Identification and analysis of veer-off risk factors in accidents/incidents

J.A. Post (NLR)

Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Project P3 "Solutions for runway excursions" of Future Sky Safety. The main objective is to better understand the causal factors of runway veer-off excursions and to identify which root factors can be measured and identified using on-board recorded flight data (Flight Data Monitoring: FDM).

Programme Manager	M.A. Piers, NLR
Operations Manager	L.J.P. Speijker, NLR
Project Manager (P3)	G.W.H. van Es, NLR
Grant Agreement No.	640597
Document Identification	D3.4
Status	Approved
Version	2.0
Classification	Public

This page is intentionally left blank

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Contributing partners

Company	Name
NLR	J.A. Post, G. van Es

Document Change Log

Version	Issue Date	Remarks
1.0	16-11-2015	First formal release
1.1	10-12-2015	Update by Operations Manager (NLR)
2.0	14-12-2015	Second formal release

Approval status

Prepared by: *(name)*	**Company**	**Role**	**Date**
J.A. Post	NLR	Main Author	12-11-2015
Checked by: *(name)*	**Company**	**Role**	**Date**
M. Greaves	Cranfield University	Quality Assurance	12-11-2015
Approved by: *(name)*	**Company**	**Role**	**Date**
G.W.H. van Es	NLR	Project Manager (P3)	16-11-2-15
L.J.P. Speijker	NLR	Operations Manager	14-12-2015

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Acronyms

Acronym	Definition
EREA	Association of European Research Establishments in Aeronautics
FDM	Flight Data Monitoring
ECCAIRS	European Coordination Centre for Accident and Incident Reporting
ICAO	International Civil Aviation Organisation
ADREP	Accident/Incident Data Reporting
MTOW	Maximum Take-Off Weight
AOM	Aircraft Operations Manager
RSC	Runway Surface Condition
NOTAMS	Notice To Airmen
ARINC	Aeronautical Radio Incorporated
QAR	Quick Access Recorders
SOP	Standard Operations Procedure
N1	Engine low pressure compressor revolutions (%)
EPR	Engine Pressure Ratio
AGL	Above Ground Level
VMC	Visual Meteorological Conditions
IMC	Instrument Meteorological Conditions
METAR	Meteorological Aerodrome Report
ILS	Instrument Landing System
FMS	Flight Management System
FSF	Flight Safety Foundation
Kts	Knots
MEL	Minimum Equipment List

EXECUTIVE SUMMARY

Problem Area

A runway excursion is the event in which an aircraft veers off or overruns the runway surface during either take-off or landing. Safety statistics show that runway excursions are the most common type of accident reported annually, both in the European region and worldwide. There are at least two runway excursions each week worldwide. Runway excursions are a persistent problem and their numbers have not decreased in more than 20 years. Runway excursions can result in loss of life and/or damage to aircraft, buildings or other items struck by the aircraft. Excursions are estimated to cost the global industry about $900M every year. The European Action Plan for the Prevention of Runway Excursions (EAPPRE) provides practical recommendations with guidance materials to reduce the number of runway excursions in Europe. The Action Plan also identified areas where research is needed to further reduce runway excursion risk. One of these areas is the use of operational flight data for veer off risk analysis. So far, developments towards ways to monitor veer-off excursions have been very limited due to lack of useable methods for analyzing on-board recorded flight data. Today no tools are available to airlines to analyze the risk of veer-off excursions using their recorded flight data. There is a need to study and develop algorithms that can be used to analyze flight data for runway veer-off excursion risk factors.

Description of Work

In the present study, an analysis of historical runway veer-off accidents/incidents is conducted. Data on these occurrences are collected from the NLR Air Safety database. The data consists largely of accidents and (serious) incidents. The majority of the occurrences have been brought in by the reporting organizations (e.g. AIB, DGAC, CAA UK, etc.). The occurrences are coded according to the ECCAIRS/ADREP taxonomy. Using this taxonomy, a first selection of veer-off occurrences is made out of runway veer-off excursions that have occurred world-wide during the period 2000-2014. The scope of the study is limited to fixed wing aircraft with two engines (jet and turboprop) or more and a maximum take-off weight (MTOW) of 5700 kg or more. The operation type is restricted to commercial or business transport flights, general aviation flights or state flights. Out of the first selection, manually a dataset has been selected at random with occurrences of which either an external investigation report was available or enough detail was found in the narrative description. The resulting set of 104 occurrences is evaluated. The evaluation results consist of up to five causal factors which are judged to be instrumental in the causal sequence of events leading to the veer-off occurrence plus a three step description of this sequence of events.

Results & Conclusions

A taxonomy consisting of 31 standard descriptions is established to describe causal factors that could contribute to a veer-off occurrence. The frequency of the causal factors, calculated as the percentage of the number of occurrences where a causal factor is present, is determined. The important causal and contributing factors related to veer-offs are identified and presented. Subsequently, it is identified which root factors can be measured and identified by means of Flight Data Monitoring (FDM).

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Causal factors with a frequency of 10% or more are presented for landing and take-off. These factors are Crew performance inaccurate, Wet/Contaminated runway, Crosswind, Inaccurate information to crew, Technical issue: Landing gear, Gust, Technical issue: Nose Wheel steering system, and Asymmetric thrust.

The causal factor "Crew performance inaccurate" shows the highest frequency for both landing and take-off. "Wet/Contaminated runway" and "Crosswind" also are ranked high for both landing and take-off and so is "Inaccurate info to crew". Both landing and take-off show a reasonably high frequency for "Gust". However technical issues with respect to the landing gear or the nose wheel steering system show a considerable higher frequency for landing than for take-off. For take-off the second highest frequency is found for the causal factor "Asymmetric thrust". For landing this causal factor has a low frequency.

For the majority of the discussed causal factors it should be possible to identify them in the FDM data. A number of the discussed causal factors cannot be identified directly in the FDM data. Typically this is the case for actual weather such as visual conditions or precipitation. Those factors could be identified by coupling the FDM data to other supporting databases such as for example a database with METAR information. It is also concluded that for a number of the discussed causal factors the accuracy and sample rate of the required parameter(s) would not be sufficient in the FDM data as it is today.

It is observed that two causal factors that show a relatively high frequency of occurrence are related to the flight crew task. These causal factors are "Crew performance inaccurate" and "Inaccurate information to crew" with a frequency of occurrence of 55% and 22% respectively. It is therefore recommended that operators take in consideration whether the subject "veer-off" could get more attention in flight crew performance training and crew awareness training. Also it is recommended that effort is given by all supporting parties to provide the flight crew with timely and accurate information so that they are able to makes the right decisions with respect to landing or take-off strategy based on this information

Applicability

The results of this study will be used, in Future Sky Safety, for development and validation of algorithms for the identification of veer-off risk factors using flight data collected on board aircraft. Such algorithms would enable assessment of the relative risk of veer-off associated with a given set of conditions.

In Future Sky Safety, the algorithms will initially be aimed at assessing risk on flights that have already occurred, through an FDM program. However, there may be scope to extend the algorithms for use on the flight deck, similar to the Airbus ROPS product, such that real-time information can be delivered to the flight crew in order to assess the risk of runway veer-off.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1. The Programme

FUTURE SKY SAFETY is an EU-funded transport research programme in the field of European aviation safety, with an estimated initial budget of about € 30 million, which brings together 32 European partners to develop new tools and new approaches to aeronautics safety, initially over a four-year period starting in January 2015. The first phase of the Programme research focuses on four main topics:

- Building ultra-resilient vehicles and improving cabin safety;
- Reducing risk of accidents;
- Improving processes and technologies to achieve near-total control over the safety risks;
- Improving safety performance under unexpected circumstance.

The Programme will also help coordinate the research and innovation agendas of several countries and institutions, as well as create synergies with other EU initiatives in the field (e.g. SESAR, Clean Sky 2). Future Sky Safety is set up with expected seven year duration, divided into two phases of which the first one of 4 years has been formally approved. The Programme has started on the 1st of January 2015.

FUTURE SKY SAFETY contributes to the EC Work Programme Topic MG.1.4-2014 Coordinated research and innovation actions targeting the highest levels of safety for European aviation in Call/Area Mobility for Growth – Aviation of Horizon 2020 Societal Challenge Smart, Green and Integrated Transport. FUTURE SKY SAFETY addresses the Safety challenges of the ACARE Strategic Research and Innovation Agenda (SRIA).

1.2. Project context

A runway excursion is the event in which an aircraft veers off or overruns the runway surface during either take-off or landing. Safety statistics show that runway excursions are the most common type of accident reported annually, in the European region and worldwide. There are at least two runway excursions each week worldwide. Runway excursions are a persistent problem and their numbers have not decreased in more than 20 years. Runway excursions can result in loss of life and/or damage to aircraft, buildings or other items struck by the aircraft. Excursions are estimated to cost the global industry about $900M every year. There have also been a number of fatal runway excursion accidents. These facts bring attention to the need to identify measures to prevent runway excursions. Several studies were conducted on this topic. Most recently a EUROCONTROL sponsored research “Study of Runway Excursions from a European Perspective” showed that the causal and contributory factors leading to a runway excursion were the same in Europe as in other regions of the world. The study findings made extensive use of lessons from more than a thousand accident and incident reports. Those lessons were used to craft the recommendations contained in the European Action Plan for the Prevention of Runway Excursions, which was published in January 2013. This action plan is a deliverable of the European Aviation Safety Plan, Edition 2011-2014. The European Action Plan for the Prevention of Runway Excursions provides practical recommendations with guidance materials to reduce the number of runway

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

excursions in Europe. The Action Plan also identified areas where research is needed to further reduce runway excursion risk.

The present study focuses on one of these areas concerning risk analysis using on-board recorded flight data. Flight data monitoring has been used by airlines as a pro-active safety tool for many years. Most airlines analyze the data recorded on-board their aircraft on a daily basis for any kind of anomalies or deviations from prescribed procedures. However the analysis capabilities are limited by the commercial software used by airlines to analyze the data and are sometimes very basic. This is also true for analyzing runway veer-off risk using flight data. Airlines themselves have often no resources or knowledge to enhance these flight data analysis software tools which also applies to the companies that develop the tools. Development towards ways to monitor veer-off excursions has been very limited due to lack of useable methods for analyzing the data. Today no tools are available to airlines to analyze the risk of veer-off excursions using their recorded flight data. Therefore this research aims to study and develop algorithms that can be used to analyze flight data for runway veer-off excursion risk factors.

In the present report, as a first step, an analysis of historical runway veer-off accidents/incidents is conducted. The important causal and contributing factors related to veer-offs are identified and presented.

1.3. Research objectives

The first objective of this study was to better understand the causal factors of runway veer-off excursions.

The study considered:

a) What is going wrong?

b) Which actors are involved and how?

c) What are the root factors which were judged to be instrumental in the causal chain of events leading to runway excursions?

d) What do these factors look like according to different views e.g. their importance and interrelations?

The second objective of this study was to identify which root factors can be measured and identified by means of flight data monitoring. The study only identifies these factors. Development of algorithms for post-processing of the factors is not included in this study. That is discussed in Task 3.3.3: Algorithms for the identification of veer-off risk factors using flight data [Ref. Project Plan FSS P3].

1.4. Approach

The study comprised of an analysis of veer-off occurrences that have happened worldwide in the past. Data on these occurrences have been collected from the NLR Air Safety database. The data consists largely of accidents and (serious) incidents. The majority of the occurrences have been brought in by the reporting organizations (e.g. AIB, DGAC, CAA UK, etc.). The occurrences are coded according to the ECCAIRS/ADREP taxonomy [Ref. ADREP taxonomy]. Using this taxonomy a first selection of veer-off occurrences has been made. This selection consists of occurrences that are coded in detail as well as occurrences that are coded in less or even poor detail. Out of the first selection manually a dataset has been selected at random with occurrences of which either an external investigation report was available or enough detail was found in the narrative description. This set has been evaluated on the basis of this information and further details that were found in the data. Factors which were judged to be instrumental in the causal chain of events have been determined and the chain of events leading to the veer-off has been described.

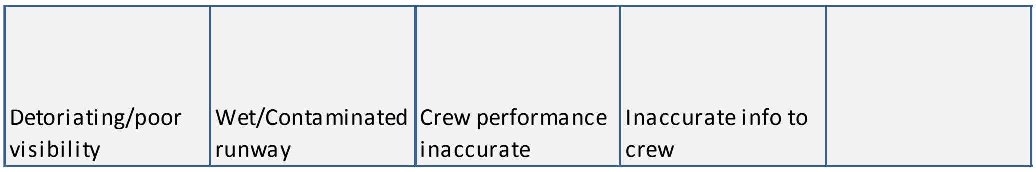
1.5. Structure of the document

Chapter 1 (this chapter) of the document gives the introduction. In chapter 2 the methodology is described and in chapter 3 the data analysis is carried out. In chapter 4 conclusions and recommendations are given. Chapter 5 finally gives the list of references.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

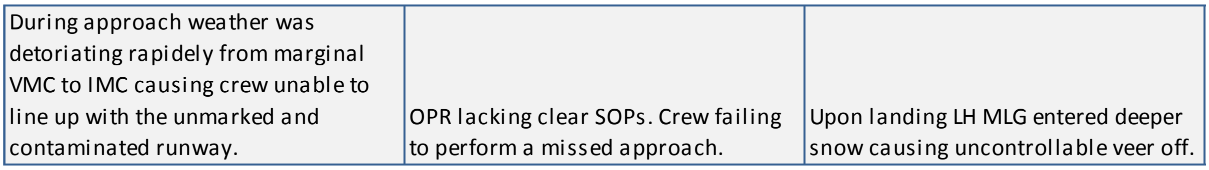
2 METHODOLOGY

For extraction of the dataset a selection was made out of runway veer-off excursions that have occurred world-wide during the period 2000-2014. The scope of the study was limited to fixed wing aircraft with two engines (jet and turboprop) or more and a maximum take-off weight (MTOW) of 5700 kg or more. The operation type was restricted to commercial or business transport flights, general aviation flights or state flights. A set of 104 occurrences has been analysed. These occurrences have been compiled in an Excel-spread sheet [Ref. XL-sheet]. This file contains occurrence parameters that have been extracted from the original database like: Aircraft make/model, Location of occurrence, Operator, Occurrence category, Operation type, Flight phase, Runway condition, Wind speed, etc., supplemented with the evaluation results. The evaluation results consist of up to five causal factors (see Figure 1 for an example) which were judged to be instrumental in the causal sequence of events leading to the veer-off occurrence plus a three step description of this sequence of events (See Figure 2 for an example).



Detoriating/poor visibility	Wet/Contaminated runway	Crew performance inaccurate	Inaccurate info to crew	

Figure 1: Example of causal factors



During approach weather was detoriating rapidely from marginal VMC to IMC causing crew unable to line up with the unmarked and contaminated runway.	OPR lacking clear SOPs. Crew failing to perform a missed approach.	Upon landing LH MLG entered deeper snow causing uncontrollable veer off.

Figure 2: Example of sequence of events description

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

3 DATA ANALYSIS

3.1. Causal factors and frequency

A taxonomy consisting of 31 standard descriptions has been established to describe causal factors that could contribute to a veer-off occurrence. The causal factors are presented in Table 1.

Table 1: Causal factors and their frequency of occurrence

Factor	Frequency %
Crew performance inaccurate	56
Wet/Contaminated runway	25
Crosswind	24
Inaccurate info to crew	23
Technical issue: Landing gear	16
Gust	12
Technical issue: NW steering system	11
Asymmetric thrust	11
Unstable Approach	8
Hard landing	7
Deteriorating/poor visibility	7
Heavy precipitation	6
Aquaplaning	5
Technical issue: Hydraulics	5
Maintenance issue	4
Technical issue: Braking system	4
Technical issue: Thrust reverse system	3
Technical issue: Engine control	3
Technical issue: Electrical power	3
Tailwind	2
Technical issue: Propeller control	2

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Runway lack of centreline lights	1
Technical issue: Elevator control	1
Technical issue: Fuel imbalance	1
Technical issue: Rudder control	1
ATC performance inaccurate	1
Technical issue: ILS	1
Technical issue: Engine	1
Technical issue: Autopilot system	1
Technical issue: Engine fire	1
Collision with animal	1

This table also shows the frequency of the causal factors that has been determined in the evaluation of the occurrences. The frequency of the causal factors is calculated as the percentage of the number of occurrences where a causal factor is present. So if a factor is present in all occurrences its frequency is 100%. (It should be noted that generally multiple factors are allocated to a simple occurrence. So the sum of the frequencies will be more than 100%).

Table 1 shows the frequency in the final set of 104 occurrences that has been evaluated. This set consists of 82% landing veer-offs and 18% take-off veer-offs. The distribution of landings and take-offs is consistent with that in the original sample of occurrences that were extracted from the ICAO/ADREP database. This sample contained 437 occurrences consisting of 84% landing veer-offs and 16% take-off veer-offs. In an NLR study from 2010 [Ref. Van Es (2010)] runway excursions were investigated with a focus on the European context. In that study the number of runway veer-off occurrences that occurred worldwide in the period 1980-2008 was determined. It was found that the distribution of landing veer-offs and take-off veer-offs was respectively 77% and 23%. These figures are fairly consistent with those found in the current study. The small difference could be allocated to the different time intervals. The current study only considers occurrences from the recent past whilst the [Ref. Van Es (2010)] study goes back to 1980.

In Table 2 the causal factors with a frequency of 10% or more are presented for landing and take-off separately.

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Table 2: Frequency of causal factors per flight phase

Factor	Frequency %		
	Total	**Landing**	**Take-off**
Crew performance inaccurate	56	55	58
Wet/Contaminated runway	25	27	16
Crosswind	24	25	21
Inaccurate information to crew	23	25	16
Technical issue: Landing gear	16	19	5
Gust	12	11	16
Technical issue: NW steering system	11	12	5
Asymmetric thrust	11	5	37

As is shown in the table both columns more or less correspond but there are also differences:

The causal factor “Crew performance inaccurate” shows the highest frequency for both landing and take-off. “Wet/Contaminated runway” and “Crosswind” also are ranked high for both landing and take-off and so is “Inaccurate info to crew”. Both landing and take-off show a reasonably high frequency for “Gust”. However technical issues with respect to the landing gear or the nose wheel steering system show a considerable higher frequency for landing than for take-off. For take-off the second highest frequency is found for the causal factor “Asymmetric thrust”. For landing this causal factor has a low frequency.

3.2. Causal factors analysis

In this section the eight causal factors with a frequency of 10% or more as represented in table 2 are discussed. The frequency is calculated as the total percentage of the number of occurrences in which a causal factor is present.

Crew performance inaccurate

This causal factor is observed in more than 50% of the occurrences for both landing and take-off. This factor was allocated to all occurrences where it was observed that action(s) or lack of action of the crew contributed to the occurrence of the veer-off. This causal factor comprises a wide range of crew handling from (in rare events) crew errors to (in most cases) non-optimal response for the situation. In the latter case this was mostly one of the conclusions from the investigation report. In the boxes below an example of both crew performances is given.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Crew lacking to follow pre-take-off and take-off checklist procedures thus failing to recognize that left hand propeller is still in start locks during take-off roll.

B737 AOM procedure was not precisely followed. Crew maintained braking after weathercock minimized tire cornering forces to counteract veer. The continued application of right wheel braking may have delayed the recovery of directional control.

The frequency of the causal factor "Inaccurate crew performance" could be lowered by crew performance training and crew awareness training. In the case of crew errors or even lack of crew discipline in following operating procedures this will be clear. In the case of crew non-optimal response when applying several on board control systems (auto braking, differential braking, nose wheel steering, rudder control) in a complex weather situation this will be more difficult.

Wet/Contaminated runway

"Wet/Contaminated runway" appears as a causal factor in 27% of the occurrences during landing and in 16% of the occurrences during take-off. In this study it was observed that in many occurrences the runway contamination was not the only factor and that the combination of factors caused the veer-off. Or, in other words: with a contaminated runway safety margins are decreased and if that is not taken into account than other factors can have worse effects. Typical observed combinations of factors are contaminated runway and:

- Loss of control due to non-optimal application of brakes or thrust reversers;
- Asymmetric landing brake force or asymmetric thrust;
- Upon landing, one landing gear entering deeper snow / snow bank;
- (Gusting) crosswind.

Another observation is that if the crew was not properly informed about the kind and/or amount of contamination directional control can be lost because the crew did not apply optimal techniques for the existing situation. In the box some examples are given.

- Runway contamination at touchdown would have been greater than reported in the RSC report;
- Crew received latest update RSC report that was almost one hour old;
- Aircraft lands on runway contaminated with 2.5 inch of slush whilst 0.75 inch of snow was reported;
- RSC report and weather report were not accurate;
- Latest RSC report passed to flight no longer accurate at touchdown of flight.

Crosswind

Controllability problems during crosswind landings on slippery runways is a well-known issue described in many studies [Ref. Cobb & Horne (1964)], [Ref. Van Es (2010)]. Crosswinds exceeding the capabilities of the aircraft or inadequate compensation by the pilots are the reasons for the influence of this factor. It can be estimated that the combination of a wet/contaminated runway and a minor to strong crosswind increases the risk of a veer-off with a factor of 7. [Ref. Van Es (2010)].

Only crosswind operations on dry runways conditions are certified. Aircraft manufacturers only give advisory information on crosswind limits for wet/contaminated runways1. These advisory crosswinds are often based on engineering models assuming steady (not gusting) wind or piloted simulations combined with engineering analyses. Normally flight tests are not conducted. Engineering simulators or engineering models are not a good tool to explore the ground part of a landing or take-off. This is because the quality of the mathematical ground model in combination with the motion and visual cues of a simulator is usually not high enough to allow sufficient confidence in the evaluation of the results. (In [Ref. Van der Zee] a literature study is conducted on methods and models for analyzing aircraft ground control, particularly in crosswind conditions and on slippery runways). Therefore limits based on pilot evaluations in a simulator may prove significantly different (optimistic in most cases) from realistic values. This also applies to engineering simulations which uses the same mathematical models as the flight simulators. Because the crosswind limits on wet and contaminated runways are advisory information only, operators can use different crosswind limits for the same aircraft and runway condition.

The crosswinds for dry runways are certified. However, there are a number of issues related to these certified crosswinds [Van Es et. al. (2001), Van Es (2006)] such as unclear means of compliance of crosswind certification and wind reporting inaccuracies. Furthermore the certification often gives demonstrated crosswinds rather than crosswind limits. This means that during the certification flights no crosswind was found that was considered limiting for a dry runway. All these above mentioned issues could play a role in the relatively high number of crosswind related veer-offs that occurred.

A factor of influence in the development of the veer-off is the fact whether the crew has enough information about the amount of crosswind and gusts to be expected. Also the crew should have enough awareness about the crosswind values that allow a safe landing.

Inaccurate information to crew

This causal factor is present in 25% of the occurrences during landing and in 16% of the occurrences during take-off. The consequence of providing the crew with inaccurate information will be clear: the

---

[1] A flight test program devised to explore the limits of aircraft crosswind performance under slippery runway conditions results in placing the safety of both aircraft and flight crew in jeopardy. It is therefore unfeasible to require such tests.

crew makes decisions with respect to landing or take-off strategy based on wrong or incomplete information. Typical examples are inaccurate reports with respect to weather, RSC or braking action (see the subsection “Wet/Contaminated runway”). But also lack of relevant information in the Flight Manual or the Operating Manual is observed (see box):

- Operator failing to provide crew with adequate guidance for utilization of full stop autoland and limitations in crosswind.
- Operator weaknesses in organization, procedures and quality assurance.
- Operator lack of training the crews with respect to the use of the nose wheel steering system.
- Airport Operations failure to conduct runway friction tests and to issue NOTAMS in accordance with existing regulations

Technical issue: Landing gear

The causal factor ”Technical issue: Landing gear” appears in 19% of the landing veer-off occurrences and in 5% of the take-off occurrences. This technical issue comprises two kinds of failure: landing gear not being locked in the down position or landing gear collapsing or breaking off. In the latter case it was observed that in a number of occurrences this was caused by a hard landing or by non optimal crew performance like landing with a lateral velocity. Also it was observed that maintenance issues were mentioned.

Gust

In combination with other factors like “crosswind” and/or “contaminated runway” gust can largely contribute to the development of a veer-off. Aircraft manufacturers only give advisory information on crosswind limits for wet/contaminated runways[2]. These advisory crosswinds are often based on engineering models assuming steady - not gusting - wind or piloted simulations combined with engineering analyses. There is often confusion among pilots how to interpret the maximum demonstrated crosswind component as given in the aircraft flight manual and in the aircraft operating manual [Ref. Van Es (2010)].

The causal factor “Gust” was observed in 11% of the landing occurrences and in16% of the take-off occurrences. In the cadre some examples are given.

---

[2] A flight test program devised to explore the limits of aircraft crosswind performance under slippery runway conditions results in placing the safety of both aircraft and flight crew in jeopardy. It is therefore unfeasible to require such tests.

- Heavy gust encounter in roll-out in severe crosswind, just as the aircraft speed was decreasing such that full rudder would be no longer effective enough to counteract.
- The combination of drift, reverse thrust, strong gusting crosswind, and the wet runway resulted in the loss of aircraft directional control.
- At touchdown gust that probably exceeded the aircrafts crosswind limit and caused it to weathercock to the left.
- During flare upon touchdown on main landing gear aircraft encounters a wind gust that lifts left hand wing.
- Crew misjudging wind/gust conditions that exceeded operator’s crosswind limitations.

Technical issue: Nose wheel steering system

This causal factor was present in 12% of the landing veer-off occurrences and in 5% of the take-off occurrences. It should be noted that here is discussed a technical issue: failing of the nose wheel steering system. Wrong usage of the nose wheel steering, for example the use of nose wheel steering when roll-out speed is still too high, also was observed but that item is part of “Crew performance inaccurate”.

The causal factor was present in 11 of the 104 occurrences. In 9 of the 11 cases it concerned an uncommanded turn generated by the nose wheel steering system caused by a runaway of the servo system: 5 times a hardover[3], 1 time a slowover[4] and in 2 occurrences there was no further information on the runaway. In one case the runaway occurred when the crew also had activated the system too soon at too high speed which may have worsened the effect of the uncommanded excitation of the nose wheel. Of the 2 cases where not an uncommanded turn was concluded in one case it was not determined how the nose wheel steering system had caused the veer-off.In the other case the nose wheel steering system was inoperative, which was in accordance with the MEL, but the flight crew was not (enough) aware of the fact that in the given wind conditions they could not control the aircraft without the system.

It is clear that a servo runaway relatively frequently occurs as failure of the nose wheel steering system. However in one of the investigation reports a discussion with a vendor is mentioned. In this discussion the vendor states that if the steering system is used as prescribed and if the crew reacts in the right way then an uncommanded turn will not result in a veer-off. The probability of occurrence of the failure is in accordance with that condition and the system is certified as such. This viewpoint implicates that specific crew training could help to reduce the number of veer-offs when the nose wheel steering system fails as

---

[3] A very fast movement to one side until the limit is reached and maintained.

[4] A slow movement to one side until the limit is reached and maintained.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

discussed above. A weak point in this assumption is however that the crew usually is not aware of the failure.

Asymmetric thrust

"Asymmetric thrust" is a factor contributing to take-off veer-off occurrences. This causal factor was observed in 37% of the take-off veer-offs and only in 5% of the landing veer-offs. Maintaining directional control with asymmetrical thrust can be difficult particularly below certain speeds. Moving the throttles to take-off thrust from asymmetrical thrust at a low power setting can result in significant thrust differences at high power. Therefore pilots should monitor the symmetric build-up of power on the engines when applying initial power. Typically the pilots of jet aircraft should advance the thrust levers to just above idle and allow the engines to stabilize momentarily then promptly advance the thrust levers to take-off thrust. Asymmetric thrust conditions are particularly hazardous in combination with slippery runways however they can also lead to difficulties on dry runways.

This causal factor was present in 5% of the landing veer-off occurrences and in 39% of the take-off occurrences. For both take-off and landing in half of the cases the asymmetric thrust was due to a technical reason and in the other half of the cases it was due to crew handling.

3.3. Flight Data Monitoring

In this section it is discussed to which extend the causal factors presented in the previous sections can be identified in flight data by means of flight data monitoring (FDM).

3.3.1. Background

In modern aircraft an increasing amount of electronic equipment is installed which uses a standardized data bus structure to communicate. This bus structure is standardized according to the ARINC protocol. Several protocols have evolved under the ARINC standard. Many commercial aircraft use the ARINC 429 standard developed in 1977 for safety-critical applications. Nowadays modern aircraft like the Airbus A380 use amongst others the ARINC 629 protocol that was developed by Boeing and NASA to overcome limitations of the ARINC 429 protocol. By making use of a bus structure parameters are available for equipment on multiple locations in the aircraft. These parameters are made available on the bus by all kind of equipment including sensors that measure aircraft flight parameters.

Flight data monitoring nowadays makes use of Quick Access Recorders (QAR) which are able to acquire large amounts of data with sufficient sample rate for automated post flight analysis. Simply spoken it can be assumed that all parameters that are available on the ARINC data bus can be recorded by the QAR. Of course it depends on the aircraft type and the ARINC protocol in use which parameters are indeed

Future Sky Safety has received funding from the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

available and with which rate. Since this study is meant for the Future Sky programme which targets the year 2050 it is assumed that there will be no restrictions in data and sample rate.

3.3.2. Identification of causal factors

In section 3.1, a taxonomy consisting of 31 standard descriptions has been defined to describe causal factors that could contribute to a veer-off occurrence. The causal factors which show a frequency of 5% or more[5] will be evaluated with respect to the possibility to identify these factors in the FDM data.

Crew performance inaccurate

This causal factor comprises a wide range of crew handling from (in rare events) crew errors to (in most cases) non-optimal response to a special situation. Typical examples are:

- Non adherence to standard operating procedures (SOPs).
- Exceeding (cross)wind limitations
- Non-optimal application of ground steering and braking techniques
- Non-optimal application of power levers

Non-adherence to SOPs and exceeding limitations can be identified if the representative parameters are included in the data set that the FDM system records. Typical SOPs are set up to assure that certain crew actions are performed (or not performed) when specific situations occur, e.g.: perform missed approach if approach is not stabilized below a certain glide slope altitude; establish a minimum value of thrust on both engines before starting take-off roll; do not apply nose wheel steering on landing roll-out before reaching a certain speed value; etc.

Of course not all non-adherence to SOPs will be identifiable. For instance it could be difficult to detect whether the pre-take-off checklist procedures have been followed completely.

Non-optimal response to a special situation is difficult to monitor. Typically FDM is applied on day to day operations. Special situations are rare and will not often occur in the data and when they do, the monitored crew performance might not be representative for that situation. For example, the crew performance during landing roll-out on a contaminated and slippery runway with crosswind and gust will depend on the awareness of the crew of that situation. If the crew estimates the situation to be slightly difficult and non-risky their performance will be more routinely than when they estimate the situation as difficult with a certain risk.

---

[5] A frequency of less than 5% is based on a very low number of observations that could be coincidental

Wet/Contaminated runway

The presence of a wet/contaminated runway and the extent and the nature of contamination cannot be determined from FDM data itself. This is in fact the case for most environmental data. Of course during post-processing it is possible to couple the FDM data with data from a weather/environmental database. This has been done for investigations. However it requires additional knowledge of data sources and query techniques and it depends on the availability of weather/environmental data.

The presence of a wet/contaminated runway cannot be measured directly but alternatively it is possible to identify its negative effects: the deteriorating braking conditions. Slippery runways can be identified from the recorded brake pressures. Low cycling braking pressure (e.g. in the order of 500 psi) are an indication of a friction limited braking on a slippery runway. If the brake pedal inputs are also recorded these data can be used to indicate the brake effort being made. Also differential braking can be identified from these recordings. See also below under “Aquaplaning”.

Crosswind

Wind speed and wind direction are available parameters in FDM data that are calculated in FMS. However these parameters cannot be used for analysis because it is known that FMS wind has a velocity bias of several knots (see figure 2), and a direction bias of several degrees. These deviations are caused by inaccuracies in the calculation of the drift angle, from the aircraft sensor data.

Wind speed and wind direction can be calculated more accurate based on the kinematic relations, which exist between the airspeed and ground speed vectors. Groundspeed and airspeed, as well as the heading, are available in FDM data. The ground track can be reconstructed from the aircraft deviations from the Localizer, in combination with the aircraft position co-ordinates. Because the orientation of the landing runway and the position of the Localizer transmitter are accurately known the ground track can be accurately determined. The remaining unknown is angle of slip of the aircraft. By knowledge of the aircraft properties (specifically the side force due to sideslip and aileron derivatives), it is possible to estimate the sideslip angle based on the measured lateral acceleration. By solving some vector equations the wind velocity and wind direction in the horizontal plane can be established. This method is less suitable for determining the wind vector during roll-out. For that it might be better to use wind measurement data of the airport or use the calculated wind values just before touch down.

Apart from that, during the final approach it is possible to detect the presence of crosswind by comparing the left and right angle of attack vanes. These vanes measure different values in sideslip conditions that typically occur in a crosswind approach, either during the decrab maneuver in a crabbed approach or during the entire approach in a sideslip approach.

During take-off when the aircraft’s speed is still low, the wind calculations will not be available yet. Crosswind then can be detected from the crew activity to keep the aircraft on its track. The combination of the parameters rudder deflection and nose wheel deflection together with the aircraft's speed are a measure for the presence of crosswind.

Inaccurate information to crew

The fact that the crew did not possess all relevant available information cannot be determined from FDM data.

Technical issue: Landing gear

In section 3.1 it was found that this technical issue comprises two kinds of failure: ”landing gear not being locked in the down position” or ”landing gear collapsing or breaking off”. The failure ”landing gear not being locked in the down position” is detected and annunciated in the aircraft and therefore is available in the FDM data. ”Landing gear collapsing or breaking off” causes an accident which will be detected anyhow.

Turbulence and gust

Turbulence and mean wind are statistical quantities, which do occur in combination. Mean wind is a constant value of the wind, averaged over a given time period of wind measurements. In theory the mean wind is invariant. However, obviously between various time periods the mean can vary. Deviations from the mean are defined as turbulence

Gust and turbulence are random deviations from the mean wind vector. When the aircraft encounters gust this is found in the longitudinal, lateral and vertical wind speeds that can be calculated as described above (see section “Crosswind”). It is possible to determine the magnitude of turbulence and gust from FDM data by post processing the calculated wind speeds.

The characteristics of turbulence are determined by the scale length (a measure of turbulence bandwidth) and standard deviation (a measure of the turbulence intensity). The intensity is defined as the ratio of standard deviation and mean wind.

Gust is by definition considered as a discontinuous and instantaneous change of the wind. Within Meteo messages gust is determined as the maximum value, over a 10 minutes period, of the wind velocity, filtered by a 3 seconds moving average filter.

For this kind of calculations the sample rate of the data should be high enough. Since this study is meant for the Future Sky programme which targets on the year 2050 it is assumed that there will be no restrictions in data and sample rate.

Technical issue: Nose wheel steering system

This technical issue concerns an uncommanded turn generated by the nose wheel steering system caused by a runaway of the servo system (hardover or slowover). As a consequence the nose wheel turns to one side to the limit position and stays in this position. On modern aircraft the nose wheel position is available on the data bus and can be recorded on the QAR. In combination with the pedal input the runaway can therefore be determined in the FDM data.

Asymmetric thrust

Asymmetric thrust can be determined directly in the FDM data. The values of N1 or (when available) EPR are monitored for both engines and these parameters are representative for the engine thrust.

Unstable Approach

According to the definition given by the Flight Safety Foundation (FSF) an unstable approach is defined as an approach that not meets the following criteria:

- ILS Approach – ILS within 1 dot of the localizer and glide slope.
- Visual Approach – Wings level at 500 feet AGL.
- Circling Approach – Wings level at 300 feet AGL.
- Only small heading and pitch changes required.
- Speed within +20/-0 kts of reference speed.
- Aircraft must be in proper landing configuration.
- Maximum sink rate of 1,000 feet per minute.
- Appropriate power settings applied.
- Briefings and checklists complete.

In general the approach should be stabilized at an altitude of 1000 ft AGL when IMC prevail and at an altitude of 500 ft AGL when VMC prevail. This may vary between operators which should be included in their SOPs. From the FDM data it cannot be determined whether the flight is in IMC or VMC unless the data is coupled with a METAR data base.

Parameters that are to be used to detect whether the approach is stable are: Glide slope deviation, Localizer deviation and relevant logic parameters that indicate that the deviations are valid[6]; Bank angle,

---

[6] The fact that Glide slope deviation and Localizer deviation are valid means that an ILS frequency has been selected and that deviation signals are received by the ILS receiver. It does not guarantee that the correct ILS

Heading angle, Pitch angle, Indicated airspeed, Vertical speed, N1 or EPR and the aircraft configuration parameters: Flap deflection. Slat deflection, Landing gear position, Ground spoilers armed logic and depending on the operators SOP parameters like autobrake settings etc.

When monitoring these parameters in FDM data, algorithms need to be developed because the unstable approach criteria as presented above are insufficient defined. For instance an algorithm that monitors the vertical speed should measure how long the maximum value is exceeded and to which extend before the approach is flagged as unstable. Also criteria should be defined for “small pitch changes”, both in magnitude and duration. The same applies for “wings level”.

The kind of approach that has actually been flown is not unambiguous determined from the FDM data. For instance: one could fly a visual manual approach with ILS stand by or one could fly a manual ILS approach. The difference could possibly be found in the autopilot modes that have been selected in the FMS.

Hard landing

A hard landing is characterized by the fact that a certain amount of vertical acceleration, or lateral acceleration, or both is exceeded. These accelerations are measured by the FDM system and thus hard landings can be identified in the FDM data. Accelerations however are difficult to measure because the high acceleration peak can be very small and the real peak value could be missed between two data samples. Therefore it is advised to monitor as well the vertical speed just before touch down because this parameter has a lower bandwidth than the acceleration. With respect to maintenance monitors Airbus the recorded vertical acceleration at aircraft CG and the recorded vertical speed using Radio Altimeter data [Ref. Parisis].

Detoriating/poor visibility

Actual visibility is not measured on board during flight and thus cannot be determined from FDM data. It is however possible that in the future actual weather information is uploaded to the aircraft and thus this parameter becomes available. Otherwise it can only be determined by coupling of FDM data and METAR data.

---

frequency has been selected. For instance, by mistake, the ILS frequency of a parallel runway could have been selected.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

Heavy precipitation

Actual precipitation is not measured on board during flight and thus cannot be determined from FDM data. It is however possible that in the future actual weather information is uploaded to the aircraft and thus this parameter becomes available. Otherwise it can only be determined by coupling of FDM data and METAR data. Perhaps wiper activation could be used to detect that precipitation did occur.

Aquaplaning

Aquaplaning, also known as hydroplaning is a condition in which standing water, slush or snow, causes the moving wheel of an aircraft to lose contact with the load bearing surface on which it is rolling with the result that braking action on the wheel is not effective in reducing the ground speed of the aircraft. A layer of water builds up beneath the tire in increasing resistance to displacement by the pressure of the wheel. Eventually, this results in the formation of a wedge between the runway and the tire. This resistance to water displacement has a vertical component which progressively lifts the tire and reduces the area in contact with the runway until the aircraft is completely water-borne. In this condition, the tire is no longer capable of providing directional control or effective braking because the drag forces are so low. Aquaplaning can occur when a wheel is running in the presence of water; it may also occur in certain circumstances when running in a combination of water and wet snow.

The aquaplaning itself cannot be measured but it is possible to detect the condition where aquaplaning could build up. Typically this is a slippery runway with low skid resistance condition. In that condition the maximum brake pressure where the wheel starts to slip and where the antiskid system reacts is relatively low. When the brake pressure is monitored, this situation is recognized by a relatively low (300-600 psi) average braking pressure which shows a cyclical variation caused by the antiskid system. By monitoring of the wheel rotation speed it can be detected that the wheel stops rotating which indicates that the wheel is slipping. This happens when the tire friction is very low and the antiskid system is not effective anymore. This might be caused by aquaplaning.

By also monitoring the brake pedal input it is possible to identify possible non-optimal crew performance in this situation.

Technical issue: Hydraulics

“Technical issue: Hydraulics” means failing of one of the hydraulic systems and as a result dropping of the hydraulic pressure of that system. Hydraulic pressure of the hydraulic systems is measured and monitored in the aircraft. These pressures are available in FDM and also the alerts that are generated by the aircraft monitoring and alerting system.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

A runway excursion is the event in which an aircraft veers off or overruns the runway surface during either take-off or landing. In the current study runway veer-off excursion occurrences that have taken place in the past have been analyzed. The objectives of the study were to better understand the causal factors of runway veer-off excursions and to identify which root factors can be measured and identified using on-board recorded flight data (Flight Data Monitoring: FDM). Data on these occurrences have been collected from the ICAO/ADREP database and a final set containing sufficient information for further analysis has been selected manually. A taxonomy consisting of 31 standard descriptions has been established to describe causal factors that could contribute to a veer-off occurrence. Eight of these causal factors that show a frequency off 10% or more in either take-off or landing or both have been discussed. The causal factors that show a frequency of 5%[7] or more for the total set (take-off plus landings) have been evaluated with respect to the possibility of identifying these factors in the FDM data.

It was concluded that for the majority of the discussed causal factors it should be possible to identify them in the FDM data. A number of the discussed causal factors cannot be identified directly in the FDM data. Typically this is the case for actual weather such as visual or precipitation. Those factors could be identified by coupling the FDM data to other supporting databases such as, for example, a database with METAR information. It was also concluded for a number of the discussed causal factors that the accuracy and sample rate of the required parameter(s) would not be sufficient in the FDM data as it is nowadays. It should be noted that in this study, it is assumed that there will be no restrictions in data and sample rate.

4.2. Recommendations

It is observed in the data analysis, that two causal factors that show a relatively high frequency of occurrence are related to the flight crew task. These causal factors are “Crew performance inaccurate” and “Inaccurate information to crew” with a frequency of occurrence of 55% and 22% respectively. It is therefore recommended that operators take in consideration whether the subject “veer-off” could get more attention in flight crew performance training and crew awareness training. Also it is recommended that effort is given by all supporting parties to provide the flight crew with timely and accurate information so that they are able to makes the right decisions with respect to landing or take-off strategy based on this information.

---

[7] A frequency of less than 5% is based on a very low number of observations that could be coincidental

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.

5 REFERENCES

Project Plan FSS P3	Van Es, G.W.H, “Project Plan P3 “Solutions for runway excursions”, NLR, 2015;
XL-sheet	J.A. Post, Veeroff Analysis on Causal factors v1.0.xlsm, NLR, 2015;
ADREP taxonomy	ICAO, http://www.icao.int/safety/airnavigation/aig/pages/adrep-taxonomies.aspx;
Van Es (2010)	Van Es, G.W.H, “A Study of Runway Excursions from a European Perspective”, NLR-CR-2010-259, NLR, 2010;
Cobb & Horne (1964)	Cobb, J., Horne, W. B., “Aircraft performance on slippery runways in crosswinds”, NASA-TM-X-54600, 1964;
Van Es (2006)	Van Es, G.W.H., “Crosswind Certification - How does it affect you?”, NLR, Technical Paper NLR-TP-2006-324, 2006;
Van Es et. al. (2001)	Van Es, G.W.H. and Van der Geest, P.J. and Nieuwpoort, T. M.H., “Safety aspects of aircraft operations in crosswind”, NLR, Technical Paper NLR-TP-2001-217, 2001;
Van der Zee	H.T.H. van der Zee, “Shortcomings in current modelling for modern aircraft”, NLR, Future Sky Report D3.2, 2015
Parisis	Capt. Marc Parisis, “ Avoiding hard landings”, Airbus presentation at 15th Performance and operations conference, Puerto Vallarta, 23 – 27 April 2007.

Future Sky Safety has received funding from the EU’s Horizon 2020 Research and Innovation Programme, under Grant Agreement No. 640597.