Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Running out of runway

Analysis of 35 years of landing overrun accidents

Probleem area
Landing overruns belong to the group of most frequently reported accident types in the world. Fortunately, landing overruns do not often result in causalities amongst passengers and crew. Despite this fact landing overruns can still be considered a major threat to aviation safety. It is therefore interesting to have an overview of factors that increase the landing overrun risk, the trends in statistics and in the influence of safety initiatives. A safety study on landing overruns of commercial transport aircraft was conducted which addressed these issues.

Description
This paper presents an analysis of landing overrun accidents of commercial transport aircraft that took place during the period 1970-2004. A total of 400 accidents were identified and analysed. The accident data were obtained from the NLR Air Safety Database. A data taxonomy was developed based on factors that influence landing performance. The data were evaluated through a straightforward single-variable analysis. This included developing frequency distributions of each risk factor considered. It also included an exploratory analysis that provided a general understanding of the landing overrun accident data. A central objective of this study was to estimate the risk associated with the various landing factors (such as excess speed, tailwind, runway condition etc.). It was therefore

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essential to understand the prevalence of these individual factors during landings which did not end up in a landing overrun. For instance to estimate the risk associated with long landings it should be known how many long landings took place without resulting in an overrun. The risk associated with the presence of a number of factors was estimated. Finally the data were analysed for trends.

Conclusions

The following conclusions are drawn from the landing overrun accident data studied in this paper:

- The Africa region demonstrated the highest landing overrun accident rate, followed by Central/South America, and Asia. All these regions had rates of more than one accident per million landings. The rest of the world demonstrated rates below one accident per two million landings which was less than half of the rate of the previous mentioned regions. North America had the lowest rate of all regions.

- No statistically significant difference in the estimated landing overrun accident rate between commercial transport jet and turboprop aircraft was found.

- On a worldwide basis, there appears to be a significant increase in landing overrun risk when one of the following factors is present during a landing: Non-precision approach, touching down far beyond the threshold (long landing), excess approach speed, visual approach, significant tailwind present, high on approach, wet/flooded runway, and/or snow/ice/slush covered runway. The highest risk increase occurred when the aircraft touched down far beyond the threshold (long landing), followed by excess approach speed.

- On a worldwide basis, the landing overrun accident rate has reduced by a factor of three over a period of thirty-five years. This reduction is most likely the result of a number of factors including improvement in braking devices (antiskid, autobrakes etc.), better understanding of runway friction issues, and safety awareness campaigns.

- Late or no application of available stopping devices was often found to be a factor in the landing overrun accident. These overrun accidents were all avoidable if the crew had used the available stopping devices, without any delay.

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Analysis of 35 years of landing overrun accidents

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Summary

Landing overruns belong to the group of most frequently reported accident types in the world. Fortunately, landing overruns do not often result in causalities amongst passengers and crew. Despite this fact landing overruns can still be considered a major threat to aviation safety. It is therefore interesting to have an overview of factors that increase the landing overrun risk, the trends in statistics and in the influence of safety initiatives. A safety study on landing overruns of commercial transport aircraft was conducted which addressed these issues.

Landing overrun accidents of commercial transport aircraft that took place during the last 35 years were analysed. A total of 400 accidents were identified and analysed.

It was found that on a worldwide basis, there appears to be a significant increase in landing overrun risk when one of the following factors is present during a landing: Non-precision approach, touching down far beyond the threshold (long landing), excess approach speed, visual approach, significant tailwind present, high on approach, wet/flooded runway, and/or snow/ice/slush covered runway. The highest risk increase occurred when the aircraft touched down far beyond the threshold (long landing), followed by excess approach speed.
Furthermore, it was found that on a worldwide basis, the landing overrun accident rate has reduced by a factor of three over a period of thirty-five years. This reduction is most likely the result of a numbers of factors including improvement in braking devices (antiskid, autobrakes etc.), better understanding of runway friction issues, and safety awareness campaigns.
Late or no application of available stopping devices was often found to be a factor in the landing overrun accident. These overrun accidents were all avoidable if the crew had used the available stopping devices, without any delay.

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1 Introduction

1.1 Background

'*On February 28, 1984 the first officer flying a DC-10 was making a manual CAT II ILS approach to Runway 04R at New York JFK airport. The captain noted that the airspeed was high and informed the first officer. The approach bug speed was 168 knots. However when the aircraft crossed the threshold the speed was 204 knots. The aircraft touched down about 4,700 ft. beyond the threshold of the 8,400 ft. runway and could not be stopped on the runway. The captain steered the aircraft to the right to avoid an approach light pier as it overran and it came to rest on the waters of Thurston Basin some 600 ft. beyond the end of the runway. The accident happened on a wet runway. The National Transport Safety Board NTSB determined that the probable cause of the accident was the crew's disregard for prescribed procedures for monitoring and controlling airspeed during the final stages of the approach, their decision to continue the landing rather than execute a missed approach and their over-reliance on the autothrottle speed control system, which had a history of recent malfunctions. The 163 passengers and 14 crewmembers evacuated the aircraft safely, but a few received minor injuries. The nose and lower forward fuselage sections, wing engines, flaps, and leading edge devices were substantially damaged at impact. (source: NTSB accident investigation report AAR-84/15).*' This is a typical example of an accident in which the pilot was not able to stop the aircraft before the end of the runway. This is event is called an '*overrun*'. Overruns can occur during both takeoffs and landings. However the vast majority took place during landing. Takeoff overruns normally occur after high-speed rejected takeoffs. Although rejected takeoffs are not uncommon the majority happen at relatively low speeds explaining the lower number of takeoff overruns. Most aircraft land on runways that are longer than the minimum required distance. Still each year landing overruns are reported worldwide. Landing overruns belong to the group of most frequently reported accident types in the world. Fortunately, landing overruns do not often result in causalities amongst passengers and crew. The landing overrun accident with an Airbus A340 that occurred recently at Toronto - Lester B. Pearson International airport clearly illustrates this. Despite this fact landing overruns can still be considered a major threat to aviation safety. It is therefore interesting to have an overview of factors that increase the landing overrun risk, the trends in statistics and in the influence of safety initiatives. This paper presents a safety study on landing overruns of commercial transport aircraft. For this purpose landing overrun accidents that took place during the last 35 years were analysed.

1.2 Objective and scope

The objectives of the study are to identify and quantify the most important risk factors associated with landing overruns; to see if there are any trends in landing overruns during the last 35 years of flying; and to try to see what influence safety initiatives possibly have had on landing overruns. This study was limited to commercial transport aircraft.

1.3 Organisation of the paper

Section 2 of this paper presents an overview of the factors that influence the landing performance. Section 3 discusses the methodology applied in this study. The findings are presented in section 4 and are discussed in section 5. Section 6 gives some final remarks. The conclusions and recommendations are presented in section 7.

2 Factors influencing landing performance

There are a number of factors that influence the landing performance. For the present study it is important to have a basic understanding of these factors without going into much detail. This section presents a brief overview of those landing performance factors

2.1 What is a 'good' landing?

In short a 'good' landing has the following characteristics. It starts with a stabilised approach on speed, in trim and on glide path. During the approach the aircraft is positioned to land in the touchdown zone. When the aircraft crosses the threshold it is at the correct height and speed. The approach is ended by a flare without any rapid control column movements which is followed by a positive touchdown without floating. Immediately after touchdown of the main gear the spoilers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), (if available) the reverse thrust or propeller reverse is selected and the nose is lowered. These actions are all conducted without delay and according to the standard operating procedures. This is the landing as it can be found in flight crew training manuals. However, not many landings are conducted exactly like this every day. Deviations from this good practice occur often without any serious consequences. However, when there are large deviations from the 'good' practice it can become more difficult to stop the aircraft on the runway. These deviations are discussed in the next sections.

A good landing is one that you can walk away from.
A great landing is one where you can use the aircraft again.

2.2 Approach speed

The approach speed is determined by a number of factors such as flap setting, weight of the aircraft, the headwind, turbulence, and the handling of the pilots. Based on a number of these factors the pilot calculates a target approach speed (bug speed) which the pilot tries to fly during the approach. In the example presented in the introduction of this paper, the DC10 was flying 36 kts too fast when crossing the threshold. Excess approach speed increases the tendency that the aircraft floats during the flare. Some aircraft have a higher tendency to float than others. This is mainly affected by the aerodynamic ground effect which varies amongst different aircraft types. In case of floating the pilot often tries to bleed off the excess speed. This action takes a significant part of the amount of runway remaining to stop the aircraft. The effect of the excess speed on the ground roll distance is usually less than the increase of the flare distance due to floating. This is explained by the fact that the declaration of the aircraft during the flare is only a fraction of what can be achieved during braking on the ground even on slippery runways. Therefore putting down the aircraft with an excess in speed is important instead of bleeding off the excess speed in the air. Excess approach speed landings are more often associated with non-precision and visual approaches than with precision approaches. Precision approaches are inherently related with a procedure in which a constant descent gradient from the final approach altitude to touchdown is defined. The descent gradient can be verified during the flight. Non-precision approaches can be designed to be a stabilised approach procedure. However this is not always the case which makes such approaches more vulnerable to excess speed.

2.3 Approach path

Atmospheric turbulence, guidance errors and inaccurate control by the pilot can result in deviations from the nominal glide path. It is important that the aircraft crosses the threshold at the correct height and with the intended glideslope. Excess height at the threshold can increase the landing distance. The same applies when the glideslope is shallower. For example the increase in landing distance for an aircraft on a 3 degree glideslope approach with excess height of 30 ft. at the threshold is approximately 700 ft. In combination with a one degree shallower glideslope this increases to approximately 1,000 ft. Some pilots tend to make a so-called duck under manoeuvre when crossing the runway threshold. In this situation the pilot is flying the aircraft below the nominal path with a shallower glideslope. The tendency to do so varies amongst the pilots, aircraft type flown and visual conditions. Such a flying technique can also result in longer landings.

Excess height landings are more often associated with non-precision and visual approaches than with precision approaches. Precision approaches are inherently related with a procedure in which a constant descent gradient from the final approach altitude to touchdown is defined. This descent gradient can be verified during the flight. Non-precision approaches can be designed to be a stabilised approach procedure. However this is not always the case which makes such approaches more vulnerable to excess height.

2.4 Flare and touchdown

During the flare manoeuvre the pilot reduces the rate of descent so that an excessively hard touchdown is avoided. In the execution of the flare the pilot relies on his/her experience and judgement. The pilot decides on the moment to initiate the flare and on the amount of elevator input during the flare. The touchdown should follow immediately upon the completion of the flare. However, often the aircraft floats for some time before touchdown. This can take a considerable amount of runway. In the example presented in the introduction of this paper, the DC10 landed some 4,700 ft. beyond the threshold. In the example the aircraft floated for some distance after the initial landing flare. The 20ft. callout was made three times. Thereafter, the captain (PNF) told the First Officer (PF) to put the aircraft down. The tendency to float depends on a number of factors which are difficult to generalise. For instance, ground effect appears to play an important role. Ground effect is the aerodynamic influence of the ground on the flow around an aircraft. It increases the lift, reduces the aerodynamic drag, and generates a nose down pitching moment as the ground is approached. The nature of and magnitude of ground effect are strongly affected by the aircraft configuration. Ground effect provides a landing cushion that feels very comfortable to the pilot. This could explain to some extent the influence of ground effect on the tendency to float. As explained already excess approach speed can also result in floating of the aircraft after the flare as the pilot tries to bleed off the excess speed.

The touchdown should be done positive without being excessively hard. When the touchdown is too smooth spin up of the tires could be delayed when the runway is slippery. As explained later this can affect the deployment of ground spoilers and the proper functioning of the antiskid system.

After touchdown of the main wheels the nose should be lowered without delay in order to maximise the load on the tires. On some fighter jets the pilots tend to keep the nose up as long as possible in order to increase drag and shorten the needed runway length. This technique is called ‘aerodynamic braking’ and is an acceptable technique on some fighter jets. However for commercial transport aircraft it is not a recommended technique. The stopping forces associated with this technique are only a fraction of those forces when the aircraft is braked with the nose down. The ‘aerodynamic braking’ technique has resulted in landing overruns with commercial transport jets in the past. Therefore it should never be used during landings with commercial transport aircraft.

2.5 Rollout

The prompt use of all available stopping systems helps to minimise the rollout distance. As soon as the aircraft has touched down these devices should be utilised without any delay. There are a number of stopping devices used: ground spoilers, reverse thrust, and tire brakes. Ground spoilers are installed on a large number of commercial transport aircraft. In particular jet transport aircraft are equipped with ground spoilers. Reverse thrust is available on a number of jet and propeller aircraft. This device provides effective means of stopping the aircraft. Tire brakes are the stopping device that every aircraft has installed. Another stopping force that comes for free during the ground roll with any aircraft is the airframe aerodynamic drag. Problems with the stopping devices and or any delay in using them can make it difficult for the pilot to stop the aircraft on the runway. Some of the issues with the mentioned stopping devices will be briefly discussed next.

Tire braking is one of the primary means of generating stopping forces on an aircraft. The tire has to slip to generate a braking force. Maximum braking force is achieved at a tire slip in the order of 10-15%. The braking force on a tire is proportional with the vertical load on the tire. Runway conditions also influence the amount of braking force a tire can generate. The highest braking forces are obtained on dry surfaces. Whenever the runway is wet, flooded or covered with snow, ice or slush, lower braking forces are obtained than on a dry runway. In case of wet runways the texture of the surface is also important. On a wet, rough surface higher braking forces are achievable than on a wet, smooth surface. Most commercial transport aircraft are equipped with an antiskid system. This system prevents tires from lockups and automatically optimises tire slip for maximum braking forces by controlling the braking pressure. The pilot can therefore apply maximum brake pedal input without being concerned of possible tire lockups and optimum braking. The antiskid needs a reference wheel speed to function. This speed is initially generated by the wheel itself just after touchdown. However wheel spin-up can be delayed when landing on flooded runways. On such runways the aircraft tires can hydroplane. The footprint of the tire is then separated from the surface by a film of water. Frictional forces between the tire and the ground are then very low as water cannot develop significant friction forces. Friction forces are needed to get the tire spinning. The speed at which a tire starts to hydroplane depends on a number of factors such as tire inflation pressure, forward speed of the tire, tire design (radial or cross-ply), etc (see Van Es, 2001 for more information on hydroplaning). The tires can become locked if the pilot applies braking before the tires are spinning. As a result the braking forces are significantly lower.

Jet transports can be equipped with an automatic braking system. The autobrake system was introduced in the early and mid seventies. The autobrake system automatically controls the braking of the aircraft after touchdown. An autobrake selector switch allows the pilot to select from several deceleration levels for landing. During the landing roll pressure is automatically applied to the brakes after touchdown. The system regulates brake pressure to compensate for the effects of aircraft drag, thrust reversers, and spoilers to maintain the selected deceleration level. The autobrakes system disarms immediately when the pilot applies manual braking. The autobrake system is a very efficient system which is not always recognised as such by the pilots. Compared to manual braking the deceleration generated by the autobrake system is usually more consistent. Furthermore pilots tend to limit their brake input. In case of the need to stop the aircraft when only limited runway is available this behaviour can be critical. Flight simulators do a great job in simulating the flight characteristics of an aircraft. However they are not good in simulating ground forces. The sensation of a truly maximum braking effort cannot be simulated correctly. The noises, the vibrations, the deceleration associated with a maximum braking effort are not similar to the real situation. Therefore simulator training to familiarise pilots with the maximum manual braking situation is in general not fully effective. So whenever the pilot applies maximum manual braking, the pilot’s reaction will often be to reduce the brake pedal input. The use of autobrakes for landing on slippery runways instead of manual braking has been recommended in the past by accident investigation agencies. For instance the National Transportation Safety Board (NTSB) and FAA gave the following recommendation after examining the MD82 overrun accident at Little Rock (June 1999): “*Autobrake systems, when available and operative, should be armed and confirmed armed by both pilots, in accordance with manufacturers’ recommended procedures for the airplane and autobrake system regarding landing on a wet or slippery runway, or landing in a high crosswind, or in accordance with equivalent approved company procedures. Those procedures should be reflected in the respective flight manual, checklists, and training program used by the pilot, or when recommended procedures are not specified by the applicable manufacturers regarding landing on a wet or slippery runway, or landing in a high crosswind, autobrake systems, when available and operative, should be armed and confirmed armed by both pilots when preparing to land in any of those conditions. Those procedures should be reflected in the respective flight manual, checklist, and training program used by the pilot.*”

Ground spoilers (also known as lift dumpers) are located on the top of the wing. When deployed they increase the aerodynamic drag. They also decrease the aerodynamic lift significantly, resulting in a higher load on the tires. Ground spoilers are most effective at high speeds. Aircraft can be equipped with wing mounted ground spoilers that can raise automatically right after main gear touchdown. For this the ground spoilers need to be armed prior to touchdown. Ground contact sensors are installed on the aircraft in order to prevent ground spoilers to deploy automatically in the air. There are different types of contact sensors in use. Wheel spin-up of the main gear tires can be used as an indication of ground contact. Main landing gear oleo compression can also be used (often in combination with wheel spin-up). On aircraft equipped with bogie main landing gears, the tilt angle of can be used as an indication of ground contact. As discussed earlier in this section wheel spin-up can be delayed when landing on flooded runways. As the friction force on a tire is proportional with the load on the tire it is important to get as much load on the tires right after touchdown. Ground spoilers are designed to do just that.

However if the ground spoilers are waiting for the tires to spin-up a major problem has raised. The ground spoilers need then to be deployed manually. On many aircraft the ground spoilers can also deploy upon activation of thrust reversers. For this the spoilers do not need to be armed before touchdown. However, it is always better to arm the ground spoilers before touchdown in the event of inoperative reversers or no use of the reversers. It can also take some time to select the reversers which delays the deployment of the spoilers.

Thrust reversers are stopping devices which do not depend on runway condition. They are very effective in generating stopping forces especially on slippery runways. Thrust reversers on jet transports generate the highest stopping forces at high speeds. Below a certain speed maximum reverse thrust is often not allowed. The reverse thrust is modulated to idle reverse between 80-60 knots IAS on a jet transport in order to avoid foreign objected damage to the engine and to avoid the ingestion of turbulent air from the reverse thrust into the main engine inlet, possibly leading to an engine surge or stall. On turboprop aircraft the propellers are normally moved out of reverse at lower speeds than on jet transports. On some turboprop aircraft full reverse cannot be selected at high speeds due to the possibility of asymmetrical reserve thrust. Another issue is that the reversers on jet transports can produce a lot of noise. This sometimes restricts their use on airports to idle thrust only. If thrust reversers are available and the conditions are marginal (e.g. wet/contaminated runway, wind conditions, short runway etc.) they should always be used regardless of environmental restrictions. Thrust reversers can also give directional controllability problems in some cases. For instance, tail mounted engine can affect the flow around the vertical tail reducing rudder effectiveness. Also the use of thrust reversers in heavy crosswind conditions can give controllability problems. These controllability problems can be solved by reducing the reverse thrust. However, the pilot then looses a valuable stopping force.

2.6 Automatic versus manual landing

Aircraft that can land during low visibility and/or cloud ceilings (CAT III conditions) are equipped with a system that allows the aircraft to make a fully automatic landing. The majority of aircraft that have these systems installed can only conduct a fully automatic landing up to touchdown (autoland with no roll-out guidance). After touchdown the crew must disengage the autopilot and take control of the aircraft. Although the autoland system is very accurate, it is not able to the get the aircraft to touchdown on the exact same spot on the runway every time. However compared to manual instrument landings the touchdown scatter of an automatic landing is much less. Unpublished flight data showed that the mean distance from the threshold to the touchdown point is about 30% higher during a manual instrument landing. The scatter in this distance (in terms of standard deviation) is about 130% higher during a manual landing. These facts are not a big surprise as the manual instrument landing is strongly influenced by pilot flight handling. Touching down far on the runway, flying fast and/or flying high above the flight path are things that are less likely to occur during automatic landings.

Normally autolands are conducted when the visibility condition or cloud ceiling is too low to make a safe manual landing. However this does not rule out the use of autoland systems during better weather conditions. Indeed autolands are conducted during fine weather conditions with excellent visibility (although not many). Full protection of the ILS is not required for that case. It is also expected that the crew will have sufficient visual references to detect and correct any deviations from the expected flight path. However there are some risks of performing autoland operations on runways not meeting CAT II/III standards. Protection of the ILS sensitive area is not assured, and other aircraft and vehicles may cause disturbance to the localiser signal. Unexpected flight control movements may occur at a very low altitude when the autopilot attempts to follow the disturbed beam bends. The crews should therefore be alert to the possibility of abnormal autopilot behaviour and guard the flight controls throughout the automatic landing. The crew should also be prepared to disconnect the autopilot and manually land or go-around. However during significant crosswind landings disconnecting the autopilot at low altitudes can be risky. The operator should always include the appropriate instructions in the flight operations manual for autoland landings under good visibility conditions. The crew should also inform ATC about the intention to conduct an autoland under the above mentioned scenario. In that case ATC can inform the flight crew of any known or anticipated disturbance of the ILS beam due to other aircraft and vehicles.

On February 21, 1986 a DC9 landed on runway 24 of Erie international airport. The aircraft touched down some 2,000ft beyond the displaced threshold. Although the pilots armed the spoilers they did not automatically deploy so that the captain armed them manually. Reverse thrust was selected and the brakes activated. The brakes were not effective. Subsequently the aircraft could not be brought to a halt before the end of the runway. The aircraft overran through a fence eventually coming to rest partly across a road. The runway was covered in snow with a reported braking action of fair-to-poor. The approach was flown with a tail wind and approximately 10kt above reference speed. Tailwind landings on Runway 24 were not authorised in wet or slippery conditions. Source: NTSB report DCA86AA018

3 Data analysis methodology

3.1 Approach

The overall data analysis approach employed in this study was to:

- Develop a taxonomy for the collation and analysis of the data;
- Identify a sample of landing overrun accidents; and,
- Analyse the data to determine what factors and to what degree they were associated with landing overrun accidents.

3.2 Data inclusion criteria

The following criteria were used to establish the data sample:

- Only occurrences that were classified as ‘accidents’ according to ICAO Annex 13 definition were included.

- Both fatal and non-fatal accidents were included.

- The accidents involved a landing overrun. An overrun is an event in which the aircraft departed the end of the runway. Also included are those events where the pilots noticed that the aircraft could not be stopped on the remaining runway and decided to deliberately steer the aircraft off the runway to avoid a collision with objects placed near the runway end. Not included are those events in which the pilots lost directional control of the aircraft on the ground resulting in a veer-off.

- Accidents related to unlawful or military action were excluded.

- The accidents involved fixed wing aircraft with a maximum takeoff mass of 5,500kg or higher that were used in a commercial operation (passenger or cargo) excluding training and ferry flights. There was no restriction to the geographical location.

- The accidents occurred during 1970 through 2004.

3.3 Data sources

The primary data source used in this study was the NLR Air Safety database. For many years National Aerospace Laboratory NLR maintains a large database with aviation safety related data called the NLR Air Safety Database. The NLR Air Safety Database is a collection of databases containing different types of data. The NLR Air Safety Database contains detailed information on accidents and incidents of fixed wing aircraft from 1960 and onwards. Currently the NLR Air Safety Database contains detailed information on more than 40,000 accidents and serious incidents that occurred world-wide. For each occurrence a wide variety of factual information is available. For a large number of occurrences the causal and contributing factors are also available. Besides data on accidents and incidents the NLR Air Safety Database also contains a large collection of non-accident related data. These data include the following: airport data, flight exposure data (hours & flights at the level of airlines, aircraft type, and airports), weather data, fleet data, and more. The NLR Air Safety Database is updated frequently using reliable sources including data from official reporting systems, insurance claims, accident investigation boards, aircraft manufacturers, civil aviation authorities and more. Queries were conducted in the NLR Air Safety Database using the data inclusion criteria. The level of detail of the information available for each individual accident varied. For a large number of accidents detailed reports were available. However for some accidents there was only limited information.

3.4 Taxonomy

The accident data were analysed using a taxonomy that was developed for this study. The taxonomy was based on the factors that influence landing performance as discussed in section 2 extended with some additional elements such as aircraft type and location. The taxonomy is listed in Table 1.

Table 1: Taxonomy.

Aircraft type
Approach type (precision, non-precision, visual)
Autoland
Date
Excess approach speed
Failure of stopping device
High on approach
Hydroplaning of the tires
Late or no application of available stopping devices (reversers, brakes, spoilers)
Location
Long landing (touching down far beyond the threshold)
Propulsion type
Runway condition (dry, wet, flooded, icy, snow covered)
Tailwind

3.5 Analytical process employed

The major steps included in the analysis of the study are listed below:

1. The data were evaluated through a straightforward single-variable analysis. This included developing frequency distributions of each risk factor considered. It also included an exploratory analysis that provided a general understanding of the landing overrun accident data.

2. A central objective of this study was to estimate the risk associated with the various landing factors (excess speed, tailwind, runway condition etc.). It was therefore essential to understand the prevalence of these individual factors during landings which did *not* end up in a landing overrun. For instance to estimate the risk associated with long landings it should be known how many long landings took place without resulting in an overrun. These data were obtained in various ways. First of all the NLR Air Safety Database contains data which allows making fairly accurate estimations of the prevalence of a number of risk factors in non-accident landings. Examples are the number of landings conducted on the different runway surface conditions. For other risk factors data obtained from Flight Data Monitoring systems from a limited number of operators were used. These data were used to estimate prevalence of a number of risk factors in non-accident landings. Examples are excess approach speed, long landings, and high approaches. It is realised that this only gives a rough order of magnitude of the prevalence of those risk factors for operations worldwide. This should be considered when analysing the results. An estimate of the risk of having a landing overrun accident with a particular risk factor present was accomplished by calculating a risk ratio. This risk ratio provides insight on the association of a factor on the risk in a landing overrun accident. The risk ratio is the rate of the accident probability with the factor present over the accident probability without the factor present. The risk ratio is given by the following formula:

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

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

3. Finally trends in the accident data were analysed. In particular changes over time were considered.

4 Findings

4.1 Univariate analysis

A total of 400 landing overrun accidents were found that met the data inclusion criteria. During the study period (1970-2004) it was estimated that approximately 796 million landings were conducted worldwide with passenger and cargo aircraft with a takeoff mass of 5,500kg or higher. The estimated landing overrun accident rate for the study period was 0.5 per million landings worldwide. Table 2 presents the accident distribution by region. The landing accident overrun rate per million landings is also given. Table 2 clearly shows the differences in landing overrun rates between the world regions.

Table 2: Aircraft accident distribution by region

Region	**Landings** millions	**Accidents**	**Rate** per million landings
Africa	31.84	86	2.70
Asia	71.64	74	1.03
Australasia	31.84	8	0.25
Central/South America	55.72	75	1.35
Europe	191.04	91	0.48
North America	397.99	61	0.15
Middle East	15.92	5	0.31
All	795.99	400	0.50

The distribution of accidents by aircraft category is shown in Table 3. The difference in landing accident overrun rate between jets and turboprop aircraft was not statistically significant at the 5% level. This means that the probability of a landing overrun accident of a jet aircraft is not different from a turboprop aircraft.

Table 3: Landing overrun accident distribution by aircraft category.

Aircraft type	**Landings** millions	**Accidents**	**Rate** per million landings
Transport jet	527.22	250	0.47
Transport turboprop	268.76	150	0.56

Table 4 shows the distributions of the landing overrun risk factors for the complete data sample. The values shown in Table 4 are raw values only. They are not corrected for the number of landings conducted which is done in the next section of the paper.

Table 4: Landing overrun risk factors distribution.

Factor	Number of accidents	Percent
Non-precision approach	289	72.3%
Long landing	211	52.8%
Excess approach speed	111	27.8%
Hydroplaning of the tires	60	15.0%
Late or no application of available stopping devices	60	15.0%
Visual approach	56	14.0%
Tailwind present	49	12.3%
High on approach	29	7.3%
Brakes inoperative	21	5.3%
Reverser inoperative	10	2.5%
Ground spoilers inoperative	2	0.5%

The different types of runway surface conditions in the landing overrun accidents are shown in Figure 1. Often the surface condition varied along the runway. For instance part of the runway can be icy and another part covered with snow. Also in the case of flooded runways it was often only a part of the runway that had pools of standing water with the remaining part of the runway being wet. For this reason the different surface conditions that can exist are grouped in Figure 1. The values shown in Figure 1 are raw values only. They are not corrected for the number of landings conducted on under such runway conditions which is done in the next section of the paper.

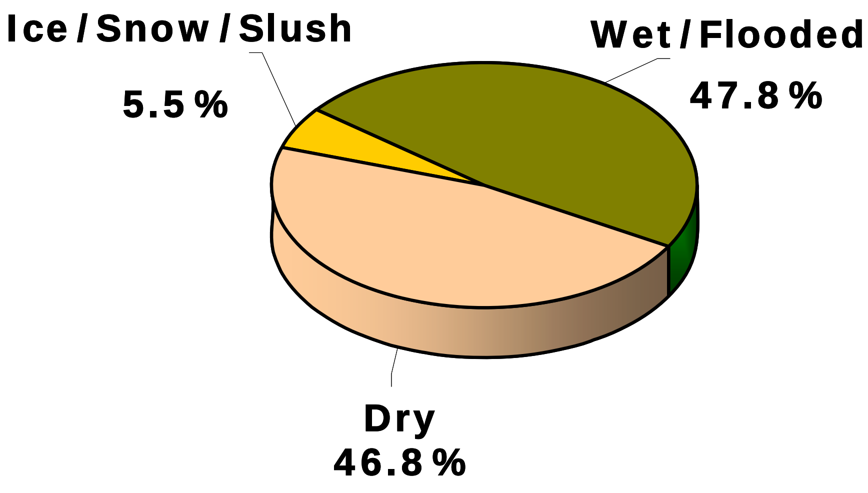

Figure 1: Runway condition distribution.

4.2 Bivariate analysis

In order to estimate risk ratios as defined in section 3.5, the number of landings with or without a factor absent should be known. Different approaches were followed to obtain these data. For instance, data from airline flight data monitoring programs were used to estimate the number of long, fast and high landings for the complete data set. The approach type flown was estimated from the NLR Air Safety Database which contains information regarding precision, non-precision and visual approaches by airport (see also Khatwa et. al., 1996). The actual runway conditions at airports (e.g. wet, snow covered etc.) are not well recorded in databases. Therefore the number of landings conducted on the different runway conditions were estimated from historical hourly precipitation observations at airports. The fact that it, for instance, rains does not automatically mean that the runway is wet. This depends on the drainage characteristics of the runway, the wind, the amount of rain that is falling and some other factors. With a precipitation like snow the runway can be made clear of it when large amounts accumulate on the surface. Therefore adjustments were made on the calculated number of landings on wet/contaminated runways based on hourly precipitation observations. These adjustments were done by using engineering judgement. Although it is realised that this approach can introduce errors in the results it is believed that the errors are small enough just to fulfil the basic objectives of this study.

The calculation of risk ratios could not be accomplished for all variables that were considered. Denominator data for the late or no use of stopping devices and the failure of stopping devices were not available. There were data available on the failure of stopping devices for a number of countries with a high safety standard. However it was felt that these data were not applicable to the overall sample.

Table 5 presents the association of landing overrun related risk factors, adjusted for the number of landings involved in each factor. A value greater than 1 indicates a greater risk. The larger the risk ratio value the stronger the association between the factor and the landing overrun accident risk. All risk ratios presented in Table 5 are statistically significant at the 5% level. The landing overrun accident risk while flying a non-precision approach was twenty-five times greater than that associated with precision approach. The risk ratio was twenty-seven when flying a visual approach compared to a precision approach. If the landing was long, the landing overrun accident risk was fifty-five times greater than when it was not long. The landing overrun risk is thirty-eight times greater when there was excess approach speed. A tailwind of 5 knots or more increases the landing overrun risk by a factor of five times. Finally being high on approach increases the risk with factor of twenty-six. The results presented in Table 5 treat the long landing (touching down far beyond the threshold), excess approach speed, high approach and approach type variables as independent. However, in some cases these variables were related. For instance high and fast landings often resulted in long landings.

Table 6 shows the risk ratios associated with runway condition. All risk ratios presented in Table 6 are statistically significant at the 5% level. The landing overrun accident risk increases with factor of ten when the landing was conducted on a wet or flooded runway. If the runway was covered with snow, ice or slush the landing overrun accident risk is fourteen times greater than when landing on a dry surface.

Table 5: Risk ratio for landing overrun related risk factors

Landing overrun related risk factor	**Risk Ratio**	**Risk-factor accidents**	**Risk-factor absent accidents**	**Risk factor landings** million	**Risk factor absent landings** million
Non-precision approach*	25	289	55	135.32	636.79
Long landing	55	211	189	15.92	780.07
Excess approach speed	38	111	289	7.96	788.03
Visual approach*	27	56	55	23.88	636.79
Significant tailwind present	5	49	351	23.88	772.11
High on approach	26	29	371	2.35	793.63

*Compared to a precision approach.

Table 6: Risk ratio for runway surface conditions.

Runway condition	**Risk Ratio**	**Risk-factor accidents**	**Risk-factor absent accidents***	**Risk factor landings** million	**Risk factor absent landings*** million
wet/flooded	10	191	187	73.71	716.42
snow/icy/slush	14	22	187	5.86	716.42

* Dry runway condition

4.3 Trend analysis

Figure 2 shows the variation in the landing overrun accident rate for the period 1970 through 2004. The data were grouped in 5-year blocks in order to increase the statistical robustness of the data. Figure 3 shows the share of landing overrun accidents in the overall number of approach and landing accidents that occurred worldwide. Again the data were grouped in 5-year blocks.

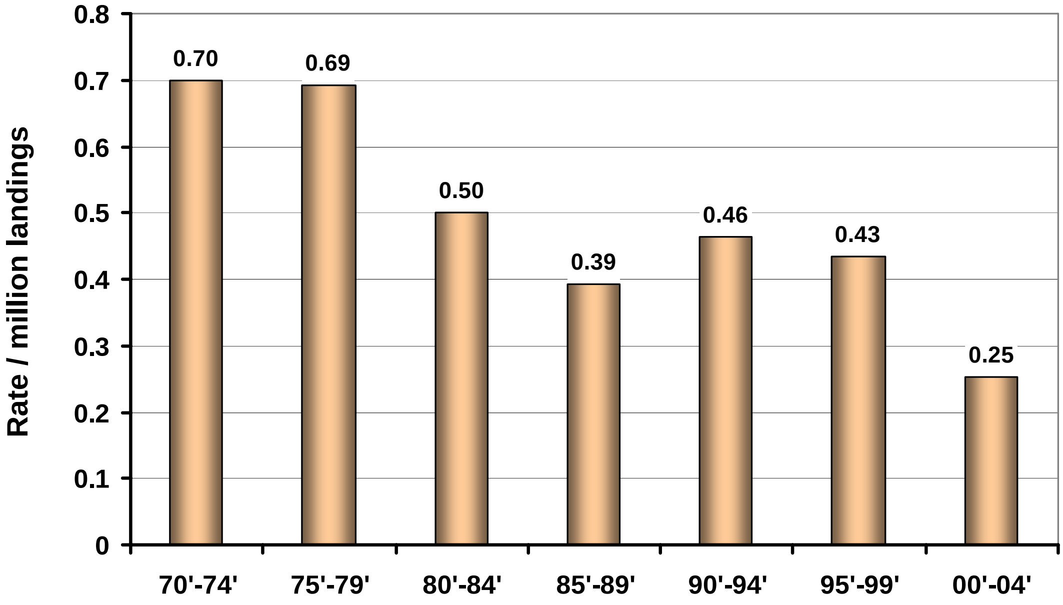

Figure 2: Landing overrun accident rate trend.

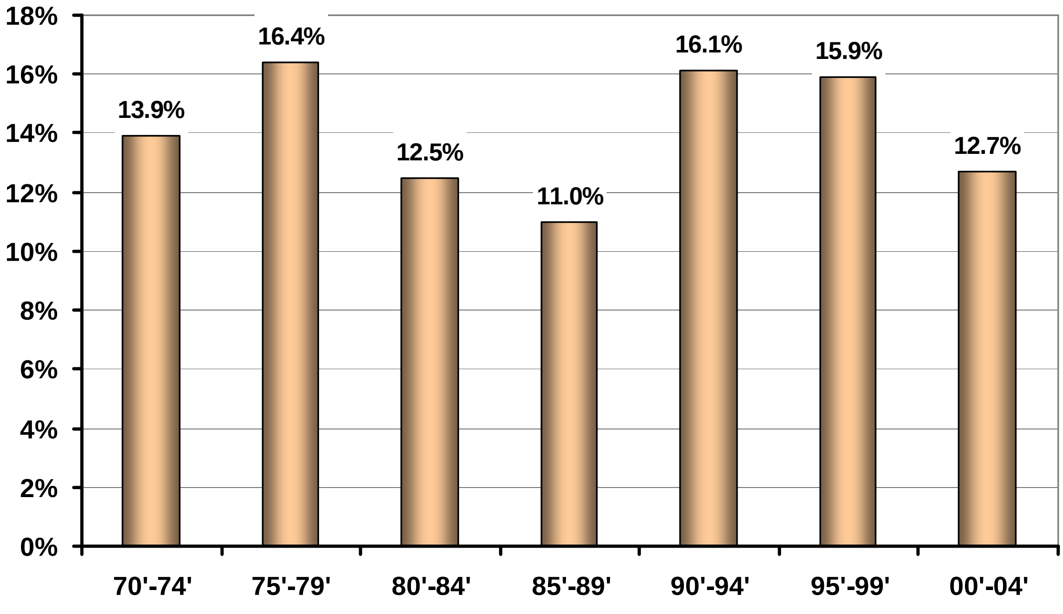

Figure 3: Trend in share of landing overrun accidents in approach & landing accidents.

5 Discussion

In this study 400 landing overrun accidents were analysed that occurred worldwide in the period 1970-2004. Based on the findings of the analysis of these accidents a discussion of the results is presented in this section.

5.1 Aircraft accident distribution by region

It was found that the landing overrun risk varies for the different world regions (see Table 2). There are several explanations for this finding. There exists a difference in the level of aviation safety between the different regions in general. This could also affect the landing overrun risk. Note that an almost similar regional distribution in accident rates was found for landing accidents in general, e.g. not limited to overruns (see Khatwa et. al., 1996).

The highest landing overrun rate was found for Africa. The lowest rate was for North America. However when comparing the rates for the different regions it should be realised that not all differences in accident rates are statistically significant (at the 5% level). Although North America seems to have the lowest rate it was not found to be statistically different from the rates estimated for the Middle East and Australasia regions. The low rate for North America was statistically different from the rate for the Europe and remaining regions.

5.2 Long, fast and high landings

In more than half of all accidents the landing was long meaning that the aircraft contacted the runway far beyond the threshold. Landing far beyond the threshold showed the highest landing overrun risk increase. A long landing itself is not always hazardous. For instance, when a small turboprop aircraft lands on a very long runway, landing long will not automatically result in difficulties stopping the aircraft on the remaining runway. However, long landings can become more hazardous when the available runway to stop the aircraft becomes shorter and/or the runway is slippery. The estimated number of long landings used to derive the risk ratio, contained landings on all kinds of runways with different lengths. In that respect the derived risk ratio for long landings represents an average risk value. Landing fast and/or high also increased the landing overrun risk significantly. Long landings are often associated with fast, high landings and/or tailwind landings. Excess approach speed is often a reason for a pilot to float the aircraft after the landing flare during which the pilot tries to get rid of the excess speed. Excess approach speed was mentioned in 37.4% (79 out of 211) of all long landings. Being high on approach can also lead to longer landings. High on approach was mentioned in 12.8% (27 out of 211) of all long landings. In only 2 high approach cases there was no long landing reported. Pilots clearly need to follow their procedures for monitoring and controlling airspeed and height during the final stages of the approach. Tailwind can also increase the tendency to float. A tailwind condition existed in 15.2% (32 out of 211) of all long landings. Long landing cannot be explained by excess speed, high approaches etc. only. Clearly pilot flying technique plays a significant role in the occurrence of a long landing. More study is required to get a better understanding of this.

5.3 Approach type

The landing overrun risk is much higher when a non-precision or visual approach is flown. These approach types are more likely to become unstabilised (e.g. flying too fast and too high) than precision approaches. Indeed the vast majority of overruns in which there was an excess approach speed occurred during a non-precision or visual approach (81%). In 80% of all landing overrun accidents that were high over the threshold the approach type was non-precision or visual. Similar in 82% of all overruns in which a long landing was reported the approach type was a non-precision or visual approach.

5.4 Runway condition

Slippery runway conditions were associated with higher risk of a landing overrun accident (see Table 6). This finding is not a surprise and is well known in the aviation community. However the quantitative increase in risk was not known. Runway condition affects the braking forces the aircraft tires can generate. Furthermore wheel spin-up can be delayed on slippery runways, which affects the proper functioning of the antiskid system and the deployment of ground spoilers. On wet/flooded or slush covered runways the tire may hydroplane which reduces the braking forces between the tire and runway significantly. On snow and ice covered runways the braking friction levels are very low making it difficult to stop the aircraft. During the last 35 years there have been many initiatives to get a better understanding into runway traction. Numerous studies have been conducted for instance in the United States by NASA, USAF and FAA and in the United Kingdom to understand the impact of runway condition on the stopping capabilities of an aircraft. These studies examined the influence of runway texture on braking friction, analysed the hydroplaning of tires, and showed what impact snow and ice had on braking friction. Several studies also looked at measuring runway friction using ground vehicles and the correlation of the outcome of these vehicles with the friction of an aircraft. Such correlations could be valuable for the pilot when making an assessment of the landing performance. Unfortunately, despite the great effort made so far, an acceptable solution to this problem of measuring runway friction and correlating it to aircraft landing performance is still to be found.

5.5 Tailwind landings

Tailwind landing are associated with higher risk of landing overruns (see Table 5). Tailwind increases the ground speed and therefore the landing distance (see Van Es & Karwal, 2001).

Typically aircraft are certified to make landings with a maximum tailwind component. For most commercial aircraft this is 10 knots on a dry runway. Some aircraft are certified for higher tailwinds. However, this is usually not more than 15 knots. On slippery runways lower tailwinds are allowed during the landing varying from 5 knots to no tailwind at all. A more detailed discussion on tailwind operations is provided by Van Es & Karwal, 2001.

5.6 Application of available stopping devices

In 8.3% of the landing overrun accidents one or more stopping devices did not function (see Table 4). This was mainly due to problems with the hydraulic systems. This sometimes also prevented the use of flaps which resulted automatically in excess approach speed landings. More worrying is the fact the in 15% of the accidents there was a late or no application of the available stopping devices (see Table 4). In many of these accidents an overrun was avoidable if the available stopping devices would have been properly used. The problems were mainly caused by the fact that the ground spoilers were not armed (52% of all cases with a late or no application of the available stopping device). In these cases the pilots often failed to notice that the spoilers did not deploy. Also late or no application of thrust reversers was often found in the accidents (67% of all cases with a late or no application of the available stopping device). In some cases reverse thrust was selected initially. However shortly afterwards it was deselected again. It could be not derived from the analysed data that insufficient manual braking was often a factor. However, to identify that fact detailed flight data recordings need to be analysed. Unfortunately, in many of the analysed accidents such information was not available to the present author.

5.7 Autolands

None of the analysed landing overrun accidents was reported to be attributable to malfunctioning or improper functioning of the autoland system. In one accident from the data sample the crew initially conducted an autoland, however, took manual control over the aircraft again just after passing the threshold. In only a very few number of other cases it was suspected that an autoland was most likely conducted due to the visibility conditions at the time of landing. However, not enough details were reported to be absolutely sure about these facts. This made it difficult to estimate a reliable risk ratio for manual landings. Still it can be argued that autolands can reduce the landing overrun probability as it reduces the likelihood of flying too high, too fast, and making long landings. As shown in this study these factors increase the risk of a landing overrun accident.

5.8 Trend analysis

Figure 2 shows the trend in the landing overrun accident rate worldwide. It is shown that in the seventies the rate was the highest for the period considered in this study (1970-2004). During the eighties the rate significantly improved. However this improvement did not continue in nineties. The first five years of the twenty first century finally showed a reduction in the landing overrun accident rate again. It is difficult to say what exactly caused the reduction in the accident rate during the period 1970-2004. However there are a number of initiatives that could have contributed to the safety improvement. Some of the more important ones will be discussed now.

The efficiency of the antiskid systems has improved significantly over the years. The early antiskid systems were simple on-off systems that produced braking efficiencies of 60% and were introduced in the fifties. Later (sixties) modulated antiskid systems were introduced that had braking efficiencies in the 70-85% range. During the seventies braking efficiencies of consistently over 90% were achieved for the first time with the newer antiskid systems. The commercial aircraft that were operated in the analysed period in this study were equipped with one of the antiskid systems described here. As time progresses older aircraft equipped with less sophisticated antiskid systems were replaced with newer models having more efficient antiskid systems.

Autobrake systems were introduced during the seventies. They are found on many jet transport aircraft today. It was estimated that autobrakes were used in 30% of all landings in the study period. In 2004 this share was estimated to be nearly 50% of all landings.

Since the sixties research on tire braking friction is conducted. These studies provided insight into runway friction and how it could be improved. This has led to the introduction of for instance grooved and porous friction course runways. Although these surfaces often gave an improvement in runway friction on wet runways they do not rule out the possibility to overrun such a runway. Indeed there were a number of landing overrun accidents that took place on grooved runways. Also many studies were conducted to measure runway friction using ground vehicles. The objective was often to correlate the braking friction of these ground vehicles with those of an aircraft. Unfortunately, despite the enormous effort a lot of work is still to be done in this area to arrive at a useful way to correlate ground vehicles with full scale aircraft.

During the late nineties different safety studies were initiated with the aim to improve the level of flight safety. Special attention was given to accidents that occurred during the approach and landing including landing overruns. Studies include those conducted by the commercial aviation safety team (CAST) on approach & landing accidents, the Flight Safety Foundation task force on approach & landing accidents (FSF, 2001), and the joint study into landing aids (Khatwa, 1996). These studies provided the aviation community with a set of mitigating measures. Especially the FSF Approach-and-Landing Accident Reduction Briefing Notes are of great importance. Several briefing notes are devoted to issues that affect the possibility of landing overruns. However, it is too early to conclude that these initiatives had a major influence on the reduction of the landing overrun accident rate during the first five years of the twenty-first century.

Another interesting technology that is worthwhile to mention here is the application of a ground arrestor system which is located beyond the end of the runway and centred on the extended runway centreline. A ground arrestor system is designed to stop an overrunning aircraft by exerting deceleration forces on its landing gear Although this technology (as explained later) cannot prevent overruns from happening its application can mean the difference between an accident and a minor incident. Different types of ground arrestor systems were studied in the UK in the seventies and later in the United States. An example of a soft ground arrestor system is Engineered Material Arresting Systems (EMAS). A soft ground arrestor system like EMAS deforms under the weight of an aircraft tire that runs over it. As the tires crush the material, the drag forces decelerate the aircraft, bringing it to a safe stop. In recent years EMAS became popular in the United States at airports that have difficulties to comply with the rules on runway safety areas defined by the FAA. There have been at least three reported overruns in which EMAS stopped the aircraft. These occurrences took place in the United States with a Saab 340 (May 1999, see Figure 4), a MD11 (May 2003), and most recently in January 2005 with a B747. Clearly no soft ground arrestor system can prevent overruns. However, it seems evident that such a system can reduce the consequences. Other arrestor systems were also studied the past. Examples are loose gravel, water ponds, and arrestor cables. Application of these systems to commercial airports has been limited.

Figure 4: Overrun with a SAAB 340 that ended in a soft arrestor bed.

6 Final remarks

The variables that increase the risk of a landing overrun were discussed in the previous sections. Each of the investigated variables played an important role in the chain of events leading to an overrun. Typically a landing overrun was not characterised by the presence of only one variable. It is often the combination of factors that finally made the aircraft to overrun the runway. The quantified risk ratios in this study demonstrate that associations exist between a number of landing related factors and the risk of a landing overrun accident. Such associations do not prove any causation and only suggest that an increase in risk for a landing overrun accident appears when the factor is present. The present study did not try to identify the underlying causal factors related to landing overruns. There have been many studies conducted in the past in which these underlying causal factors have been identified (see e.g. FSF, 2001).

On September 19, 1972 a Fokker F28 made an NDB approach to Runway 22 in conditions of heavy rains and poor visibility at Port Harcourt, Nigeria. The final approach to touchdown was steep. Finally the aircraft touched down smoothly with a speed 20 kts in excess of the recommended touchdown speed at 3,300ft. beyond the threshold. During flare the pilot added power. The remaining runway length after touchdown was some 3,700ft.. After touchdown there was no appreciable deceleration of the aircraft. The ground spoilers did not deploy due to the lack of wheel spin up. This was caused by hydroplaning of the main gear tires. The pilot did not select ground spoilers manually. The aircraft was not stopped on the runway and it overran across an area of soft ground before impacting an embankment, breaking off the left wing. The aircraft eventually came to rest some 750ft beyond the end of the runway. In the final part of the approach the controller informed the crew that the runway was wet. However in actual fact the runway was flooded. This was due to the heavy rains in combination with the fact that the runway contained undulations in the surface which favoured the flooding of the runway. Source: Accident Investigation Report published by the Dutch Civil Aviation Authorities and Nigerian Government, 1973.

7 Conclusions and Recommendations

7.1 Conclusions

The following conclusions can be drawn from the landing overrun accident data studied in this paper:

- The Africa region demonstrated the highest landing overrun accident rate, followed by Central/South America, and Asia. All these regions had rates of more than 1 accident per million landings. The rest of the world demonstrated rates below 1 accident per two million landings which was less than half of the rate of the previous mentioned regions. North America had the lowest rate of all regions.

- No statistically significant difference in the estimated landing overrun accident rate between commercial transport jet and turboprop aircraft was found.

- On a worldwide basis, there appears to be a significant increase in landing overrun risk when one of the following factors is present during a landing: Non-precision approach, touching down far beyond the threshold (long landing), excess approach speed, visual approach, significant tailwind present, high on approach, wet/flooded runway, and/or snow/ice/slush covered runway. The highest risk increase occurred when the aircraft touched down far beyond the threshold (long landing), followed by excess approach speed.

- On a worldwide basis, the landing overrun accident rate has reduced by a factor of three over a period of thirty-five years. This reduction is most likely the result of a number of factors including improvement in braking devices (antiskid, autobrakes etc.), better understanding of runway friction issues, and safety awareness campaigns.

- Late or no application of available stopping devices was often found to be a factor in the landing overrun accident. These overrun accidents were all avoidable if the crew had used the available stopping devices, without any delay.

7.2 Recommendations

- It is recommended to disseminate the results of this study to all interested parties including airlines, regulators, and pilot unions.

- It is recommended to analyse in detail the characteristics associated with long landings using recorded flight data of normal day-to-day landings.

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