Risk analysis study on the need for a runway surface friction layer

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ABSTRACT: Significant extension and widening of the runway was undertaken at an existing airport with infrequent scheduled Boeing 747 operations and Airbus A380 alternate operations. The airport was in a very dry climatic region. The new runway did not fully comply with ICAO requirements in terms of a flatter transverse slope. The new asphalt surfacing was well below ICAO requirements in terms of macrotexture and friction. Despite the dry climate, there was a risk to aircraft operations in wet weather. The risk analysis related relevant operational hazards to runway design features. The analysis included target levels of safety, functional hazard analysis to identify the hazards to operations, and the development of a quantitative risk model. This allowed the characterisation of risk in terms of the likelihood of occurrence of hazard scenarios such as runway over-run, the location of an aircraft during such an event in relation to the intended path, the safety margin provided by the relevant aerodrome design feature, and the severity of the incident consequences.

KEY WORDS: Runway, friction, risk, hazard, overrun.

1 BACKGROUND

A major upgrade to an existing airport included significant extension and widening of the existing single runway, together with an asphalt overlay on the existing runway. The runway was extended to a length of 3440m and a width of 60m, to ICAO 4F classification (suitable for the Airbus A 380 aircraft). The new runway has full instrument landing facilities.

The new asphalt overlay was a continuously graded hotmix. The design did not include the provision of a friction layer such as open graded asphalt or grooving of the continuously graded asphalt. This was justified on the basis of the very low rainfall at the airport. However later consideration of friction issues initiated this in-depth risk analysis on the need for a runway surface friction layer or treatment at the airport.

The airport serves the local region, as well as acting as an international alternate airport. It is lightly trafficked, with less than 0.25 million passengers per year. It is served by a single scheduled Boeing 747 per week, and several daily Boeing 737, regional jet and turboprop services. As a diversion airport, it takes Boeing 747, 777 and Airbus A340 aircraft, and is planned to take Airbus A380 aircraft.

The climate is warm and arid (Koppen’s classification BWk: desert climate – cool and dry). Significant climatic aspects which impact on operations include fog, wind, and sand. Climatic data over 12 years gave the daily rainfall range as 0-21mm, with a mean of 0.027mm/day.

Statistical analysis based on a Beta distribution gave the probability of 1mm rain in a day as 0.4%. Fog/sea mist is very common, as is reduced visibility due to blowing sand. The visibility is less than 800m for 8.7% of weather observations (15991 datasets). In ICAO (2004) Annex 14, Attachment A, section 7.6, it is noted that: “it may be known that under unusual conditions, such as after a long dry period, the runway may have become slippery”. The ruling climatic condition at this airport can be stated to be “dry with heavy morning mist” and it could be postulated that both dry and wet conditions as contemplated may well prevail. The probability of a cross-wind of 27 kph (15 knots) or more was low at 0.6%.

2 RUNWAY GEOMETRICS AND FRICTION

The airport was an ex-military one, and the existing runway did not meet ICAO standards, which is not uncommon. The extension was built to the same geometric standard as the existing runway. The runway transverse slope was 0.6%, which does not comply with ICAO Annex 14 recommendations for a transverse slope of 1.0-1.5%.

The new asphalt overlay had poor friction and macrotexture. For friction measurement, wet Griptest values were determined on the new asphalt, and the minimum recorded was 0.22 and the maximum was 0.80. The average value of each run ranged from 0.4 to 0.6 at 65 kph, and 0.3 to 0.5 at 95 kph. ICAO have set the design objective for a new surface using the Griptester at 65kph and 95kph to be higher than 0.74 and 0.64 respectively, which clearly was not met. The macrotexture minimum was 0.16mm and the maximum was 0.49mm. ICAO Annex 14 recommends that the average surface texture depth of a new surface should be not less than 1.0 mm, and again this was not met.

3 RISK ANALYSIS

A hazard and risk analysis was undertaken of the wet weather friction issues at the airport. Australian standard AS 4360:1999 Risk Management is one of a number of similar hazard and risk analysis techniques in use in aviation, and was used here.

The process related the risk associated with relevant operational hazards with the design features that provide protection against those hazards. In this study, the hazard was poor wet weather friction, but the same process could be applied to other aerodrome design elements such as RESA length. The analysis considered the implications of proceeding with or without a runway surface friction layer/treatment given the flat cross-fall, poor friction and inadequate macrotexture. It started with a function hazard analysis to identify the risks, and then a quantitative analysis to assess the risk level.

3.1 Functional Hazard Analysis

Functional Hazard Analysis (FHA) 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 study was to determine relevant hazards to aircraft associated with aerodrome operations (e.g. approach, landing, taxiing, take-off roll, and associated fault sequences) which involve the friction and macrotexture of pavements on aerodromes. The FHA enabled the identification of the associated controls currently (or potentially) in place to manage these hazards.

The hazard analysis process identified all the possible hazards in each operational phase, and there were 64 in total. Then each hazard was 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, using the usual risk matrix. From the risk matrix, the identified hazards were ranked as being of either high, medium or low risk. The hazards were then prioritised for each operational mode.

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 provided the insight to support the quantitative risk analysis. For this airport, the generic types of causal factors of most significance are summarised in Table 1.

Table 1: Summary of most significant FHA hazard causal factors

Operational mode	Key generic hazard causal factors	
Takeoff roll	Loss of friction Fog Foreign object debris Too fast for abort Wind	Communication misunderstanding Bright sunlight Aircraft performance characteristics
Rejected takeoff	Surface contaminants High momentum Jet reverse thrust less effective than turboprop Crosswinds	Fog & darkness Bright sunlight Crew Low momentum
Landing	Crosswinds High momentum Wind shear Impaired visibility	Loss of aircraft flaps No reverse thrust Information accuracy Variable winds

It is evident that there are quite a number of risks that exist at the airport, and that mitigation measures are needed in terms of providing “Good Wet (and dry) Friction and Texture for Stopping” and “Uniform Friction for Veer-Off”.

3.2 Quantitative Risk Analysis

3.2.1 Generic rate of overrun

The quantitative risk analysis was based on the assessment of the probability of overrun and the subsequent risk of injury and damage, using historical accident data. A database consisting of 180 cases was used, that was normalised due to the effects of terrain, aircraft performance and required distances on the accident locations. This data is based on all turbine powered aircraft overruns in native English speaking countries from 1980 to 1998. The description of the database is in Kirkland and Caves (2002), and the detail of the data normalisation is described in Kirkland et al. (2003).

Given that ICAO aerodrome regulations are typically followed closely by native English speaking countries, with generally a high level of enforcement and compliance, it is considered likely that this database consists of runways which meet ICAO requirements. Some adjustment was needed to apply this data to the scenario at this airport where the ICAO runway requirements are not met. Further adjustment was needed for the differences in weather between the airports in the database (primarily Europe) and this airport.

Analysis of the database by Kirkland et. al (2004) found the main influencing factors of overrun accidents to be:

- operating weight of the aircraft relative to its maximum allowable weight;
- the amount of runway available in excess of that required (as calculated in accordance with normal operating practices);
- approximately 50% of overrun landings and 20% of takeoff overruns involved a tailwind;
- poor weather (precipitation and/or poor visibility) and its effect on runway condition appeared likely to induce overruns, particularly after landings;
- fast and high approaches that continued to an attempted landing are frequently a feature of landing overruns.

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 MTOW, an overrun incident rate of 1.02×10^{-6} overrun incidents per movement was presented by the CAA (1997) in its draft working paper on overrun risk. Further analysis of this and other data yielded the following estimated overrun rates for jet and turboprop passenger aircraft:

- best estimate average take-off overrun rate: 0.33 per million movements,
- estimate for average landing overrun rate: 1 per million movements.

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 study by Eddowes et al. (2001) 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. Based on that study, and adjusting the average landing overrun rates from above, the estimates for overrun rates for precision and non-precision/visual approach movements used here were as follows:

- best estimate precision approach landing overrun rate: 0.6 per million movements;
- best estimate non-precision/visual approach landing overrun rate: 4.68 per million movements.

3.2.2 Overrun on takeoff

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). From the work by Kirkland et al. (2004), it is possible to derive a cumulative probability distribution 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. From the work in the 1997 CAA paper, 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) can be plotted. Assuming that there is an equal probability of movements with any given excess runway available between 0m and 1200m, the frequency with which a overrun of x metres (beyond the ASDR) occurs, F(x) can be calculated. Integrating F(x) enables the derivation of the frequency with which an overrun of greater than x metres occurs. This enables a relative probability of an overrun for an excess runway length of x metres to be assessed (Figure 1). The same procedure was used to enable a relative probability of an overrun on landing based on landing distance required (LDR) (Figure 2).

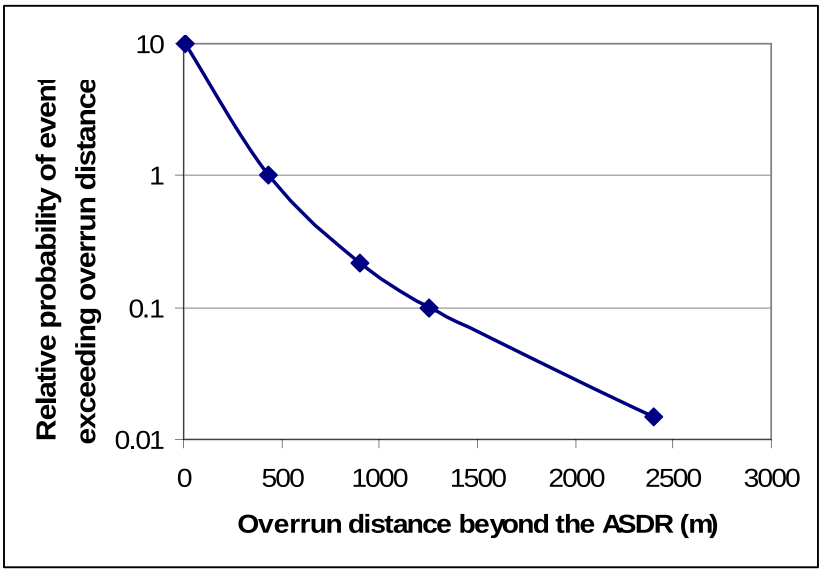

Figure 1: Relative Probability of Take-Off Overrun Events Exceeding Specified Distance

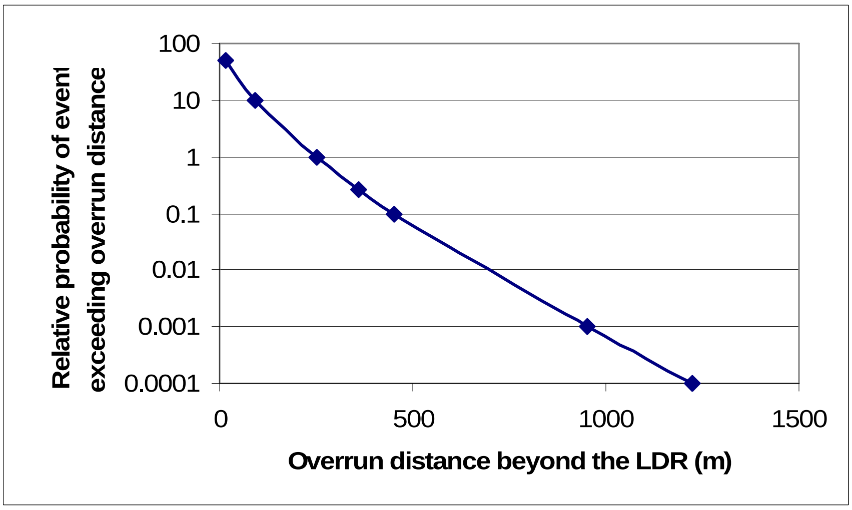

Figure 2: Relative Probability of Landing Overrun Events Exceeding Specified Distance

3.2.3 Overrun on takeoff at this airport

For the three largest aircraft at the airport, the excess distance was calculated for takeoff and landing using data from the aircraft manufacturers (Table 2).

The normalised probability of overrun on takeoff was then found for each aircraft type using Figure 1. The expected annual takeoff overrun rate at the airport was then found for each of the three classes of aircraft taking the general probability of overrun, adjusted by the relative probability, and then the annual frequency of takeoffs at the airport (Table 3). A similar process was used to find the probability of overrun on landing at the airport, based on the landing distance required and precision approach (not shown here for reasons of space). This assumes that this airport meets the same standards as the airports in the historic accident database which is likely to be ICAO standards, and will need later adjustment to reflect the actual standard at the airport.

Table 2: Excess distance for takeoff and landing

Aircraft type	ASDR (m) (1)	Excess distance (m) (2)	LDR (m) (3)	Excess distance (m) (2)
Boeing 737-400 (23,500 lb engines)	2700	740	1870	1570
Boeing 747-400ER	3440	0	2500	940
Airbus A380	3000	440	2050	1390

ASDR: Accelerate Stop Distance Required. LDR: landing distance required.

Notes: 1 ISA+15 ^{o}C, sea level, level runway, MTOW

2 Takeoff and landing distance available = 3440 m

3 ISA, sea level, level runway, MLW, wet runway

Table 3: Expected annual takeoff overrun rate at the airport

Parameter	Aircraft		
	Boeing 737-400	Boeing 747-400ER	Airbus A380
General takeoff overrun rate per million movements	0.33		
Annual frequency takeoffs	250	150	12
Takeoff overrun rate per year	8.3E-05	5.0E-05	4.0E-06
Relative probability of overrun	0.34	10	1
Expected takeoff overrun rate per year	2.8E-05	5.0E-04	4.0E-06

3.2.4 Preliminary fatality risk from overruns at the airport

The preliminary annual fatality risk from overruns was found for the three largest aircraft at the airport; ‘preliminary’ because it has yet to be adjusted to the ‘final’ risk for weather and other airport specific differences from the accident database.

The expected rate of overrun for the operational phase of takeoff is given in Table 3. Many overruns are not fatal or have a limited number of fatalities. The link between fatalities and overruns was assessed through review of accident and incident records. The main source of data on the scale of consequences was found to be the FAA Incident Database System (FIDS) and US National Transport Safety Board (NTSB) databases. The consequences were assessed in terms of damage sustained to the aircraft (described on a four point scale of “destroyed”, “substantial”, “minor” or “none”) (Eddowes et al., 2001).

The assumed fatalities per overrun was taken as dependent on the damage sustained to the aircraft and the number of passengers carried; a load factor of 100% was assumed. It was assumed that there were 100% fatalities for the aircraft destroyed case, and 25% fatalities for the aircraft substantially damaged case, and nil for the other cases.

So that the fatalities could be matched up to known acceptable levels of risk, the risk to the passengers was found using a population-based measure. The population-based measures are categorised as: collective risk, individual risk, and survival functions (that are closely related to societal risk paradigms) (Fulton et al., 2009).

The population at risk (from fatalities upon overrun) varies with the nature of operations at the airport. The Boeing 737 aircraft at the airport essentially operate an airline passenger service within the country and neighbouring countries, and so the population at risk for that aircraft was taken as that of all airline passengers in the country. This was estimated at 550,000 passengers per annum. The Boeing 747 and Airbus A380 are inter-continental aircraft, and while the airport is used as a destination in its own right, there is a larger population potentially at risk of an overrun at the airport by these aircraft and this is all airline passengers that could use the airport upon diversion of the aircraft.

The preliminary individual fatality risk from overruns on an annual basis is shown in Table 4 for takeoffs; a similar calculation was done for landings and is omitted here for brevity.

Table 4: Individual fatality risk per annum upon takeoff overrun

Parameter	Aircraft		
	Boeing 737-400	Boeing 747-400	Airbus A380
Passengers/aircraft	140	420	520
Aircraft destroyed upon takeoff overrun (1)	20%		
Aircraft substantial damage upon takeoff overrun	29%		
Average fatalities per overrun (2)	38	114	142
Population at risk	5.50E+05	1.66E+06	1.66E+06
Individual risk of fatality on overrun	6.91E-05	6.87E-05	8.55E-05

Notes:
1. Data from FIDS and NTSB databases (Eddowes et al., 2001). In takeoff incidents, 20% of aircraft were destroyed and 29% substantially damaged.
2. Assumed 100% fatalities for the aircraft destroyed and 25% fatalities for the aircraft substantially damaged cases, with 100% load factor.

The results of takeoff and landing overruns were combined, and the preliminary annual fatality risk from all overruns at the airport estimated (Table 5).

Table 5: Preliminary annual fatality risk from all overruns at the airport

Parameter	Aircraft		
	Boeing 737-400	Boeing 747-400	Airbus A380
Adjusted takeoff overrun rate per year	2.8E-05	5.0E-04	4.0E-06
Individual risk of fatality per takeoff overrun	6.9E-05	6.9E-05	8.6E-05
Adjusted landing overrun rate per year	1.5E-08	9.0E-08	7.2E-10
Individual risk of fatality per landing overrun	5.1E-05	5.1E-05	6.3E-05
Fatality risk per annum - all operational phases	1.9E-09	3.4E-08	3.4E-10
Preliminary annual fatality risk at the airport from overruns	3.6E-08		

3.2.5 Final annual fatality risk from all overruns at the airport

The preliminary overrun fatality risk per annum at the airport for airline aircraft was 3.6E-08 (3.6×10^{-8}) from Table 5. The final risk was found by adjusting for differences between this airport and the typical airports in the historic incident database described in section 3.2.1. The adjustment was made for:

- Very dry weather at this airport, but with the presence of reduced visibility and drifting sand,
- Below ICAO standard for surface geometry (crossfall) at this airport,
- Two levels of wet weather friction and macrotexture: poor and good.

The effect of weather at this airport was considered by comparing it to weather at a typical European airport. In this case, data were available for another single runway airport with 737 and 747 traffic, being Gatwick, UK. After data analysis, weather at this airport was considered to be less of a problem than at Gatwick (as the proxy for the airports in the historical accident database). This would tend to reduce the overrun rate. The surface geometry (crossfall), friction and macrotexture at this airport were worse than Gatwick. These would tend to significantly increase the overrun rate.

The balance between a reduction in rate for good weather and a significant increase in rate for poor geometrics and poor friction/macrotexture is such that the friction dominates. The impact of poor wet friction would be to reduce braking action and increase braking distance. This was modelled by considering a change in deceleration from 0.45g for the (good) case of wet weather friction (where the runway meets ICAO requirements) to 0.2375 g for the poor weather friction (current airport case). The change in stopping distance was calculated with appropriate allowance touchdown point and engine spool-up. Poor wet weather friction obviously increased the stopping distance required, and this would increase the relative probability of events exceeding the overrun distance.

The original overrun analysis was based on data from airports probably meeting ICAO standards. This was now repeated using the landing distances for poor wet friction, and this showed a major jump in overrun rates, especially for the Boeing 747 which had the shortest excess distance. The final annual fatality risk for all overruns at this airport with its poor geometry and friction/macrotexture was 3.4E-06, which is significantly more than the preliminary risk of 3.6E-08 based on meeting ICAO standards.

Such a process necessarily involved an extrapolation of the database and there will be imprecision in the modelling as a result. It relies 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, the author recognises that such models have their limitations. Notwithstanding these, the author believes that the "risk-based" approach is the best available given these constraints.

4 ASSESSMENT OF RISK LEVEL AT THE AIRPORT

The final annual individual fatality risk from overruns at this airport with poor geometric/friction was found to be 3.4E-06. This wet weather friction risk was compared to other measures of individual risk. The expected accidental risk of death to an individual as a member of the population is called the actual (de facto) individual risk-level. It is defined from a knowledge of the expected number of fatalities per annum, occurring in the population of at-risk people (The Royal Society, 1992). A set of reference levels for this measure has been well investigated, and this helps to categorise of risk for different activities and place the risk at this airport into perspective (Table 6).

Table 6: Reference levels for individual risk

Risk level	Description
1E-05	The community as a whole becomes aware of the emergent rise of risk (Kletz, 1982)
3.4E-06	Current overrun risk at the airport with poor wet weather friction
1E-06	The Dutch government assessed this level as requiring effort to reduce risk (Schipol aviation accident, 1992) (Robinson and Fulton, 2002).
7.8E-08	The average individual risk in Australia for the national population due to mid-air collision (1961 - 2004) (Fulton et al, 2009).
3.6E-08	Future overrun risk at the airport with good wet weather friction
3E-08	The death risk from dam failure in Australia per annum (Ingles, 1985).

It can be seen that the risk level for individual passengers at the current airport with poor wet weather friction is slightly high, and requires effort to reduce risk. The author suggests that the risk for any individual stage of a flight should be similar to that of other stages, which means that the risk of overrun should be around the 1E-07 (1×10^{-7}) level (similar to the mid-air collision risk). With the addition of a runway surface friction layer, the airport will meet this requirement. Without it, the airport does not.

5 CONCLUSIONS

This airport is deficient in geometrics, friction and macrotexture, and so there is a risk associated with wet weather friction. This is mitigated because the airport is in a very dry climate. However the hazard analysis and the quantitative risk study show that there is a high level of individual fatality risk as a result of these deficiencies. The contribution to risk at the airport is dominated by the Boeing 747 operations, which require all the runway for takeoff leaving no excess distance, and carrying a large number of passengers per operation. The risk at the airport, by the widely accepted Dutch Government criteria for risk in aviation, requires effort to reduce risk. A runway surface friction layer or treatment is therefore required. An interim measure such as ‘NOTAM: slippery when wet’ is also a practical step to take. The methodology used here can be applied to the risk analysis of other aerodrome design features. It is particularly suited to risk analysis of different lengths of Runway End Safety Area (RESA) for a particular aerodrome.

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