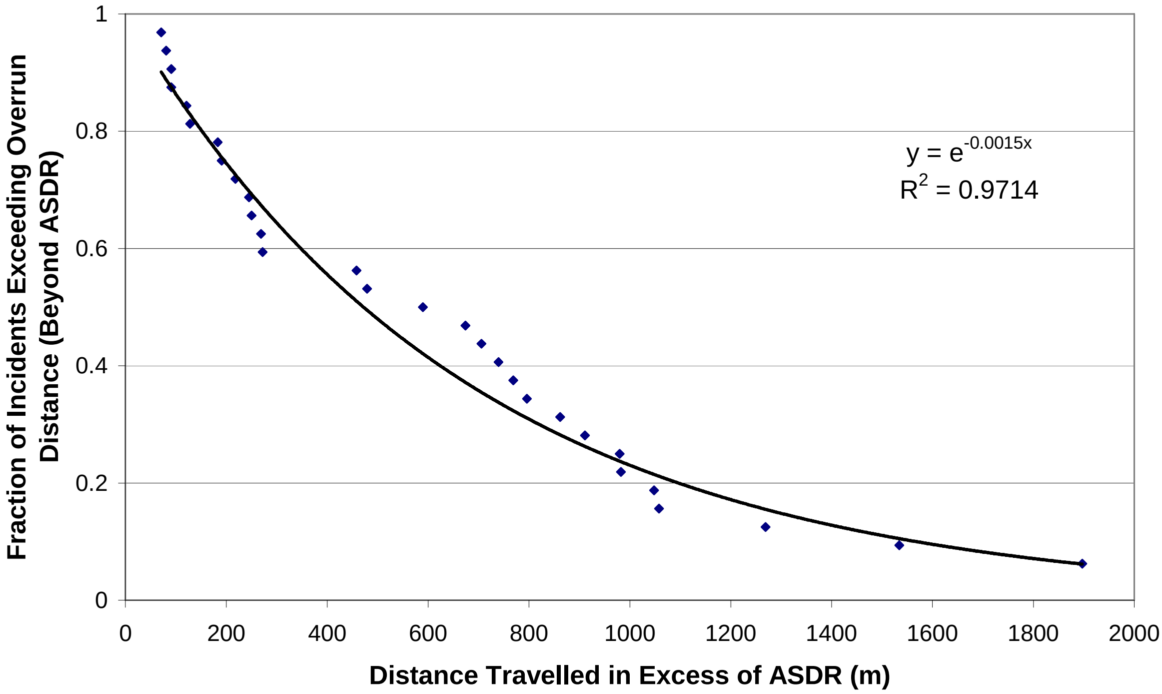
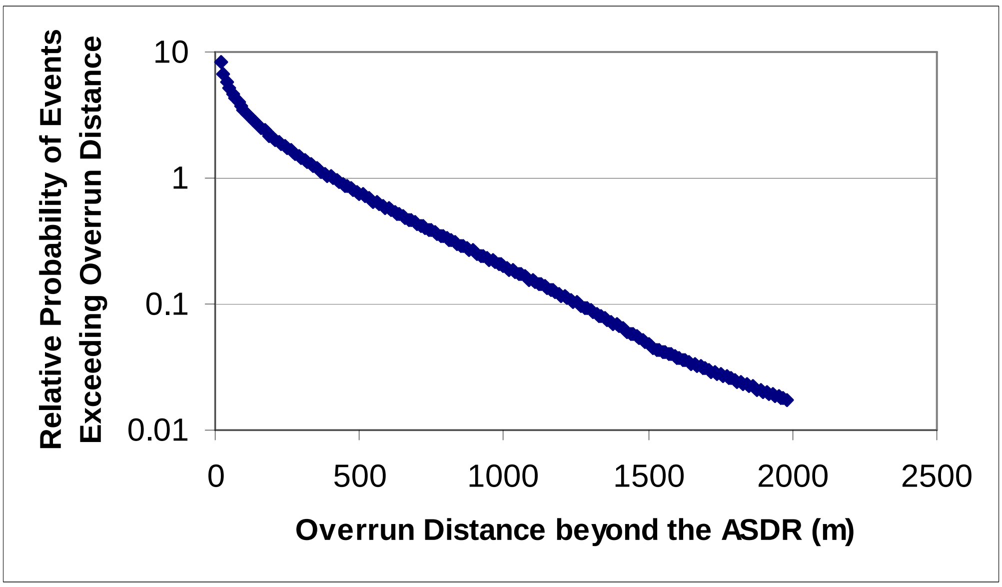


Figure A5-3 CCPD for Overrun Distance for Take-Off Events



FigureA5-4 Relative Probability of Take-Off Overrun Events Exceeding Specified Distance

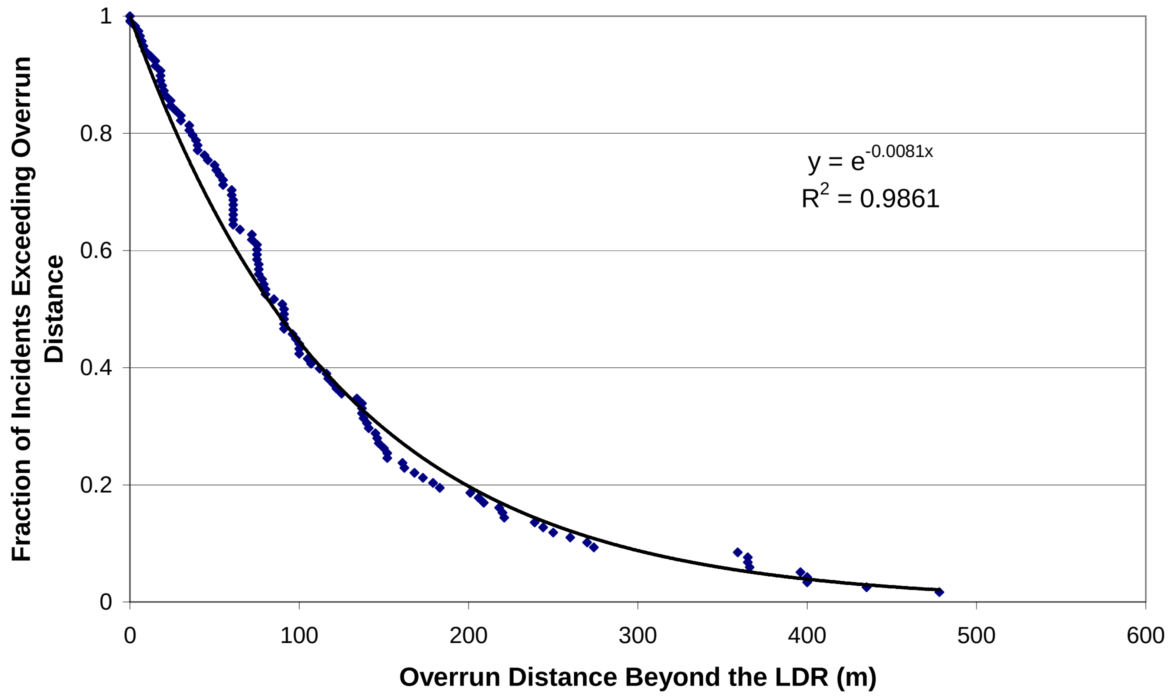


Figure A5-5 CCPD for Overrun Distance for Landings Events

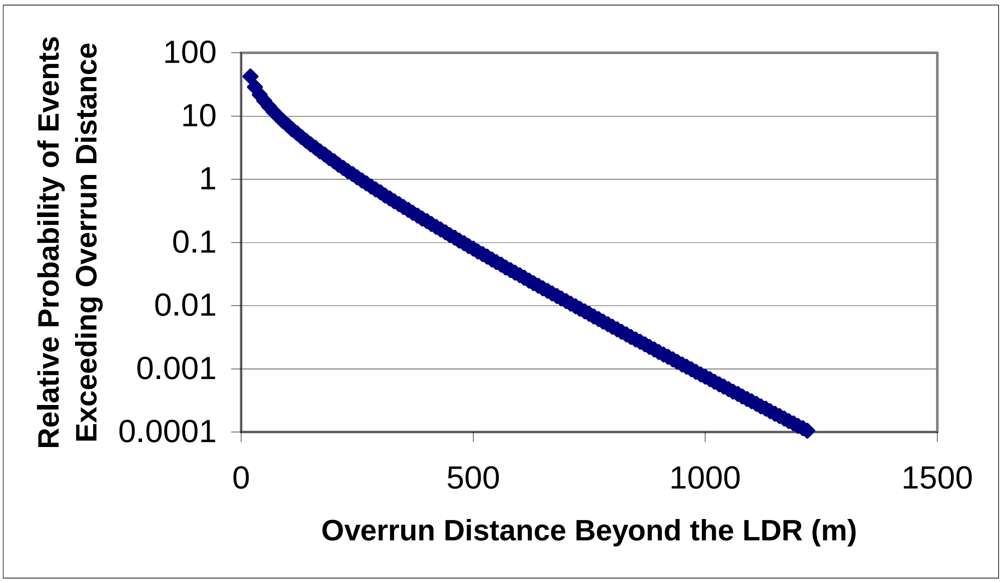


Figure A5-6 Relative Probability of Landing Overrun Events Exceeding Specified Distance

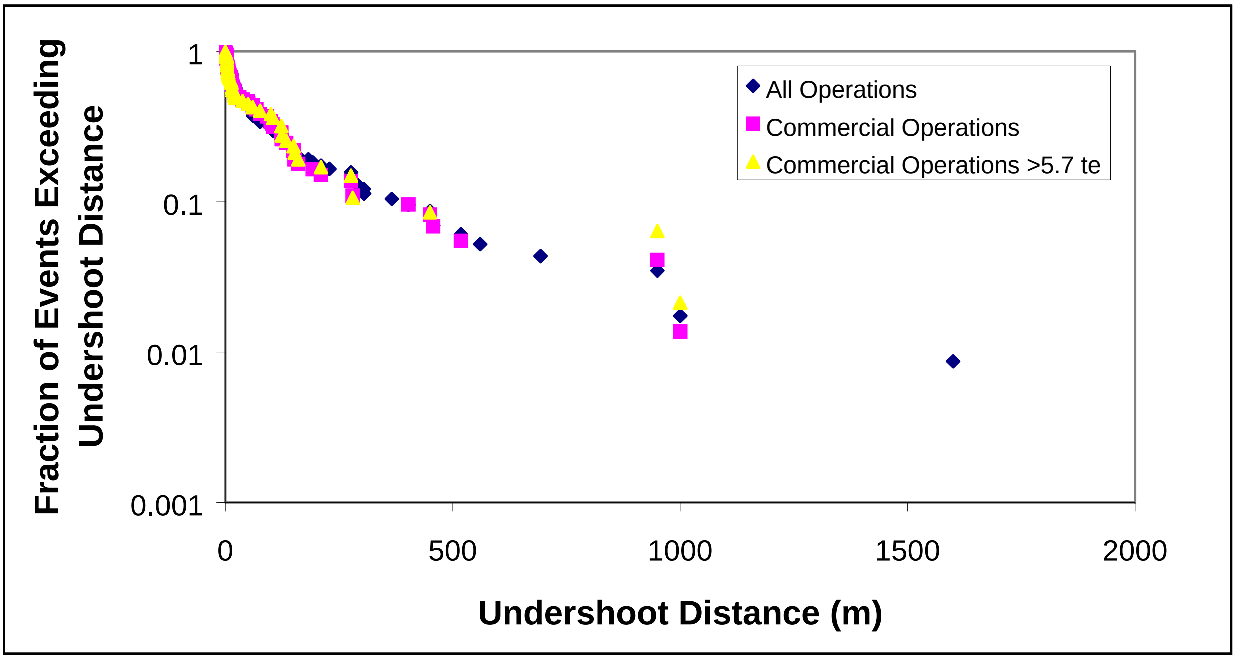


Figure A5-7 CCPD for Undershoot Distance

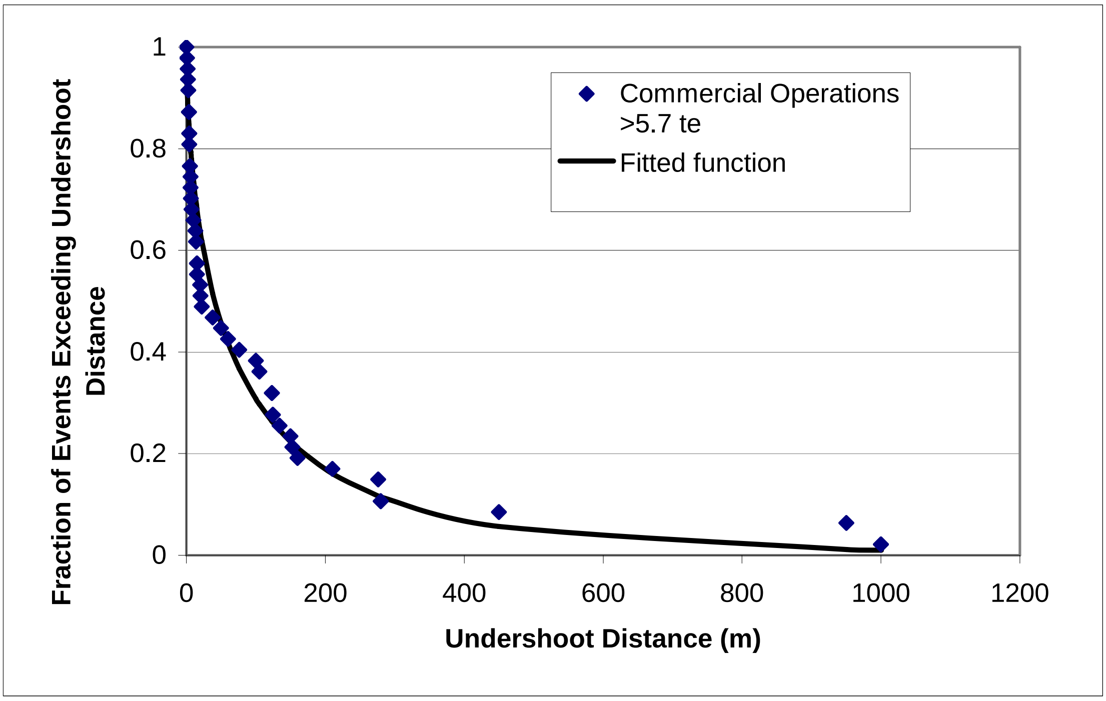


Figure A5-8 Fitted CCPD Function for Undershoot Distance for Commercial Operation Undershoots

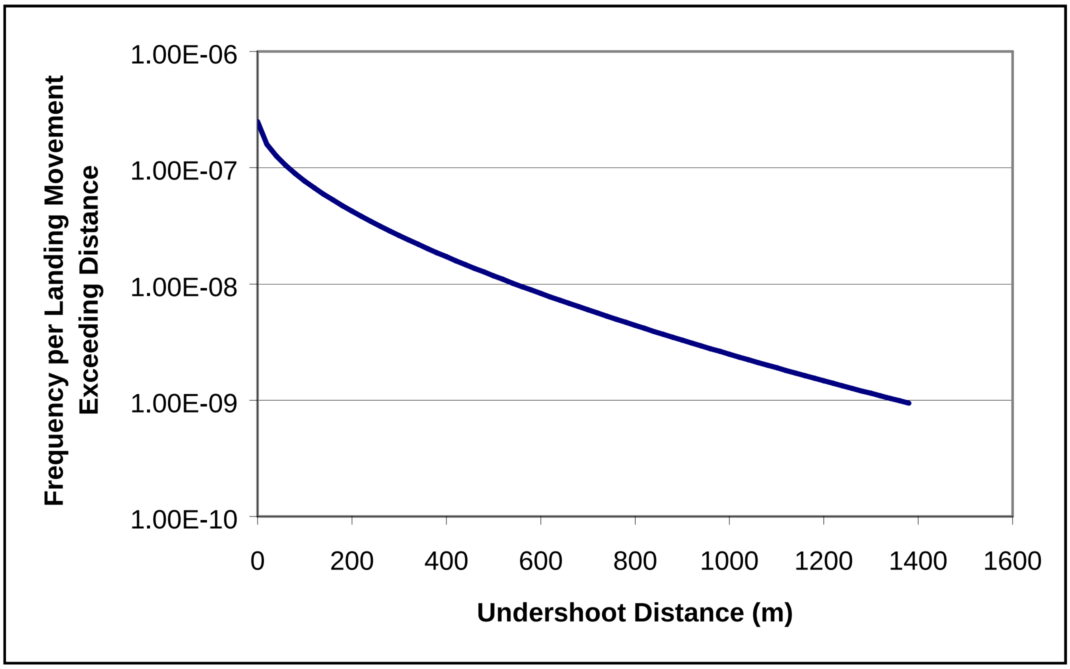


Figure A5-9 Frequency of Undershoot Distance

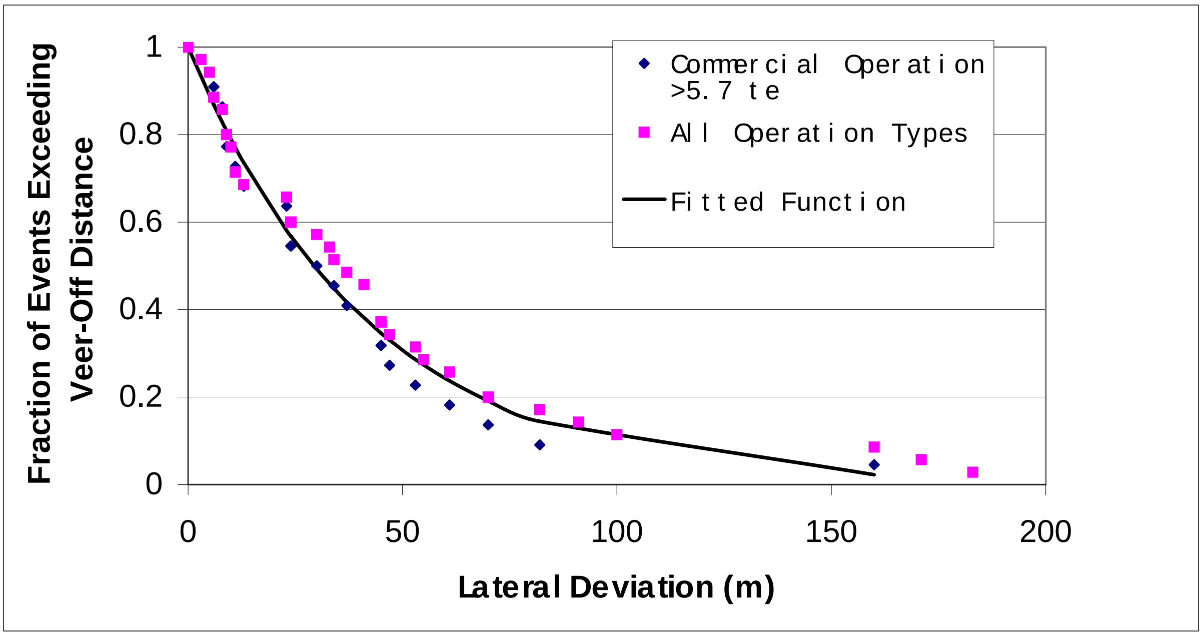


Figure A5-10 CCPD for Veer-Off Distance for Landing Veer Events

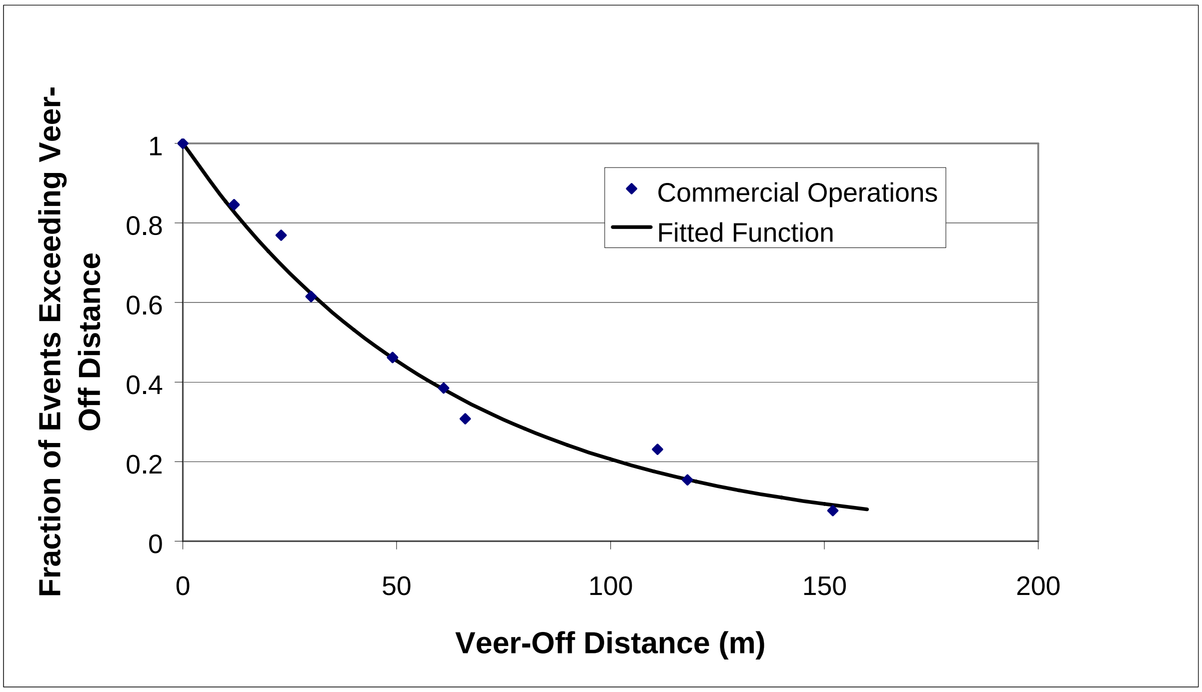


Figure A5-11 CCPD for Veer-Off Distance for Take-Off Veer Events

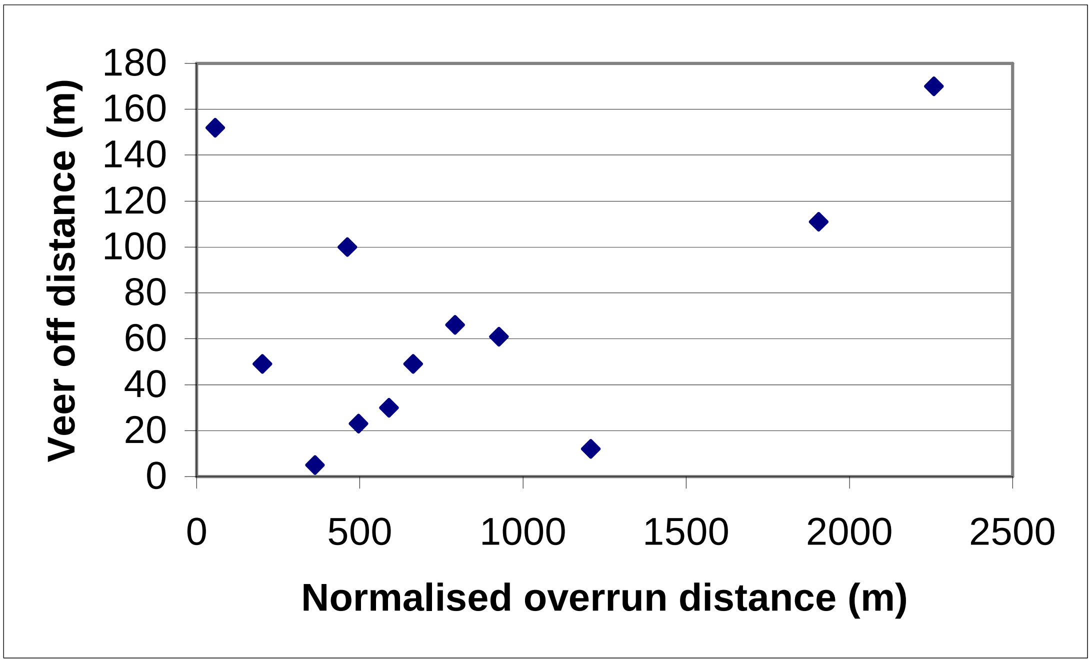


Figure A5-12 Scatter Plot of Veer-off Distance Versus Normalised Overrun Distance

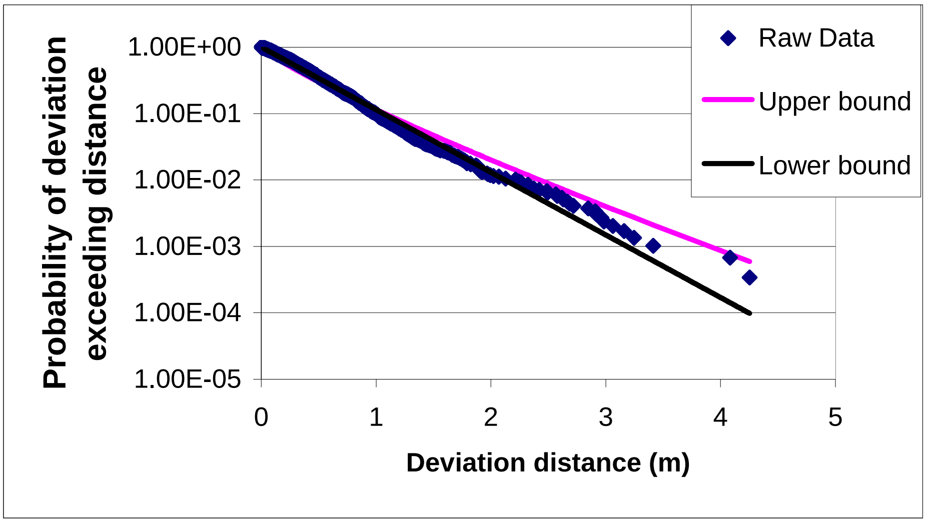


Figure A5-13 Fitted CCPD Curve Bounds

Appendix 6
Obstacle Limitation Surfaces Risk Assessment

Appendix 6: Obstacle Limitation Surfaces Risk Assessment

A6.1 Introduction

This appendix provides an account of the risk analysis undertaken into hazard scenarios associated with airborne operations in the vicinity of an aerodrome. Within this context, an assessment has been made of those risks associated with obstacle collision during airborne operations within the airspace around aerodromes that are protected by the Obstacle Limitation Surfaces (OLS).

Assessment of the risks associated with aircraft deviation during airborne operations is somewhat more complex than is the case with ground operations. For ground operations the risk models described in Appendix 5 have essentially been reduced to consideration of deviations in a single direction. However, for air operations, the deviation needs to be considered for both the vertical and horizontal lateral directions. Furthermore, the range (*i.e.* distance from the runway as measured along the runway extended centreline) on the flight path at which the deviation occurs is also important as this affects the protection offered by the various obstacle limitation surfaces. The data requirements for the development of risk models for airborne operations are therefore more onerous than is the case for ground operations and it is anticipated that a greater degree of extrapolation of available data will be required to construct the risk models for these operations.

This appendix describes the implementation of the modelling approach and presents suggested OLS definitions to meet the required Target Levels of Safety.

A6.2 Background to the OLS

During airborne operations, aircraft may deviate about their intended flight path. This deviation has both a vertical and horizontal lateral component. Within the vicinity of an aerodrome, the intended aircraft altitude is sufficiently low that deviation from the flight path may expose the aircraft to the risk of collision with obstacles, such as terrain, buildings or other man-made structures, that penetrate into the airspace. Review of aircraft accident data from around the world finds that the most common category of total hull loss accidents is Controlled Flight Into Terrain (CFIT). In the period 1989 to 1999 ICAO reported an average of 31 CFIT total hull loss accidents world-wide [1]. Although the percentage of CFIT accidents in Europe is slightly less than for the rest of the world, it is still the most common fatal accident type. It is also reported that the majority of the CFIT incidents occurred during the approach and landing phases. As such it can be seen that such incidents and the aerodrome design rules to safeguard against their occurrence around aerodromes merit consideration within the context of the current project.

In order to control collision risks, 3-dimensional surfaces are defined on and around the aerodrome above which penetration of obstacles is controlled. These surfaces are known as the Obstacle Limitation Surfaces and the various elements that comprise the OLS are defined by ICAO in Annex 14 [2].

A more detailed description of these surfaces has been provided in the Interim Project Report [3] and is not repeated in full here. Nonetheless, the requirements in Annex 14 for the provision of the various surfaces for the different classes of runway are summarised in Table A6-1. Each of these surfaces is devised to safeguard against deviation in the various airborne operations in and around the aerodrome airspace. In the project Functional Hazard Analysis (FHA – see Appendix 4), the key risks associated with aircraft deviation were assessed in relation to the OLS. The following operational modes were identified as being of particular importance:

- Balked landing;
- Landing (defined from the Missed Approach Point (MAPT) to touchdown);
- Approach;
- Missed approach (precision approach only);
- Take-off climb-out.

(The missed approach operations were considered to be important in relation to the OLS for precision approaches only. This is because the minimum decision height for non-precision approaches is well above the height of the inner horizontal surface of 45m and, therefore, intrusions into the OLS affecting such operations are considered to be very unlikely.)

The surfaces associated with safeguarding against deviation risks within each of the above modes of operation were also identified as part of the FHA, and these are summarised in Table A6-2.

The various Annex 14 surfaces are essentially afforded one of three levels of protection:

1. No fixed objects are allowed above the surface except for frangible objects.
2. No new objects are allowed above the surface (unless shielding by existing obstacles can be demonstrated) and it is recommended that existing obstacles above the surface are removed as far as practicable.
3. It is recommended that no new objects are permitted above the surface unless aeronautical studies can demonstrate that the object would not adversely affect safety.

Exceptions to the Annex 14 Standards and Recommended Practices (SARPS) are recorded for each aerodrome in the Norwegian Aerodrome Information Publication (AIP). Review of the Norwegian AIP finds that none of the Annex 14 exceptions reported for the aerodromes relates to the OLS. However, further review of the AIP, in particular the Type A charts, reveals that obstacles exist at a number of aerodromes that penetrate certain elements of the Annex 14 OLS. These include both natural features (*e.g.* terrain) and man-made objects (*e.g.* communication masts). Under the recommendations of Annex 14, aeronautical studies should have been carried out for any new structures that penetrate these surfaces and studies should be undertaken to assess the practicality of removing existing objects. Discussions with NCAA staff suggest that such studies have not previously been undertaken.

The broad purpose of the OLS is to define the volume of airspace that should ideally be kept free from obstacles so as to ensure that the intended aircraft operations at aerodromes are adequately safe and to prevent the aerodromes from becoming unusable by the growth of obstacles around the aerodrome. The OLS are the main safeguarding surfaces for approaching aircraft, either during an entirely visual approach or during the visual segment of an instrument approach.

A second set of surface criteria are also specified by ICAO in PANS-OPS [4] that are intended for use by procedure designers for the construction of instrument flight procedures and for specifying minimum safe altitudes/heights for each segment of the procedure and, for these procedures, the PANS-OPS surfaces can take precedence over the OLS. It may be noted that the PANS-OPS procedures and associated minimum heights may vary with aircraft speed, the type of navigational aid being used, and the equipment fitted to the aircraft. The Annex 14 surfaces, on the other hand, are intended to be of a permanent nature and it is these surfaces that that are enacted as part of national planning consultation schemes. A further distinction between the PANS-OPS and Annex 14 surfaces is that the former guarantees obstacle clearance above the surfaces, while the Annex 14 is essentially used to identify and control obstacles but does not guarantee obstacle-free airspace above the surfaces. Finally, it is noted that PANS-OPS surfaces do not apply to visual approach operations.

The aim of the present project is to assist in the development of aerodrome design rules rather than flight procedures. Therefore, it is the development of permanent surfaces of the type described in Annex 14 (*i.e.* the OLS) that is the aim of the present risk assessment study. It is noted, however, that the dimensional requirements for the surfaces derived in the assessment are based only on physical safeguarding only and do not account for technical safeguarding (*i.e.* protection of CNS system signals). Allowance for technical safeguarding may lead to increased restrictions for certain elements of the OLS.

A6.3 Data Availability

The main source of data for the assessment of deviation during airborne operations is the ICAO Collision Risk Model (CRM) and its underlying data. The Collision Risk Model was developed by the ICAO Obstacle Clearance Panel (OCP) to facilitate the quantitative estimation of the risk of collision of aircraft with obstacles during the precision segment of approach (down to the Obstacle Clearance Height (OCH)) and during missed precision approaches.

The development of the CRM and its underlying data is briefly described here for the approach phase and the missed approach phase in turn:

Precision Approach

As part of the development of the CRM for the precision approach segment, aircraft location monitoring was undertaken at a number of airports world wide in order to develop statistical distributions of aircraft deviations around their intended flight path at various distances from the runway threshold. This data was collated and analysed by members of the OCP and cumulative probability distributions were developed for both lateral and vertical deviation at three points on the precision approach segment, namely: at 1,200m, 4,200m and 7,800m ranges from the runway threshold.

Analysis of the raw monitoring data also enabled separate distributions to be produced for Cat I, Cat II (flight director) and Cat II (autopilot) approaches. For vertical deviations, separate distributions were also developed for three different glide slopes, namely 2.5°, 3° and 3.5°. Each distribution is presented in the CRM manual in tabular format in 0.2 standard deviation increments. The standard deviations for each distribution are presented in Table A6-3.

Missed Approach

Distributions of the lateral and vertical deviations during missed approaches were developed for the CRM from data collected from flight simulator studies and also from theoretical considerations.

For both Cat I and Cat II operations, the simulation study enabled the estimation of the standard deviation of the lateral dispersion of the aircraft from its intended location at a number of range points from the runway threshold. However, the OCP concluded that the sample sizes were insufficient to provide complete information of the distribution shape. It was decided by the OCP members that the distribution shape should be based on the lateral deviation distribution generated for the approach at 1,200m (see above).

For Cat I operations, the vertical deviations are based on a reference OCH of 200 feet and are described as normal distributions. Values of the mean and standard deviation of the aircraft height above the ground have been produced for combinations of glide angle (2.5°, 3° and 3.5°) and touchdown velocity (100kt, 120kt, 140kt and 160kt) for a range of distances from the runway threshold.

For Cat II operations, the vertical deviations are based on a reference OCH of 100 feet. The deviation distributions were found to be best fitted by Johnson SU[1] distributions; the mean and standard deviation of the height above ground level and the values of the four parameters defining the Johnson SU distribution are presented in the CRM manual for a range of distances from the runway threshold.

For balked landing operations data for the assessment of lateral displacement are available from a flight-simulation study to assess lateral deviations during landing operations by the Obstacle Clearance Panel (OCP) Working Group [5]. However, this data is restricted to New Larger Aircraft (NLA) only and therefore provides only limited information, particularly in relation to operations at many Norwegian aerodromes. The OCP study comprised an assessment of the lateral deviation of Boeing 747s during balked landing operations (including incidents of landings balked after touchdown). The study used a B747-400 flight simulation model to represent the performance of New Larger Aircraft (NLA) on approach. The model requires a variety of input parameters such as:

- Aircraft related data (weight, centre of gravity, airspeed);
- Instrument Landing System (ILS) variables;
- Runway related inputs (*e.g.* runway length, elevation and surface condition);
- Meteorological data (*e.g.* wind speed and heading); and,
- Balked landing related data inputs (*e.g.* go-around initiation point).

[1] The Johnson SU distribution is a hyperbolic transformation of the normal distribution.

Certain input parameters were considered to be constant for the assessment, for example those relating to the aircraft specific data (representative data for B747-400s were assumed) and the runway specific data. Other parameters were considered to be variable, and their values were selected from assumed probability density functions using a Monte Carlo sampling scheme. Variable parameters considered in the study included wind speed and direction, turbulence, ILS error sources and Flight Technical Error (FTE) sources. For each simulation model run, a Monte Carlo sample was taken from each input variable and the simulated flight track was used to assess the lateral deviation of the aircraft during balked landings at different altitudes.

The study found that the lateral spread of the aircraft location is contained within a ±10m deviation from the runway centreline with a probability of 10^{-7}. The authors extrapolate from this to claim that the wingtips of an 80m wingspan NLA will not deviate more than ±50m from the centreline with a probability of 10^{-7}. While this work is seen as valuable in the development of a collision risk model for landing veer-off, the following points are noted:

- The sampling of the model input variables appears to be a straightforward Monte Carlo method. However, the key interest in the study output is on the extreme (*i.e.* low probability) levels of lateral deviation. As such it is considered that a sampling scheme that places greater emphasis on the tails of the input variable PDF's, such as Latin Hypercube Sampling, would have been more appropriate.
- The assessment has been based on flight simulation for a single aircraft, the B747-400 (with a 65m wingspan aircraft). However, it would be difficult to justify the extrapolation of the findings of this study to other aircraft, particularly lighter and/or older aircraft without further detailed assessment. (Though it may be noted that the authors of the OCP study implicitly assumed that the level of deviation of the B747-400 may be applied equally to larger NLA, *i.e.* no correlation is assumed between deviation and differences in aircraft characteristics.)

For the other relevant operations, *i.e.* landing and take-off, incident data has been sought from the following databases:

- the FAA incident database;
- the CAA incident database; and,
- the ICAO ADREP incident database.

However, review of these databases has shown that deviation data for air operations is generally sparse, particularly for the reporting of relevant details in incidents (more detailed data is generally available for accidents). Other sources of information, for example aircraft tracking during landing and take-off for noise monitoring purposes are currently being investigated.

Due to the current lack of data, extrapolation from the CRM has been required to form the basis of the deviation PDFs for the landing phase (below the OCH) for precision approaches. However, such extrapolation is not readily possible for each non-precision and visual approach nor for take-off operations.

A6.4 Development of Risk Targets

Recognising the apportionment of the total risk between hazards, a basic benchmark risk "target" of 10^{-8} to 10^{-9} accidents per movement for any given aerodrome design related hazard has been proposed for the fatal accident rate in Appendix 2. It proposed that this should be taken as a preliminary basis of the Target Level of Safety (TLS) for airborne collision risks. While this provides the basis for the TLS benchmark, the actual TLS needs to be developed with consideration of the level of safety that is practically achievable by the provision of the OLS. We note that CFIT accidents are a primary contributor to the total hull loss rate of 2 x 10^{-7} per movement and that, without very significant increases in the areas protected by the current OLS, it may be impracticable to expect to meet a TLS significantly below 10^{-7} per movement. Additionally, it is noted that ICAO utilise a TLS of 10^{-7} collision per approach operation for the assessment of obstacle risks with the CRM and the TLS to be used in the current project may sensibly use this value as a higher bound.

A6.5 Precision Approach, Landing and Missed Approach

A6.5.1 Overview

The aircraft deviation functions developed for the CRM have been used as the basis for assessing the frequency with which various OLS are impinged during approach and missed approach operations. By undertaking this assessment, we can define the characteristics of the various surfaces that are required to ensure that the risk of collision with obstacles contained within the limits of these surfaces meets the Target Level of Safety (TLS). By undertaking the assessment under cautious assumptions, we can define the OLS such that all obstacles contained below the surfaces pose acceptable risks during approach and landing operations without the need for case specific aeronautical studies. In this way, OLS may be defined such that they act as appropriate surfaces for the identification of obstacles for the design of operating procedures and also provide screening criteria for planning purposes.

As described earlier, deviation distributions during approach and missed approach operations have been developed for the CRM as a function of a range of parameters:

- Precision approach segment.
  - Lateral deviation as a function of range from runway threshold and approach type (Cat I, Cat II flight director and Cat II autopilot);
  - Vertical deviation as a function of glide angle, range and approach type.
- Precision missed approach.
  - Lateral deviation as a function of range from runway threshold and approach type;
  - Vertical deviation as a function of glide angle, range, Velocity at Threshold (VAT), Obstacle Clearance Height (OCH) and approach type.

In order to develop cautious OLS, the assessment has been undertaken assuming pessimistic though nonetheless realistic operational characteristics. In particular, the risk of vertical deviation below the approach surface has been assessed assuming a relatively low glide angle of 2.5° as well as the common 3° glide slope, as this represents a higher risk approach type. For missed approach operations, the risks of a combined vertical and lateral deviation impinging on the transitional/inner transitional surfaces have been estimated assuming:

- a relatively steep glide slope of 3.5°;
- a relatively high VAT of 160kt; and,
- an OCH of 200 feet for Cat I approaches and 100 feet for Cat II approaches.

These characteristics will result in the aircraft flying closest to the ground and hence more significantly within the funnel prescribed by the transitional surfaces.

In assessing the risk of penetrating the OLS we need to consider the overall risk of penetration over the whole of the relevant section of the flight path. However, in doing this, consideration needs to be made of the possible path prescribed by the deviating aircraft in order to ensure that the risk of penetration is estimated without double counting. Following the methodology developed in the CRM, surfaces are described by a series of vertical plane obstacles positioned perpendicular to the flight path and at 100m intervals. The “shadowing” of each obstacle by preceding obstacles is taken into account. Following the CRM, the following shadow angles are assumed:

- 25.2% lateral shadow angle for all phases of the flight;
- 0.5% vertical shadow angle for the approach phase; and
- 0% vertical shadow angle for the missed phase (reflecting the upward movement of the aircraft for much of this phase).

In order to assess the OLS required to maintain approach, landing and missed approach operations within the TLS, the underlying aircraft deviation data have been utilised rather than the CRM software model itself. The reasons for this are twofold:

- For the approach/landing phase, we wish to assess the required surfaces down to touchdown – this requires an extrapolation of the CRM below the OCH.
- For the missed approach phase, the angled sides of the transitional slope surface cannot be modelled by the CRM software as it only has the functionality to model vertically sided obstacles.

The assessments have therefore been undertaken using specifically developed Excel-based software tools.

A6.5.2 Precision Approach and Landing

The Annex 14 OLS offer protection to approach and landing aircraft via the approach and inner approach surfaces. For Cat I approaches for runway codes 1 and 2, the approach surface comprises two elements; for all other precision approaches the surface comprises three elements. The dimensions of these surfaces are summarised in Table A6-4.

As an initial assessment of the frequency with which aircraft penetrate these surfaces, the risks have been assessed at the three points at which aircraft deviation data is available in the CRM, namely at 7,800m, 4,200m and 1,200m ranges from the runway threshold.

The risks of penetrating beyond the lateral extent of the approach surface are presented in Table A6-5 as a function of aircraft wingspan (the wingspans shown represent the maximum wingspans in each of the aircraft code letters A to F). It can be seen that the risk of lateral veer-off beyond the approach surface is small, suggesting that the current Annex 14 recommendation of a divergence angle of 15% provides a more than adequate safety margin in comparison to the TLS. It is noted that if this angle were reduced to 10% (*i.e.* lowest angle for any surface Annex 14 and equal to the requirement for the take-off surface at code 1 & 2 runways and the approach surface for non-instrument runways), the risk of aircraft deviation laterally beyond the surface edge is estimated to be within 1 x 10^{-8} per movement in all cases (and generally very much lower). Even allowing for the integration along the length of the approach track, these risks would remain within the TLS of 1 x 10^{-7} per movement. However, a reduction in the approach surface divergence should be made allowed provided that this can also be justified from a technical safeguarding perspective.

The risks of penetrating vertically below the approach surfaces at these points are shown in Table A6-6 for three separate glide slope angles. It can be seen that the frequency of penetration below the approach surface is greater than 1 x 10^{-7} per movement, particularly for the less stringent surfaces for Cat I code 1 & 2 runways, and for the shallow approach angle of 2.5°. For Cat I code 3 & 4 and Cat II operations, the risk of penetration diminishes at the larger ranges. This is not the case for Cat I code 1 & 2 operations and reflects the two rather than three stage surface. The risks at the further distances for this case would be reduced to be within 1 x 10^{-7} per movement if a third, horizontal surface element were adopted.

Nonetheless, the risk of vertical penetration of the approach surface merits further assessment, particularly within the final approach and landing segment. With this in mind, the risk of penetration of the first element of the approach surface has been assessed in further detail (*i.e.* between 3000m and the runway threshold), including consideration of the whole of the flight path in this segment. The surface in this segment has been modelled as a series of obstacles at 100 metre intervals that together form the approach slope. Between the ranges of 3000m and 1200m, the assumed standard deviation of the aircraft location around its intended path is interpolated from standard deviation values presented in the CRM for the 4200m and 1200m ranges. At the start of the approach surface, the standard deviation of the aircraft location is inferred from previous assessment of undershoot distance (the undershoot distance distribution was modelled as having an exponential form – see Appendix 5). The standard deviation at each point between the runway threshold and the 1200m range point is then estimated by interpolation. The shape of the vertical position distribution was taken to be the same as that at 1200m for all distances between 3000m and the runway threshold.

The frequency of penetration of the first approach surface (per movement) based on the Annex 14 standard approach surface dimensions is presented in Table A6-7 for the different types of precision approach and for different intended glide slopes. It should be noted that these frequencies provide a conservative estimate of the *collision* risks associated with vertical deviation below the surface, as the assessment is based on the assumption that the volume under the surface is comprised entirely of solid obstacles; in reality, of course, only a portion of this volume will contain obstacles. Similarly, this risk assessment does not take account of operational procedures (based on PANS-OPS) to control collision risks. As such, the tolerable risk of penetration of this surface may be higher than our basic TLS (of between 10^{-7} and 10^{-8}). Nonetheless, it can be seen from review of the results presented in Table A6-7,that the current approach surface does not provide adequate protection against collision with obstacles below this surface for certain operations. As such, the surface as presently defined by Annex 14 may not be considered to provide an adequate base level of safety and obstacles below this surface cannot be assumed to pose negligible collision risks without further assessment.

Additionally, it is noted that the risks are considerably higher for Cat I code 1 & 2 runways. This suggests that the less restrictive approach surface gradient for this category may not be justified. The gradient of the first approach surface required to meet target penetration frequencies of 10^{-6} and 10^{-7} per movement respectively for Cat I and Cat II operations are shown in Table A6-8. Notwithstanding the conservative nature of the assessment, the results presented in this table show that the slope gradient required to ensure penetration risks are within the TLS are very shallow for certain types of operation, particularly low glide scope (*i.e.* 2.5°) approach and for Cat I approaches.

It is suggested that a practical way forward may be to define the approach surface requirements as a function of approach type and also for a minimum glide slope angle. For the approach type, the CRM data only distinguishes between Cat I, Cat II Flight Director and Cat II Autopilot. The risks are similar for the two Cat II types of operation, with the Flight Director operations having the generally high levels of deviation. It is therefore suggested that a single approach surface be defined for Cat II, but that this is based on the Flight Director risk assessment. For Cat I operations, the CRM data does not distinguish between runways designed for different aeroplane reference codes. Without such information it is difficult to justify the use of different approach slope definitions for codes 1&2 and codes 3&4 as is presently the case in Annex 14. It is therefore suggested that a single approach slope surface is defined for all Cat I approach operations.

Finally, Cat III approaches are not considered within the CRM data. Nonetheless, it is reasonable to consider that such operations maintain the aircraft on its intended path at least as accurately as in Cat II operations. It is therefore suggested that the approach surface definition for Cat III operations is the same as for Cat II (this is as presently assumed in Annex 14).

Suggested appropriate approach surface definitions are presented in Table A6-9 applicable to precision approaches with glide slope angles equal to or greater than 3°. It is suggested that where aerodromes wish to operate with glide slopes below 3°, separate and operation specific aeronautical studies are required.

A6.5.3 Precision Missed Approach

The key surfaces that protect against collision during missed precision approach are the approach and inner approach surfaces, the transitional and inner transitional surfaces and the inner horizontal surface. During the phase of the missed approach between the missed approach point and the runway threshold, it is considered reasonable to assume that the approach and inner approach surfaces required to protect normal landing operations (as discussed in the section above) will be sufficient also to protect missed approach operations in this region. This is because the intended path during missed approach operations will be significantly higher than for normal approach/landing. Also, CRM data on the level of lateral deviations in this phase are relatively small and thus well protected by the approach surface width.

However, as an aircraft travels further along its missed approach path, its vertical and lateral deviations increase. In this phase, the aircraft is protected against collision risks by the presence of the transitional surfaces (and hence the inner horizontal surface which forms the upper bound of the transitional surface). The dimensions of these surfaces that are required in order to maintain collision risks to tolerable levels have been assessed using the lateral and vertical deviation distributions developed in the CRM for this type of operation.

As noted earlier, the risks of a combined vertical and lateral deviation during missed approach operations impinging on the transitional/inner transitional surfaces have been estimated under the following cautious assumptions:

- a glide slope of 3.5°;
- a VAT of 160kt; and
- an OCH of 200 feet for Cat I approaches and 100 feet for Cat II approaches.

When estimating the risks per operation for missed approaches, it is required that the frequency per approach with which a missed approach is undertaken is known. In the CRM, it is assumed that this frequency is 10^{-2} per approach. However, review of incident records from the FAA FIDS incident database and other incident frequency analysis [6] suggests that the actual frequency is more likely to be in the region of 10^{-4} per approach and this frequency rate has been adopted in the current study.

The inner transitional surface is intended to be the controlling obstacle limitation surface for navigation aids, aircraft and other vehicles that must be near the runway. This surface runs along the edge of the runway strip and slopes perpendicularly away from the runway (the current Annex 14 gradient for this slope is 40% for Cat I codes 1&2 and 33% for Cat I, II & III codes 3&4) until it meets the inner horizontal surface (Annex 14 sets the height of the inner horizontal to 45m for all precision runways). The transitional surface, on the other hand, is more restrictive surface (Annex 14 recommends or requires a slope of 14.3% for all precision runways) that is intended to control other types of obstacles, such as buildings.

Because of this distinction in the type of obstacles that these surfaces are intended to control, it was decided that:

- The assessment of the inner transitional surface was best undertaken by consideration of the risk of the aircraft penetrating this surface at single points along the missed approach flight path. This approach was adopted as, in reality, only a very limited number of obstacles may be present close to the limit of the inner transitional surface.
- The assessment of the transitional surface would be undertaken by consideration of the risk of the aircraft penetrating any part of the surface. This approach was adopted to reflect the fact that obstacles, such as stand buildings, may theoretically occupy a much higher proportion of the volume bounded by the transitional surface.

The frequencies of missed approach aircraft penetrating the inner transitional surface were assessed at 100m intervals beyond the runway threshold. The maximum of these values is taken for comparison with the required TLS. The maximum frequencies of penetration of the inner transitional surface (per approach operation) are presented in Table A6-10 for a range of aircraft codes for the current Annex 14 inner transitional and inner horizontal surface recommendations/requirements. It should be noted that Annex 14 distinguishes between codes 1&2 and codes 3&4 in its requirements for the inner transitional. However, according to the CRM, the level of deviation is independent of code number but the collision risks are dependent on the wingspan (and hence the code letter) as this determines the position of the outer wingtip. Hence, Table A6-10 presents the penetration risks for a range of code letter wingspans.

It can be seen from Table A6-10 that the current Annex 14 inner transitional surface dimensions provide adequate protection against the risk of collision with ILS instrumentation and aircraft *etc*. Nonetheless, it is noted that use of a less restrictive surface gradient (combined with a less restrictive strip width) for the code 1&2 runways results in a much lower safety margin for this type of runway. It is suggested that the inner transitional surface dimensions are made consistent across all code numbers. However, some breakdown of requirements between different code letters may be beneficial.

For Cat II missed approaches, the risk of penetration of the inner transitional surface is higher, due to the lower assumed OCH (100 feet compared with 200 feet for Cat I operations). It is noted that the frequency of penetration for larger wingspan aircraft (*e.g.* code E) is around 10^{-9} per approach. Given that the geometry of any obstacle will not be such that it butts up to the inner transitional surface along its entire height and, further that transitory obstacles such as other aircraft will not be present during all missed approach operations, this represents a cautious estimate of any actual collision risk. Additionally, the penetration risks are dominated by penetration of the surface at heights between 35m and 45m above the ground and this suggests that the surface provides adequate protection against collision with other aircraft and ground vehicles even for larger wingspan aircraft and also ILS equipment which will not reach this lower height. It may be noted that the penetration risks may be reduced by around one order of magnitude if the inner transitional surface truncated at a height of 35m and a new horizontal surface at this height connected the top of the inner transitional surface to the slope of the transitional surface (see Figure A6-1 for a cross-sectional view).

The risk of penetration of the transitional surface has been assessed through consideration of the total penetration risks along the whole of the transitional surface. The frequency of penetration of the transitional surface during missed-approach (per approach) are presented in Table A6-11, based on the current ICAO recommendations and requirements for the dimensions of the inner horizontal and transitional surfaces and the runway strip width. Given the generally cautious nature of this assessment, it can be seen that the existing transitional surface definition provides adequate protection to aircraft during precision missed approaches to a target level of 10^{-8} per approach (and generally very much lower risk levels). However, it is again noted that there is no justification based on the CRM data in providing a distinction between code 1&2 and code 3&4 runways as the key driver behind the risks is the aircraft code letter (based on the wingspan).

A6.6 Assessment of Other Operational Phases

A6.6.1 Balked Landing

The transitional and inner transitional surfaces, together with the strip width, also provide protection against collision for aircraft during balked landing operations. Data for the assessment of lateral deviation during landing operations, including balked landings, has been assessed from flight-simulation studies by the Obstacle Clearance Panel (OCP) Working Group [5]. The OCP study comprised an assessment of the lateral deviation of Boeing 747s during balked landing operations, including incidents of landings being aborted after touchdown. The study found that the lateral deviation from the runway centreline is contained within a ±10m deviation from the runway centreline with a probability of 10^{-7} per landing operation. Even for a wingspan of 80m, this would mean that the outer wing tip of the aircraft would remain comfortably within the 150m runway strip required for code 3&4 runways at a TLS of 10^{-7}. For code 1&2 runways, the largest aircraft code letter identified is D which, at most, equates to a wingspan of 52m. This means that the outer wing tip is displaced by 36m at the 10^{-7} frequency level and this level of deviation is contained within the current Annex 14 recommendation of a 75m strip width.

It is not clear over what flight height ranges these results apply. However, in the current absence of further information, we may assume that the lateral deviations at higher flight levels as the aircraft pulls away from the ground are similar to the levels of deviation found during missed approaches (see above). Under this assumption we may tentatively suggest that the dimensions suggested above for the inner transitional and transitional surface may provide adequate collision protection.

Nonetheless, a number of reservations have been identified with regard to the use of the OCP data, in particular with regard to the method of sampling and the extrapolation of 747 data to other aircraft (see above). It should therefore be noted that all recommendations regarding the OLS in relation to balked landing are prone to high levels of uncertainty. In order to provide more assurance in this area, further data collection studies, for example flight simulation studies, would be required.

A6.6.2 Take-off

At present, insufficient data are available to enable a detailed quantification of the deviation risks during take-off to be made. Efforts made by the NCAA and AEA Technology project team to identify and obtain such information, for example from aircraft tracking studies, have been unsuccessful on the timeframe of the current project. Nonetheless, some consideration of the requirements of the take-off surface can be made, at least with regard to vertical displacement, through consideration of the frequency of engine out scenarios.

Multiple-engine aircraft are required to be capable of achieving a minimum take-off gradient in the event of a single engine failure. Typically, this minimum ascent gradient is 1.2%. Review of engine failure incidents during take-off has been made using the online FAA FIDS and NTSB accident and incident databases. Since 1978, 58 such incidents have been recorded, which equates to an estimated frequency of 4×10^{-9} engine failure incidents per take-off operation. Allowing for non-reporting of such incidents, we may cautiously assume a frequency of 10^{-8} per take-off. Assuming that aircraft will obtain a climb gradient of 1.2% in such circumstances, a take-off surface gradient of this value would represent a reasonable level of protection.

This would also have the benefit of providing consistency between the OLS take-off surface and the AIP Type A chart obstacle identification surfaces; given the use of the OLS for planning purposes, this consistency would ensure that all proposed new obstacles penetrating the Type A chart surfaces would be caught in the aeronautical safety aspects of the planning process.

A6.6.3 Non-Precision and Visual Approaches

Within the CRM, data are only available for precision approaches and it is difficult to extrapolate this data to assess the risks associated with non-precision and visual approaches. Nonetheless, some general points are offered:

- In the initial stages of approach below the minimum decent height for visual and non-precision approaches, the aircraft will have good visual contact with the aerodrome to ensure collision risks with obstacles are well managed. As such, the use of less restrictive approach surfaces in Annex 14 for these types of operations than for precision approaches may be justified.
- However, the higher instance of overrun and undershoot for non-precision/visual approach suggests than the touchdown position of the aircraft in these operations is less accurate than is the case for precision approach. This suggests that the vertical and lateral deviation of the aircraft in the segment prior to touchdown is greater for non-precision/visual landings than for precision. This further suggests that the first approach surface should, in fact, be more restrictive for these operations than for precision approach landing. This is contrary to the Annex 14 requirements.

A6.7 Conclusions

Data on aircraft deviation during precision approach and missed approach has been identified from the CRM. This data has been used as the basis of risk-based assessment of the frequency with which aircraft penetrate the relevant OLS intended to protect the aircraft from collision with obstacles in these flight phases. From the performance of these analyses, OLS have been defined such that the risk of collision with obstacles that exist up to the limit of the surfaces is within the target level of risk of 10^{-7} per approach operation.

For precision approach, the risk of lateral veer-off beyond the approach surface is small, suggesting that the current Annex 14 recommendation of a divergence angle of 15% provides a more than adequate safety margin in comparison to the TLS. It is also noted that if this angle were reduced to 10% (*i.e.* equal to the Annex 14 requirement for the take-off surface), the risk of aircraft deviation laterally beyond the surface edge is estimated to be within 1 x 10^{-8} per movement in all cases (and generally very much lower). However, a reduction in the approach surface divergence should be made allowed provided that this can also be justified from a technical safeguarding perspective.

For vertical deviation during approach, the risks of penetration below the approach surface are more significant. At distances further out, the risks of deviation below the approach surfaces are small in comparison to the TLS, except for Cat I code 1&2 operations and it has been noted that these risks may be suitably reduced by making the dimensions of this surface consistent with those required by Annex 14 for other types of precision approach.

The risks of deviation below the approach surface are greater within the final approach segment below the OCH and the touchdown point. Detailed assessment of these risks has been undertaken, and recommendations have been made regarding the approach surface gradients required to meet the TLS. In particular it is noted that:

- the less restrictive OLS definition for Cat I code 1&2 runway approaches is not supported by the assessment based on the CRM aircraft deviation data.
- glide slopes below 3° may require very restrictive approach surface gradient in order to meet the TLS.

For missed precision approach operations, the key OLS are identified as the inner transitional and transitional surfaces, the inner horizontal surface and the runway strip width. The CRM aircraft deviation data has been used as the basis of the risk-based derivation of suitable definitions of these surfaces. The assessment has found that the current Annex 14 inner transitional surface dimensions provide adequate protection against the risk of collision with ILS equipment and aircraft *etc* for Cat I operations. However, it is noted that the less restrictive surface gradient required for code 1&2 runways, combined with the shorter strip width requirements for these runways, results in a much lower safety margin. It is suggested that the inner transitional surface dimensions are made consistent across all runway code numbers to remove this anomaly.

For Cat II approach the risk of penetration of the inner transitional surface is greater (though still well within the TLS) due to the lower OCH assumed in the assessment. It is suggested that the risk may be suitably maintained within the TLS by truncating the inner transitional surface to 35m (from the Annex 14 height of 45m).

Assessment of the risk of aircraft penetrating the transitional surface during missed approach operations has found that the existing Annex 14 surface requirements provide adequate protection relative to the TLS. However, it is noted that there appears to be no justification based on the CRM data in providing a distinction between code 1&2 and code 3&4 runways. For the transitional surfaces, a key driver behind the risk of penetration is the wingspan of the aircraft. It may therefore be beneficial to consider defining separate dimensions for these surfaces for different aircraft wingspans (and hence runway code letters).

The transitional and inner transitional surfaces, together with the strip width, also provide protection against collision for aircraft during balked landing operations. Data for the assessment of lateral deviation during landing operations, including balked landings, has been assessed from flight-simulation studies by the Obstacle Clearance Panel (OCP) Working Group [5]. This study found that the lateral deviation from the runway centreline is contained within a ±10m deviation from the runway centreline with a probability of 10^{-7} per landing operation. Even for a wingspan of 80m, this would mean that the outer wing tip of the aircraft would remain comfortably within the 150m runway strip required for code 3&4 runways at a TLS of 10^{-7}. Nonetheless, a number of reservations have been identified with regard to the use of the OCP data, in particular with regard to the method of sampling and the extrapolation of 747 data to other aircraft. It should therefore be noted that all recommendations regarding the OLS in relation to balked landing are prone to high levels of uncertainty. In order to provide more assurance in this area, further data collection studies, for example flight simulation studies, would be required.

For take-off operations, little data has been identified for the performance of a quantified risk assessment of the collision risks. However, arguments based on the frequency with which single engine failures occur during take-off of multiple engine aircraft are made which suggest that a take-off surface gradient of 1.2% may represent a reasonable level of protection based on the requirement of aircraft to achieve this minimum take-off gradient in engine-out conditions.

Within the CRM, data are only available for precision approaches and it is difficult to extrapolate this data to assess the risks associated with non-precision and visual approaches. Nonetheless, some general points are offered:

- In the initial stages of approach below the minimum decent height for visual and non-precision approaches, the aircraft will have good visual contact with the aerodrome to ensure collision risks with obstacles are well managed. As such, the use of less restrictive approach surfaces in Annex 14 for these types of operations than for precision approaches may be justified.
- However, the higher instance of overrun and undershoot for non-precision/visual approach suggests that the touchdown position of the aircraft in these operations is less accurate than is the case for precision approach. This suggests that the vertical and lateral deviation of the aircraft in the segment prior to touchdown is greater for non-precision/visual landings than for precision. This further suggests that the first approach surface should, in fact, be more restrictive for these operations than for precision approach landing. This is contrary to the Annex 14 requirements.

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Table A6-1 Summary of ICAO OLS Provision Requirements

Surface Type	Non-Instrument	Non-Precision Approach		Precision Approach	
		Code # 1, 2	Code # 3,4	Category I	Category II, III
Conical	Required	Required	Required	Required	Required
Inner horizontal	Required	Required	Required	Required	Required
Approach	Required	Required	Required	Required	Required
Transitional	Required	Required	Required	Required	Required
Inner approach	-	-	-	Recommended	Required
Inner transitional	-	-	-	Recommended	Required
Balked landing	-	-	-	Recommended	Required
Take-off climb[1]	Required	Required	Required	Required	Required

[1] The take-off climb surface is only required for runways meant for take-off

Table A6-2 Summary of Key Surfaces by Air Operation Mode

Surface	Take-off	Approach	Missed Approach	Landing	Balked landing
Conical	4	4			
Inner horizontal	4		4		4
Approach		4	4	4	4
Transitional	4		4	4	4
Inner approach				4	4
Inner transitional	4		4	4	4
Balked landing					4
Take-off climb	4				

Table A6-3 Standard Deviation of aircraft Displacement During Precision Approach

ILS Category	Range (m)	Lateral Displacement (m)	Vertical Displacement (m)		
			2.5° Glide Path	3° Glide Path	3.5° Glide Path
Cat I	1,200 4,200 7,800	16.4 35.9 67.5	4.9 11.3 22.8	5.8 13.6 27.4	6.8 15.9 31.9
Cat II Flight Director	1,200 4,200 7,800	11.4 23.7 41.9	4.5 7.7 16.9	5.3 9.2 20.3	6.1 10.8 23.7
Cat II Autopilot	1,200 4,200 7,800	11.4 16.8 29.7	3.7 5.2 10.4	4.4 6.3 12.4	5.1 7.3 14.5

Table A6-4 Annex 14 Approach Slope Dimensions

	Cat I codes 1&2	Cat I codes 3&4	Cat II
Divergence	15%	15%	15%
Dist from threshold	60	60	60
Length of inner edge	150	300	300
Length 1st section	3000	3000	3000
Slope 1st section	2.5%	2%	2%
Length 2nd section	12000	3600	3600
Slope 2nd section	3%	2.5%	2.5%
Length 3rd section	-	8400	8400
Slope 3rd section	-	0%	0%

[1] All distances in metres

Table A6-5 Risk of lateral Penetration of the Approach Surface (Incidents per Movement) at Set Range Points

Cat I Codes 1&2					
Code	A	B	C	D	E
1200m range	5.50 x 10^{-13}	7.69 x 10^{-13}	1.51 x 10^{-12}	2.95 x 10^{-12}	5.82 x 10^{-12}
4200m range	<9.63 x 10^{-16}	<9.63 x 10^{-16}	<9.63 x 10^{-16}	<9.63 x 10^{-16}	<9.63 x 10^{-16}
7800m range	<9.63 x 10^{-16}	<9.63 x 10^{-16}	<9.63 x 10^{-16}	<9.63 x 10^{-16}	<9.63 x 10^{-16}
Cat I Codes 3&3					
Code	A	B	C	D	E
1200m range	<6.88 x 10^{-16}	<6.88 x 10^{-16}	<6.88 x 10^{-16}	1.45 x 10^{-15}	3.02 x 10^{-15}
4200m range	<9.625 x $^{-16}$	<9.625 x $^{-16}$	<9.625 x $^{-16}$	<9.625 x $^{-16}$	<9.625 x $^{-16}$
7800m range	<5.01 x 10^{-16}	<5.01 x 10^{-16}	<5.01 x 10^{-16}	<5.01 x 10^{-16}	<5.01 x 10^{-16}
Cat II Flight Director					
Code	A	B	C	D	E
1200m range	<7.62 x 10^{-16}	<7.62 x 10^{-16}	<7.62 x 10^{-16}	<7.62 x 10^{-16}	<7.62 x 10^{-16}
4200m range	<3.38 x 10^{-19}	<3.38 x 10^{-19}	<3.38 x 10^{-19}	<3.38 x 10^{-19}	<3.38 x 10^{-19}
7800m range	<6.88 x 10^{-20}	<6.88 x 10^{-20}	<6.88 x 10^{-20}	<6.88 x 10^{-20}	<6.88 x 10^{-20}
Cat II Autopilot					
Code	A	B	C	D	E
1200m range	<7.62 x 10^{-16}	<7.62 x 10^{-16}	<7.62 x 10^{-16}	<7.62 x 10^{-16}	<7.62 x 10^{-16}
4200m range	<2.36 x 10^{-15}	<2.36 x 10^{-15}	<2.36 x 10^{-15}	<2.36 x 10^{-15}	<2.36 x 10^{-15}
7800m range	<4.10 x 10^{-17}	<4.10 x 10^{-17}	<4.10 x 10^{-17}	<4.10 x 10^{-17}	<4.10 x 10^{-17}

Table A6-6 Risk of Vertical Penetration of the Approach Surface (Incidents per Movement) at Set Range Points

Cat I Codes 1&2			
Distance	2.5° Glide Slope	3° Glide Slope	3.5° Glide Slope
1200m range	3.19×10^{-04}	9.19×10^{-06}	2.04×10^{-07}
4200m range	1.94×10^{-06}	9.06×10^{-09}	2.05×10^{-10}
7800m range	1.37×10^{-05}	8.70×10^{-08}	1.43×10^{-09}
Cat I Codes 3&4			
Distance	2.5° Glide Slope	3° Glide Slope	3.5° Glide Slope
1200m range	1.58×10^{-05}	3.50×10^{-07}	1.27×10^{-08}
4200m range	9.00×10^{-09}	1.00×10^{-10}	1.12×10^{-11}
7800m range	1.22×10^{-09}	3.39 x 10-11	4.37×10^{-12}
Cat II Flight Director			
Distance	2.5° Glide Slope	3° Glide Slope	3.5° Glide Slope
1200m range	1.37×10^{-07}	4.05×10^{-10}	1.35×10^{-11}
4200m range	7.27×10^{-13}	5.57×10^{-15}	1.80×10^{-16}
7800m range	1.60×10^{-13}	2.08×10^{-15}	4.46×10^{-17}
Cat II Autopilot			
Distance	2.5° Glide Slope	3° Glide Slope	3.5° Glide Slope
1200m range	3.65×10^{-08}	8.97×10^{-11}	3.75×10^{-12}
4200m range	1.90×10^{-17}	8.62×10^{-18}	9.17×10^{-18}
7800m range	1.94×10^{-16}	1.67×10^{-16}	1.28×10^{-16}

Table A6-7 Integrated Risk of Vertical Penetration of the First Approach Surface (Incidents per Movement)

Approach Type	2.5° Glide Slope	3° Glide Slope	3.5° Glide Slope
Cat I codes 1&2	3.42×10^{-03}	5.69×10^{-05}	1.70×10^{-06}
Cat I codes 3&4	1.85×10^{-04}	2.90×10^{-06}	1.11×10^{-07}
Cat II Flight Director	2.76×10^{-06}	5.59×10^{-09}	1.71×10^{-10}
Cat II Autopilot	9.38×10^{-07}	1.71×10^{-09}	4.71×10^{-11}

Table A6-8 Required Approach Surface Gradient to Meet Set Risk Levels

	2.5° Glide Slope		3° Glide Slope		3.5° Glide Slope	
Approach Type	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-7}	1×10^{-6}	1×10^{-7}
Cat I	1.1%	0.7%	1.9%	1.4%	2.5%	2%
Cat II Flight Director	1.9%	1.5%	2.8%	2.5%	3.5%	3.1%

Table A6-9 Suggested Approach Slope Definitions[1] for Glide Slopes ≥ 3°

	Cat I codes 1&2	Cat II	Cat III
Divergence	10%	10%	10%
Dist from threshold[2]	60	60	60
Length of inner edge[2]	150	300	300
Length 1st section	3000	3000	3000
Slope 1st section[3]	1.4% (1.1%)	2.5% (1.9%)	2.5% (1.9%)
Length 2nd section	3600	3600	3600
Slope 2nd section	2.5%	2.5%	2.5%
Length 3rd section	8400	8400	8400
Slope 3rd section	0%	0%	0%

[1] All distances in metres
[2] The definition of the start and inner edge length are defined by the runway strip in Annex 14. It is suggest that where changes to the strip dimensions are suggested in the current study the distance from the threshold of the approach surface remains at 60m as extending this would lead to reduced lateral deviation protection. Additionally, it is recommended that the inner edge length is set to the determined strip width, but with minimum values as shown in the above table.
[3] Values in brackets show suggested gradients for glide slopes between 2.5° and 3°.

Table A6-10 Frequency of Missed Approach Penetration of the Inner Transitional Surface[b] (per Approach)

	Aircraft Code Letter (and max wingspan (m) for code)				
Approach Type	A (15m)	B (24m)	C (36m)	D (52m)	E (65m)
Cat I codes 1&2	1.47×10^{-10}	1.97×10^{-10}	2.66×10^{-10}	4.24×10^{-10}	-[a]
Cat I codes 3&4	1.16×10^{-12}	1.35×10^{-12}	1.76×10^{-12}	2.64×10^{-12}	3.94×10^{-12}
Cat II codes 3&4	4.04×10^{-09}	4.68×10^{-09}	5.87×10^{-09}	7.84×10^{-09}	1.03×10^{-09}

[a] No code E aircraft have been identified for codes 1&2
[b] Assessment based on current Annex 14 recommendations and requirements for the inner transitional and inner horizontal surfaces and the strip width.

Table A6-11 Integrated Frequency of Missed Approach Penetration of the Transitional Surface[b] (per Approach)

	Aircraft Code Letter (and max wingspan (m) for code)				
Approach Type	A (15m)	B (24m)	C (36m)	D (52m)	E (65m)
Cat I codes 1&2	5.95×10^{-13}	9.36×10^{-13}	1.72×10^{-12}	4.13×10^{-12}	-[a]
Cat I codes 3&4	7.18×10^{-15}	8.04×10^{-15}	9.60×10^{-15}	1.28×10^{-14}	1.68×10^{-14}
Cat II codes 3&4	7.99×10^{-11}	9.81×10^{-11}	1.23×10^{-10}	1.92×10^{-10}	2.60×10^{-10}

[a] No code E aircraft have been identified for codes 1&2
[b] Assessment based on current Annex 14 recommendations and requirements for the inner transitional and inner horizontal surfaces and the strip width.

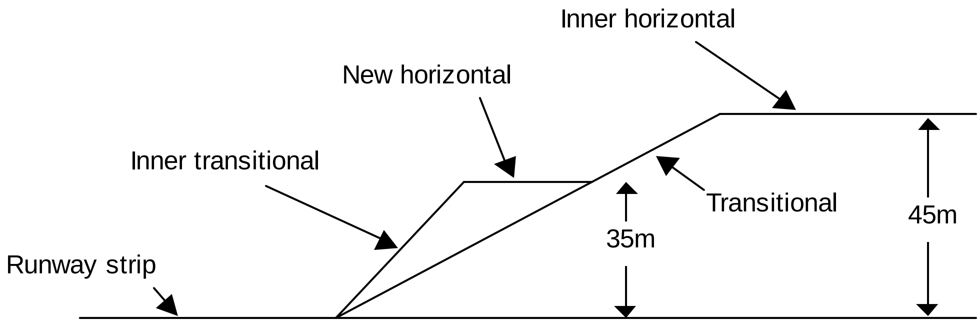

Figure A6-1 Cross Section of Suggested New Inner Transitional Horizontal Surface