Executive summary

Quantification of Event Sequence Diagrams for a causal risk model of commercial air transport

Problem area
In support of the Federal Aviation Administration’s Systems Approach for Safety Oversight (SASO), the FAA has initiated research for the development of a causal risk model of commercial air transport. The model is intended to become part of a methodology to identify hazards and assess risks within the 14CFR Part 121 aviation system. The Netherlands Ministry of Transport has initiated a similar research effort to develop a causal model for aviation safety. The objective of that model is to represent the causes of air transport accidents and the safeguards that are in place to prevent them. In both models the proposed risk model architecture introduces a hybrid causal model of event sequence diagrams, fault trees and Bayesian belief networks. In a previous study, generic accident scenarios that form the upper layer of the two integrated risk models have been developed. Event sequence diagrams are used to represent these accident scenarios. The combined set of accident scenarios provides a similar ‘backbone’ for both model development efforts. The current study is aimed at quantifying these previously developed event sequence diagrams by expressing the probability of occurrence of the various accident scenarios as a function of the probability of occurrence of the initiating events.

Description of work
An event sequence diagram is a flowchart with paths leading to different end states. Each path through the flowchart is a scenario. Along each path, pivotal events are identified as either occurring or not occurring. The event sequence starts with an initiating event such as a perturbation that requires some kind of response from operators or pilots or one or more systems. Intentionally, the building blocks of the scenarios are kept broad and generic to cover many ‘similar’ situations. The event sequence diagram provides a qualitative description of the scenarios. It is quantified by assessing the probability of occurrence of each of the different pathways. Probabilities of occurrence initiating events, pivotal events and end states are estimated from historical data. The data sample was limited to commercial air transport with ‘western built’ aircraft heavier than
5,700 kg maximum take-off weight. Only fixed wing aircraft are considered. The NLR Air Safety Database was used as a primary source of data, details of the data sources are provided in the appendix. The general approach was to quantify the probability of occurrence of the end states from accident data, where the probability of occurrence of the initiating events was determined from ‘occurrence data’ such as an airline’s occurrence reporting system. Conditional probabilities of pivotal events where then calculated from the initiating event and end state probabilities.

Results and conclusions
For each event sequence diagram, this report provides a definition of the initiating events, pivotal event and end states as well as an estimation of their (conditional) probability of occurrence. Pivotal event probabilities are presented as conditional probabilities, whereas initiating events and end state probabilities are described as absolute probabilities, i.e. probability of occurrence per flight.

All probabilities are provided as point estimates. During the qualitative and quantitative development of the event sequence diagrams several assumptions have been adopted. These are explicitly stated in the report.

Applicability
The causal models of which the event sequence diagrams are the backbone are intended to be used for improving understanding of the causes of air transport accidents, identifying areas where improvements could be made to the technical and managerial safeguards against accidents, and quantifying the risk implications of alternative technical and managerial changes, allowing evaluation of their cost-effectiveness. In this respect it is important that the numerical estimates derived in this report apply to ‘average’ world-wide commercial air transport. For particular applications of the model, it may be necessary to derive probability estimates that take into account local effects.
Quantification of Event Sequence Diagrams for a causal risk model of commercial air transport

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Summary

In support of the Federal Aviation Administration’s Systems Approach for Safety Oversight (SASO), the FAA has initiated research for the development of a causal risk model of commercial air transport. The Netherlands Ministry of Transport has initiated a similar research effort to develop a causal model for aviation safety. The proposed risk model architecture of both models introduces a hybrid causal model of event sequence diagrams, fault trees and Bayesian belief networks. Both models use a similar ‘backbone’. In a previous study, generic accident scenarios that form the backbone of the integrated risk models have been developed. Event sequence diagrams are used to represent these accident scenarios. The current study is aimed at quantifying these previously developed event sequence diagrams by expressing the probability of occurrence of the various accident scenarios as a function of the probability of occurrence of the initiating events. These probabilities are estimated from historical data. The data sample was limited to commercial air transport with ‘western built’ aircraft heavier than 5,700 kg maximum take-off weight. Only fixed wing aircraft are considered. The NLR Air Safety Database was used as a primary source of data. The general approach was to quantify the probability of occurrence of the end states from accident data, where the probability of occurrence of the initiating events was determined from ‘occurrence data’ such as an airline’s occurrence reporting system. Conditional probabilities of pivotal events where then calculated from the initial event and end state probabilities. For each event sequence diagram, this report provides a definition of the initiating events, pivotal event and end states as well as an estimation of their (conditional) probability of occurrence.
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26.1 Definitions

26.2 Quantification

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27.1 Definitions

27.2 Quantification

28 ESD29 - Thrust reverser failure

28.1 Definitions

28.2 Quantification

29 ESD30 - Aircraft encounters unexpected wind

29.1 Definitions

29.2 Quantification

30 ESD31 - Aircraft are positioned on collision course

30.1 Definitions

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<tr>
<td>ACAS</td>
<td>Airborne Collision Avoidance System</td>
</tr>
<tr>
<td>AIDS</td>
<td>Accident and Incident Database System</td>
</tr>
<tr>
<td>ASAP</td>
<td>Aviation safety Action Program</td>
</tr>
<tr>
<td>ASR</td>
<td>Air Safety Report</td>
</tr>
<tr>
<td>ASRS</td>
<td>Aviation Safety Reporting System</td>
</tr>
<tr>
<td>ATA</td>
<td>Air Transport Association of America</td>
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<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>CAA</td>
<td>Civil Aviation Authority</td>
</tr>
<tr>
<td>CFIT</td>
<td>Controlled Flight Into Terrain</td>
</tr>
<tr>
<td>CRM</td>
<td>Crew Resource Management</td>
</tr>
<tr>
<td>ECAC</td>
<td>European Civil Aviation Conference</td>
</tr>
<tr>
<td>EGPWS</td>
<td>Enhanced Ground Proximity Warning System</td>
</tr>
<tr>
<td>ESD</td>
<td>Event Sequence Diagram</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>GPWS</td>
<td>Ground Proximity Warning System</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>MOR</td>
<td>Mandatory Occurrence Report</td>
</tr>
<tr>
<td>MTOW</td>
<td>Maximum Take-Off Weight</td>
</tr>
<tr>
<td>NTSB</td>
<td>National Transportation Safety Board</td>
</tr>
<tr>
<td>P</td>
<td>Probability</td>
</tr>
<tr>
<td>RTO</td>
<td>Rejected Take-Off</td>
</tr>
<tr>
<td>SDR</td>
<td>Service Difficulty Report</td>
</tr>
<tr>
<td>SOP</td>
<td>Standard Operating Procedure</td>
</tr>
<tr>
<td>STCA</td>
<td>Short Term Conflict Alerting System</td>
</tr>
<tr>
<td>TAWS</td>
<td>Terrain Avoidance Warning System</td>
</tr>
<tr>
<td>TCAS</td>
<td>Traffic Collision Avoidance System</td>
</tr>
<tr>
<td>$V_1$</td>
<td>Take-off decision speed</td>
</tr>
<tr>
<td>$V_{ref}$</td>
<td>Reference speed</td>
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</table>
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1 Introduction

1.1 Background
An essential element of safety management is a system to achieve safety oversight. FAA is moving towards a Systems Approach for Safety Oversight (SASO). In support of the SASO program, FAA has initiated research requirements, including a requirement to develop a methodology to identify hazards and assess risks within the 14CFR Part 121 aviation system. To meet requirement CA-02, University of Maryland, Hi-Tec Systems and the National Aerospace Laboratory NLR are jointly developing an integrated risk model. The proposed risk model architecture introduces a hybrid causal model of Event Sequence Diagrams, Fault Trees and Bayesian Belief Networks.

The Netherlands Ministry of Transport has initiated a similar research effort to develop a causal model for aviation safety [Ale et al 2005]. The purpose of the model being developed in the Netherlands is to describe the air traffic system and its safety functions in such a way that it is possible to analyze risk reduction alternatives and that it will serve as a means of communication between experts and managers within the industry. The model being developed in the Netherlands also combines Event Sequence Diagrams, Fault Trees and Bayesian Belief Nets into a single structure.

Because of the similarities between the two research efforts it was decided to frequently exchange results and if possible use similar components in the model and the model structure. Both causal models use the same backbone structure of generic accident scenarios. In a previous study [Roelen and Wever 2005] those generic accident scenarios that form the upper layer of the integrated risk model have been developed. Main accident types have been defined based on the ICAO definition of an accident, in order to systematically develop accident scenarios: abrupt maneuver, cabin environment, uncontrolled collision with ground, controlled flight into terrain, forced landing, mid-air collision, collision on ground, structure overload and fire/explosion. The accident scenarios are grouped by accident type and different flight phases. The Event Sequence Diagram (ESD) methodology is used for representing accident scenarios. In [Roelen and Wever 2005] 35 generic accident scenarios have been developed based on a combination of retrospective analyses and prospective analyses. These scenarios describe qualitatively the sequence of events at a high level of abstraction. The high level of abstraction is required to make the scenarios easy to understand for users and to keep the model transparent and simple at the top layer of the integrated risk model.
1.2 Objective
The current study is aimed at quantification of the set of Event Sequence Diagrams that were developed and described in [Roelen and Wever 2005].

1.3 Research approach
The scope was limited to commercial air transport with ‘western-built’ aircraft heavier than 5,700 kg. There are no geographical restrictions. Only fixed wing aircraft are considered. The NLR Air Safety database was used as a primary source of data. Appendix A provides an overview of the types of data collected in this database. The general approach was to quantify the probability of occurrence of the end states from accident data, where the probability of occurrence of the initiating events was determined from ‘occurrence data’ such as an airline’s occurrence reporting system. Some of this occurrence data is confidential. Conditional probabilities of pivotal events where then calculated from the initial event and end state probabilities.

Airclaims and ADREP were the primary accident data sources. The time period considered was 1990-2003. This period provided a dataset that is large enough for quantification and is considered representative for ‘current’ air transport. When only Airclaims was used the time period was slightly expanded to 1985 - 2005 to provide a larger data sample. Because of the size of most databases involved, much of the initial analysis was done by running queries, e.g. looking for particular key words. Each incident in the resulting dataset was then individually analyzed to verify whether it ‘fitted’ the particular ESD under consideration.

The primary source of data for quantification of the probability of occurrence of the initiating event are the databases of Service Difficulty Reports and Air Safety Reports (see Appendix A) but sometimes other sources of data were used if these were considered to be more accurate.

1.4 Acknowledgements
The authors are indebted to Jennelle Derrickson (FAA – William J. Hughes Technical Centre) and Rob van der Boom (Netherlands Ministry of Transport) for overall monitoring and co-ordination. Many thanks also to Ali Mosleh (University of Maryland) and Linda Bellamy (White Queen) who provided comments and ideas for this research. Fred Leonelli, Tommy McFall, Richard C. Berg and Harold Donner (all of FJLeonelli Group) provided a much appreciated review of the first set of ESDs.

1.5 Contents of this report
Chapter 2 of this report provides a general description of Event Sequence Diagrams. In the next chapter, each Event Sequence Diagram is individually described and quantified. Definitions of each of the initiating events, pivotal events and end states are provided, and the (conditional) probabilities are derived. A description of the data sources is provided in Appendix A.
2 Event Sequence Diagrams

2.1 General theory
An Event Sequence Diagram (Figure 1) is a flowchart with paths leading to different end states. Each path through the flowchart is a scenario. Along each path, pivotal events are identified as either occurring or not occurring. The event sequence starts with an initiating event such as a perturbation that requires some kind of response from operators or pilots or one or more systems [Stamatelatos et al. 2002].

![Figure 1: Event Sequence Diagram](image)

Conditional operators can be included to represent different outcomes depending on whether the condition is met or not. Figure 2 and Figure 3 show types of events and conditions in an ESD and their iconic representation.

Intentionally, the building blocks of the scenarios are kept broad and generic to cover many ‘similar’ situations. The detailed specific or possible causes or contributing factors of these events are not directly of interest at the scenario level. They are added, when such details are necessary, through other layers of the model, such as Fault Trees of Bayesian Belief Nets. Event Sequence Diagrams are often combined with fault trees. In practice, Event Sequence Diagrams are typically used to portray progression of events over time, while fault trees best represent the logic corresponding to failure of complex systems [Stamatelatos et al. 2002]. Fault trees are used to model initial and pivotal events in Event Sequence Diagrams in sufficient detail. The initiating and pivotal events in the Event Sequence Diagram are the top events in the fault trees.
Only active events are put in the accident sequence. Latent events are dealt with in the Fault Trees and Bayesian Belief Nets. This is done to limit the size of the accident scenarios and to make them easier to understand. Furthermore, latent failures are often ‘common mode’ and/or ‘soft’ causal relations, which can be better expressed in influence diagrams rather than ESDs.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Initiating event</strong></td>
<td>The first event in an ESD which initiates a sequence of events terminating in an end state</td>
</tr>
<tr>
<td><strong>Pivotal event</strong></td>
<td>An event which has two outcomes, typically ‘yes’ and ‘no’, corresponding to event occurrence and non-occurrence.</td>
</tr>
<tr>
<td><strong>End state</strong></td>
<td>It is the terminating point of an ESD scenario. An ESD can have multiple end states.</td>
</tr>
<tr>
<td><strong>Comment box</strong></td>
<td>Used for providing information regarding the development of the accident sequence.</td>
</tr>
</tbody>
</table>

*Figure 2: Types of events in an ESD and their iconic representation*

<table>
<thead>
<tr>
<th>Condition Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time condition</strong></td>
<td>Represents a condition of the form $a &lt; t &lt; b$. Leads to two outcomes depending on whether the condition is met or not.</td>
</tr>
<tr>
<td><strong>Physical variable condition</strong></td>
<td>Represents a condition of the form $a &lt; p &lt; b$. Leads to two outcomes depending on whether the condition is met or not.</td>
</tr>
</tbody>
</table>

*Figure 3: Types of conditions in an ESD and their iconic representation*
2.2 Quantification
The objectives of the risk model require that the model can be used for probabilistic risk assessments. The probability of occurrence of the various accident scenarios must be expressed as a function of the initiating events. The event sequence diagram provides the qualitative description of the scenarios. It is quantified by assessing the probability of occurrence of each of the different pathways.

An event sequence diagram is comparable to a river that starts big and then branches off into smaller arms, eventually ending up in the sea. The total amount of water that passes through at the beginning is equal to the amount that eventually flows into the sea. The difference between the ESD and the river is that instead of water, probabilities flow through the ESD.

There are basically three different ways of describing how big the river and its individual branches are.

1) We can describe the total amount of water in absolute terms for each part of the river. In the ESD this means that all probabilities are expressed as absolute probabilities (see Figure 4).

2) We can normalize each branch of the river by the size of the river at the beginning. The quantities at the end all add up to one (see Figure 5).

3) For each individual branch point, we can describe the relative distribution of the flow among the different branches. The quantities at each individual pivotal point add up to one. In the ESD this means that all probabilities are expressed as probability of occurrence conditional to the preceding pivotal event (see Figure 6).

From the point of view of accuracy and completeness, the three different ways are equal. There are practical reasons why it could be more appropriate to use one way instead of another. Three different criteria are important for determining the most practical representation:

- Communication with experts and non-experts
- Retrieving numbers from existing datasets
- Configuration control of the ESD

Option 1 is a good option if the numbers in itself make sense. It provides an immediate picture on the overall size of the ‘river’ (or ESD) and can be compared to other ‘rivers’ (ESDs), for instance for comparing probabilities of end states. Option 2 is suitable to assess the individual ESD at a glance. Because all numbers are normalised to the size of the river (or the probability of the initiating event) the probabilities will usually not be very small, and this way of
expressing provides a good overall picture and allows easy comparison of the sizes of the different branches. Absolute probabilities can be calculated by multiplying with the probability of occurrence of the initiating event. Option 3 has big advantages for configuration control of the ESDs. If changes are made upstream or downstream, the relative distribution for each branch point is unaffected. Calculation is also straightforward; the probability of occurrence is calculated by multiplying the probability of occurrence of the initiation events with the conditional probabilities along its respective branch points.

In retrieving numbers from datasets, in practice we often use combinations of options 1, 2 and 3, so from that point of view there is no real preference. Absolute probabilities are calculated by multiplying with the probability of the initiating event and all relative probabilities of all preceding branches.

In this report, all probabilities are calculated according to the system in Figure 6. The numbers at the pivotal events represent conditional probabilities. Numbers at the initiating event and the end states are absolute probabilities. The sum of the probabilities of the end states is equal to the probability of the initiating event. At each pivotal event, the conditional probabilities add up to 1.

![Figure 4: ESD quantification, absolute probabilities](image-url)
2.3 Numerical accuracy

All quantitative data in this report are provided as point estimates. The authors are keenly aware of the fact that many calculations are based on relatively small datasets, and some numbers will have large bands of uncertainty. For reasons of consistency, all probabilities in this report are displayed as numbers with two decimal places. This may create an illusion of numerical accuracy.
2.4 Changes relative to initial set of ESDs

After the first ESD report [Roelen and Wever 2005] was released, several changes have been made to the original set of ESDs. Most of these changes were made as a result of an effort to integrate all ESDs in a single master logic diagram [Bellamy and Roelen 2006].

In comparison with the set of ESDs described in [Roelen and Wever 2005] the following changes have been made:

ESD 11 - Fire onboard aircraft
The original ESD ‘fire onboard aircraft’ had 3 possible pathways out of the pivotal events ‘flight crew fails to detect smoke/fire’ and ‘flight crew fails to extinguish fire’. These 3 possible pathways are ‘flight control system failure’, ‘aircraft structural failure’ and ‘flight crew incapacitation’. In the current version of the ESD this distinction has been abandoned. The investigation after fatal fire accidents (such as the Swissair 111 accident and the Concorde accident) often fails to determine the exact reason of the loss of control. Quantification of the relative frequency of occurrence of the three possible pathways is therefore speculative. Because in the original ESD the sequence following the three pivotal events ‘flight control system failure’, ‘aircraft structural failure’ and ‘flight crew incapacitation’ was similar in all three cases, the distinction was considered less relevant. An added advantage of the new ESD is that it is consistent with common practice of Event Sequence Diagram logic. The original ESD had 3 possible ‘yes’ pathways out of the pivotal events ‘flight crew fails to detect smoke/fire’ and ‘flight crew fails to extinguish fire’. It is more conventional to have only two possible pathways, one for ‘yes’ and one for ‘no’.

ESD 13 and 22 Flight control system failure.
In the original set of ESDs there were two similar ESDs related to the initiating event flight control system failure. The only difference between the two ESDs was the flight phase they represented. Because most other ESDs represent event sequences that can occur in more than one flight phase, it was deemed unnecessary to have two separate ESDs only for this specific initiating event. ESD 13 and ESD 22 were integrated into a single ESD 13. ESD 22 has been deleted.

ESD 15 Anti-ice/de-ice system not operating
The initiating event of this ESD has been replaced by ‘ice accretion on the aircraft’, which was the first pivotal event in the original ESD 15. The original initiating event ignores the fact that ice build-up may occur even when the anti-ice / de-ice system is operational. It is also slightly confusing because even if the anti-ice / de-ice system is not operational, ice accretion will only occur if the aircraft flies in icing conditions. By replacing it with the new pivotal event ‘ice
accretion on aircraft’ these problems were solved. The remainder of the ESD is similar to the original ESD.

ESD 17 Aircraft encounters adverse weather, ESD 34 Aircraft encounters unexpected wind and ESD 36 Aircraft encounters turbulence.

These three ESDs have been integrated into a single ESD 17 ‘aircraft encounters adverse weather’. The reason for integration is that the original three ESDs describe occurrences that are very similar and are easily represented in a single ESD. By folding the three ESDs into a single Event Sequence Diagram, a lot of potential confusion on which occurrence should be classified to which ESD has been removed. The logic has not been changed.

ESD 19 Unstable approach, ESD 20 Flight crew fails to execute missed approach according to missed approach procedures, and ESD 24 Unstable approach.

These ESDs have been integrated into a single new ESD 19 ‘Unstable approach’. Although the three separate ESDs describe distinctly different scenarios, these are easily combined into a single ESD. The single ESD is more compact and easier to understand than the 3 original ESDs. The logic has not been changed.

ESD 25 Aircraft handling by flight crew during flare inappropriate.

The original ESD 25 had a pivotal event ‘failure to achieve maximum braking’ following the pivotal event ‘aircraft touchdown fast or long’. In the new ESD 25 the pivotal event failure to achieve maximum braking has been deleted. A long or fast touchdown by definition is considered to result in a runway overrun, even if maximum braking is achieved.

ESD 33 Cracks in aircraft pressure cabin

The pivotal event ‘failure of maintenance to detect and repair cracks’ has been deleted from the original ESD. It was the only pivotal event in the entire set of ESDs that described an occurrence which takes place before the aircraft is pushed back from the gate. All other events happen somewhere between the gate-to-gate cycle.

2.5 Assumptions

During the qualitative and quantitative development of the event sequence diagrams several assumptions have been adopted. These assumptions are necessary in order to restrict the complexity of the model or because of limitations on available data. It is important to recognise these assumptions and to determine the impact of the assumptions on the model results.
The following general assumptions have been made:

- It is assumed that the data samples which are being used for quantification are representative for the type of air transport at which the risk model is aimed.

- It is assumed that during analysis of the data sample no mistakes have been made by the analysts, i.e. that all relevant cases in the data sample have been included in the analysis.

- It is assumed that each occurrence in the data samples can be uniquely and unambiguously assigned to a particular ESD.

- It is assumed that the data bases which are being used in the analysis are complete, i.e. that there is no overreporting, underreporting or any other bias in the data bases.

- In cases where no examples of specific accident scenarios are found in the data sample, it is assumed that the probability of occurrence of that scenario is 0.

- It is assumed that there are no dependencies between the different ESDs.

- It is assumed that events in the ESDs cannot occur ‘partially’, i.e. initiating events and pivotal events have only ‘yes’ or ‘no’ output pathways.
3 ESD1 - Aircraft system failure

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft system failure.

3.1 Definitions

Aircraft system failure
The initiating event ‘aircraft system failure’ includes all system failures that could lead to an aborted take-off, with the exception of engine failures and system failures that can result in directional control problems. Engine failures and directional control system failures are addressed in ESD 9 and ESD 4 respectively. Pitch control problems during the take-off roll are addressed in ESD10.

Flight crew rejects take-off
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway remaining. At a certain point, the amount of runway available may not be sufficient to bring the aircraft to a complete stop. For this reason a decision speed $V_1$ is calculated before each take-off. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$ the take-off can be safely rejected, at speeds above $V_1$ the take-off should be continued. Typical $V_1$ values for large commercial jet aircraft vary from 125 to 160 knots. The actual $V_1$ depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some
operators and aircraft manufactures have defined a speed up to which a take-off should be rejected for all observed failures. At speeds between this speed and the take-off decision speed \( V_1 \), the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

\[ V > V_1 \]

The event \( V > V_1 \) describes a situation where the rejected take-off is initiated at a speed higher than the decision speed \( V_1 \). The decision speed \( V_1 \) is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below \( V_1 \) the take-off can be safely rejected, at speeds above \( V_1 \) the take-off should be continued. Typical \( V_1 \) values for large commercial jet aircraft vary from 125 to 160 knots. The actual \( V_1 \) depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient.

**Failure to achieve maximum braking**

Immediately following the decision to reject a take-off, the flight crew must start reducing the speed of the aircraft. Particularly in the case of a high speed rejected take-off, braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

### 3.2 Quantification

A data sample of Service Difficulty Reports (see Appendix A for a description of this sample) was used to determine the probability of a system failure during take-off and the likelihood of a rejected take-off in the event of a system failure. The analysis was limited to air carrier operations from 1985 through 2003. Overall exposure is 216 million flights. Failures of systems with ATA codes 2710-2722 (aileron and rudder), 3244-3245 (tyre) and 3250-3251 (nose wheel steering) are not included here, these are dealt with in ESD 4. The results are presented in Table 1.
Table 1: Conditional probability of rejected take-off given a system failure

<table>
<thead>
<tr>
<th>System</th>
<th>ATA code</th>
<th>Number of SDRs</th>
<th>Likelihood of RTO in the event of a system failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flap</td>
<td>2750 – 2752</td>
<td>320</td>
<td>0.5</td>
</tr>
<tr>
<td>Drag control</td>
<td>2760 – 2761</td>
<td>255</td>
<td>0.9</td>
</tr>
<tr>
<td>Instrument</td>
<td>3100 – 3110, 3160 – 3197, 3412 – 3414, 3416 – 3417, 3420 – 3425</td>
<td>430</td>
<td>0.8</td>
</tr>
<tr>
<td>Landing gear</td>
<td>3200 – 3243, 3246, 3252 – 3297</td>
<td>664</td>
<td>0.2</td>
</tr>
<tr>
<td>Stall warning</td>
<td>3418</td>
<td>310</td>
<td>0.7</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>3600 – 3697</td>
<td>186</td>
<td>0.4</td>
</tr>
<tr>
<td>Doors</td>
<td>5200 – 5297</td>
<td>1083</td>
<td>0.7</td>
</tr>
<tr>
<td>Other</td>
<td>All¹ ATA codes between 2100 and 6199 or between 7100 and 8097 that are not taken into account in the items listed above.</td>
<td>2977</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>6225</strong></td>
<td><strong>0.59</strong></td>
</tr>
</tbody>
</table>

The table lists both the number of occurrences of the initial event as well as the conditional probability of the pivotal event ‘flight crew rejects take-off’ for the various aircraft systems that are considered. Based on these results, the probability of a system failure during the take-off roll is estimated at 6225 / 216 million = 2.92·10⁻⁵ per flight. Obviously, the conditional probability of a rejected take-off in the event of a system failure depends on which system fails and ranges from 0.2 up to 0.9. The average value, taken across all system failures, is 0.59.

To estimate the frequency of occurrence of the end states, a data sample of accidents and incidents from the Airclaims database was analysed. The sample was restricted to accidents and incidents involving western-built aircraft heavier than 5,700 kg MTOW in commercial operations. Data from 1985 through 2005 was used, representing a total of 399 million flights.

The data sample contains 4 take-off overrun accidents resulting from system failures and subsequent take-off rejection. In 3 cases the take-off was aborted at a speed above V₁, in 1 case the take-off was aborted at a speed below V₁. There were no veer-off accidents in the data sample. Based on this data, the probability of an overrun after a system failure and a take-off abort above V₁ is estimated to be 7.50·10⁻⁹. The probability of an overrun after a system failure and a take-off abort below V₁ is estimated to be 2.50·10⁻⁹.

¹ Engine related failures, as well as directional control and pitch control failures are not taken into account. For associated ATA chapters, see the description of ESD 4 and ESD 9.
The conditional probability that the speed is above $V_1$ when a take-off is rejected because of a system failure is $7.50 \cdot 10^{-9} / (2.92 \cdot 10^{-5} \times 0.59) = 4.35 \cdot 10^{-4}$.

The conditional probability of ‘failure to achieve maximum braking’ in the event of a system failure and take-off rejection at a speed below $V_1$ is $2.50 \cdot 10^{-9} / (2.92 \cdot 10^{-5} \times 0.59 \times (1 - 4.35 \cdot 10^{-5})) = 1.45 \cdot 10^{-4}$.

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft system failure.
4 ESD 2 – ATC event

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: Air traffic related event.

4.1 Definitions

ATC event
For the purpose of this ESD, an ATC event is defined as any ATC related occurrence which could result in a decision to reject a take-off, with the exception of runway incursions. Possible separation infringements with other traffic on the departure runway (runway incursions) are excluded from this ATC event and are treated separately in ESD 32. Examples of ‘ATC events’ are possible separation infringements with another departure or with a missed approach on another runway. The problem situation could be caused by the aircraft in take-off (it did not have a take-off clearance yet) or by ATC (a take-off clearance is given while other traffic nearby). ATC can give an instruction to abort the take-off or the crew can independently decide to perform a rejected take-off (RTO). An instruction by ATC to abort the take-off because of the presence of birds in the vicinity of the runway is also included in this initiating event.

Flight crew rejects take-off
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take-off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway.

remaining. At a certain point, the amount of runway available may not be sufficient to bring the aircraft to a complete stop. For this reason a decision speed $V_1$ is calculated before each take-off. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$ the take-off can be safely rejected, at speeds above $V_1$ the take-off should be continued. Typical $V_1$ values for large commercial jet aircraft vary from 125 to 160 knots. The actual $V_1$ depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some operators and aircraft manufactures have defined a speed up to which a take-off should be rejected for all observed failures. At speeds between this speed and the take-off decision speed $V_1$, the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

$V > V_1$

The event $V > V_1$ describes a situation where the rejected take-off is initiated at a speed higher than the decision speed $V_1$. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$ the take-off can be safely rejected, at speeds above $V_1$ the take-off should be continued. Typical $V_1$ values for large commercial jet aircraft vary from 125 to 160 knots. The actual $V_1$ depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient.

Failure to achieve maximum braking

Immediately following the decision to reject a take-off, the flight crew must start reducing the speed of the aircraft. Particularly in the case of a high speed rejected take-off, braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

Runway overrun

A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the
side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**Aircraft continues take-off**

There are two situations leading to this end state:
- ATC instructs the crew to reject the take-off but the crew does not comply, e.g. because they decide that it is not possible any more or because of communication problems;
- During take-off roll, an ATC event occurs but neither ATC nor the crew detects it or reacts to it.

### 4.2 Quantification

**Air Safety Database**

The NLR Air Safety Database contains several sources for RTO related incidents and accidents. One source is an airline occurrence reporting system with occurrence reports from several airlines. Only commercial operations with large (>5700 kg MTOW) Western built aircraft are considered. A search on incidents in the take-off flight phase from 1993 to 2004 (corresponding with 10.5 million flights) resulted in 416 RTOs in which ATC was a key factor, including runway incursions. Further study of the first 195 incidents resulted in the following causes for the RTOs:
- 58 ATC event related;
- 58 runway incursion related;
- 60 of which it is not clear whether it is an ATC event or a runway incursion;
- 19 which are outside the scope (e.g. ATC detects smoke coming out of the engines during take-off).

Given the fact that there are as many ATC events as runway incursions, it is assumed that the 60 unclear causes can be equally divided over the ATC events and the runway incursions. This means that for the incidents that are in scope of the “air traffic situation” definition, 50% can be related to an ATC event and 50% to runway incursions.

Based on this sample, the probability of a RTO, given an ATC event according to the definition of ESD 2 is 45% of 416 incidents in 10.5 million flights is $1.78 \times 10^{-5}$ per flight.

A second sample of the airlines reported incidents focused on those situations during take-off where no RTO had taken place but the incident was ATC related. Analysis of the first 300
incidents out of a set of 627 showed one incident in which ATC requested a RTO because of a runway incursion but the crew decided not to abort because of the high take-off speed at that time. Many of the 627 incidents were related to separation infringements in mixed mode\(^2\) runway operations and wake turbulence problems with a preceding take-off. Again, the set represented 10.5 million flights.

This data suggests that a small percentage (0.5 \%) of the ATC events will not result in a rejected take-off. Therefore it is assumed that the probability of the ATC event equals \(1.78 \times 10^{-5} / 9.95 \times 10^{-6} = 1.79 \times 10^{-5}\) per take-off.

**RTO with V\(>\)V\(_1\) and runway overruns**

In [Roelen & Wever, 2004] the take-off overrun probability is given based on historical data. A distinction is made between different aircraft generations:

Table 2: Probability of a take-off overrun per flight for the different aircraft generations

<table>
<thead>
<tr>
<th>Aircraft generation</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.77 \times 10^{-7}</td>
</tr>
<tr>
<td>2</td>
<td>1.09 \times 10^{-7}</td>
</tr>
<tr>
<td>3</td>
<td>6.20 \times 10^{-8}</td>
</tr>
</tbody>
</table>

The traffic mix for 2001 at Amsterdam Airport Schiphol is considered: 6\% generation 2 and 94\% generation 3 aircraft [Roelen & Wever, 2004]. This leads to a probability of a runway overrun of \(6.48 \times 10^{-8}\) per flight, considering all possible causes for an RTO.

An analysis of the RTO overrun accidents/incidents [FAA, 1992] showed that in 58\% of the cases the RTO initiation speed was greater than V\(_1\). In 23\% of the cases it was less than V\(_1\). For the other 19\% the initiation speed was unknown. Hence, in 72\% of the overruns in which the initiation speed was known, the initiation speed was greater than V\(_1\). According to this information the probability of an overrun with an RTO initiation speed greater than V\(_1\) is \(0.72 \times 6.48 \times 10^{-8} = 4.67 \times 10^{-8}\) per flight and the probability of an overrun with an RTO initiation speed smaller than V\(_1\) is \(0.28 \times 6.48 \times 10^{-8} = 1.81 \times 10^{-8}\).

The generic probability of an overrun given an RTO speed above V\(_1\) considers all possible causes of a RTO. According to [Roelen & Wever, 2004], the distribution of RTO causes for different speeds is as follows:

\(^2\) Mixed mode means that a runway is simultaneously used for take-offs as well as landings
Table 3: Distribution of the RTO speed for the different causes of the RTO

<table>
<thead>
<tr>
<th>Cause</th>
<th>$V_{RTO} \leq 80\text{ kts}$</th>
<th>$80\text{ kts} &lt; V_{RTO} \leq 120\text{ kts}$</th>
<th>$V_{RTO} &gt; 120\text{ kts}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft configuration</td>
<td>26%</td>
<td>15%</td>
<td>10%</td>
</tr>
<tr>
<td>Engine</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
</tr>
<tr>
<td>Aircraft system</td>
<td>29%</td>
<td>25%</td>
<td>20%</td>
</tr>
<tr>
<td>Air traffic situation</td>
<td>15%</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>Wheel/tyre</td>
<td>2%</td>
<td>10%</td>
<td>12%</td>
</tr>
<tr>
<td>Bird strike</td>
<td>3%</td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>Flight crew</td>
<td>5%</td>
<td>5%</td>
<td>8%</td>
</tr>
</tbody>
</table>

According to the table, the air traffic situation causes 5% of all RTO at speeds above 120 kts. It is assumed here that the distribution for speeds above 120 knots is similar to the distribution for speeds greater than $V_1$. Assuming that 58.8% of the air traffic situations are the ATC events that are considered in ESD 2, this means that 2.9% of the RTOs given a speed larger than $V_1$ are related to an ATC event. With this, the probabilities of the end states “runway overrun” can be determined:

- Probability of runway overrun, given an ATC event and a RTO with a speed larger than $V_1$ is $2.9\% \times 4.67\times10^{-8} = 1.35\times10^{-9}$ per flight; and
- Probability of runway overrun, given an ATC event and a RTO with a speed smaller than $V_1$ is $2.9\% \times 1.81\times10^{-8} = 5.25\times10^{-10}$ per flight.

Using these probabilities of a runway overrun and the probability that a flight crew rejects the take-off given an ATC event, the conditional probability of ‘$V > V_1$’ at the time of rejection is $1.35\times10^{-9} / 1.78\times10^{-5} = 7.58\times10^{-5}$.

**Pivotal event “Failure to achieve maximum braking” and end state “Aircraft stops on runway”**

The probabilities of this pivotal event and end state can be determined by using the probabilities that are estimated so far.

The probability of the flight crew rejecting a take-off because of an ATC event with a speed lower than $V_1$ is $(1-7.58\times10^{-5}) \times 1.78\times10^{-5} = 1.78\times10^{-5}$ per flight. This is input to the event “failure to achieve maximum braking”. The conditional probability of ‘failure to achieve maximum braking’ in the event of a take-off rejection below $V_1$ is $5.25\times10^{-10} / 1.78\times10^{-5} = 2.95\times10^{-5}$.

**End state “aircraft continues take-off”**

According to the definition of this end state, there are two situations leading to it:

- ATC instructs the crew to reject the take-off but the crew does not comply, either because they decide that it is not possible any more or because of communication problems;
- During take-off roll, an ATC event occurs but neither ATC nor the crew detects it.
It appears to be very difficult to quantify this end state. Of the first situation (crew does not reject the take-off after receiving an instruction from ATC to do so) no incidents have been found in the NLR Air Safety Database. The second situation is related to separation infringements. In the NLR Air Safety Database no clear incidents of this type have been found although there are a few cases where TCAS alerts were received during climb or ATC instructions are received soon after take-off to make a turn because of other traffic. Also there are a few cases where the flight crews decide not to start the take-off roll because of conflicting traffic without ATC noticing it.

To get an idea of the order of magnitude of this event, the focus is on the first situation: the crew does not reject the take-off although they have received an instruction from ATC to abort. Reasons for this could be that the aircraft already has a speed close to $V_1$ or that the communication is down. When looking at the data in [Roelen & Wever, 2004], the probability of a RTO because of an air traffic situation with a speed lower than 120 knots is more than 200 times higher than the probability of a RTO with a speed more than 120 knots. This means that RTO instructions because of an ATC event are given mainly during low speeds, so that it is not likely that the crew does not follow this instruction. In fact, in the analysed set of incidents from NLR Air Safety Database only one incident was reported where the crew did not follow a RTO instruction (in this case because of a runway incursion). Considering that only half of the set has been analysed and that 50% of the air traffic situations are assumed to relate to the ATC event of ESD 2, we assume that only one incident in 10.5 million flights relates to this particular end state, which would result in a frequency of $9.52 \cdot 10^{-8}$ per flight.

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: Air traffic related event.
5  ESD 3 – Aircraft handling by flight crew inappropriate

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: Aircraft handling by flight crew inappropriate.

5.1 Definitions

Aircraft handling by flight crew inappropriate
This event refers to aircraft handling errors that can result in loss of directional control of the aircraft. Examples are improper use of the steering tiller, improper directional braking, improper rudder input, and asymmetric engine thrust settings, etc. External conditions, including crosswind and runway surface condition may play a role. Directional control problems due to technical failures, such as a failure of the nose wheel steering system, are out of scope of this ESD but are covered in ESD 4. A momentary configuration warning following the application of take-off thrust, due to the main gear steering (if available) not being correctly aligned is not considered within the scope of this initiating event.

Flight crew rejects take-off
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take-off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway remaining. At a certain point, the amount of runway available may not be sufficient to bring the
aircraft to a complete stop. For this reason a decision speed \( V_1 \) is calculated before each take-off. The decision speed \( V_1 \) is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below \( V_1 \) the take-off can be safely rejected, at speeds above \( V_1 \) the take-off should be continued. Typical \( V_1 \) values for large commercial jet aircraft vary from 125 to 160 knots. The actual \( V_1 \) depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some operators and aircraft manufacturers have defined a speed up to which a take-off should be rejected for all observed failures. At speeds between this speed and the take-off decision speed \( V_1 \), the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

\[ V > V_1 \]

The event \( V > V_1 \) describes a situation where the rejected take-off is initiated at a speed higher than the decision speed \( V_1 \). The decision speed \( V_1 \) is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below \( V_1 \) the take-off can be safely rejected, at speeds above \( V_1 \) the take-off should be continued. Typical \( V_1 \) values for large commercial jet aircraft vary from 125 to 160 knots. The actual \( V_1 \) depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient.

Flight crew fails to maintain control
Either after a rejected take-off with a speed lower than \( V_1 \) or during take-off with a loss of traction and steering capability, the crew may not be able to maintain control of the aircraft. This event describes a situation where the flight crew has lost control of the aircraft, i.e. the aircraft’s lateral movements are not in accordance with the flight crew’s intentions.

Runway overrun
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.
Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

5.2 Quantification

Initiating event
Safety reports from several airlines were examined to determine the frequency of occurrence of the initiating event of this ESD. The safety reports are from Western airlines and cover mainly flights in the period of 1993 to 2004. The occurrences relate to a total of 10.5 million flights. Using keywords as directional control, veer off, steering, flight control and flight phase take-off, a set of 617 safety reports has been retrieved. Of these 617, 48 occurrences were considered applicable to the initiating event of ESD 3. Sometimes the narratives of the occurrences provided very little information. In case of doubt, an occurrence is considered applicable to keep the estimate on the conservative side. In 36 of these 48 occurrences, the crew decided to reject the take-off. Based on these results the estimated probability of the initiating event is 4.57·10⁻⁶ per flight.

End states
Analysis of the Airclaims database showed 26 accidents or incidents that were initiated as a result of inappropriate aircraft handling by the flight crew during the take-off roll. The data sample was limited to Western-built aircraft heavier than 5,700 kg MTOW in commercial operations between 1990 and 2005. These occurrences are divided as follows:
- Veer-off without RTO: 17
- Veer-off after RTO: 7
- Overrun after RTO: 2 (in both cases take-off was rejected at a speed > V₁)

A search in the ADREP database for the same period and flights in scope (Western-built aircraft heavier than 5,700 kg in commercial operations) showed some additional occurrences to those already identified:
- Veer-off without RTO: 4
- Veer-off after RTO: 2.
Overall exposure for the data sample is 453 million flights (1990-2005). This results in the following probabilities:

- Veer-off without RTO: $4.64 \times 10^{-8}$ per flight
- Veer-off after RTO: $1.99 \times 10^{-8}$ per flight
- Overrun after RTO: $4.42 \times 10^{-9}$ per flight

Pivotal event ‘flight crew rejects take-off’
Analysis of airline safety reports in the NLR Air Safety Database, shows that the flight crew rejects the take-off in 75% of the directional control problems (36 of the 48 occurrences). The conditional probability of ‘flight crew rejects take-off’ in the event of inappropriate aircraft handling by the flight crew is $7.50 \times 10^{-1}$.

Pivotal event ‘$V > V_1$’
The conditional probability that $V > V_1$ if the take-off is rejected after ‘inappropriate aircraft handling by the flight crew’ is $4.42 \times 10^{-9} / (4.57 \times 10^{-6} \times 7.50 \times 10^{-1}) = 1.23 \times 10^{-3}$.

Pivotal event ‘flight crew fails to maintain control’ (take-off rejected)
The conditional probability that the ‘flight crew fails to maintain control’ if the take-off is rejected after ‘inappropriate aircraft handling by the flight crew’ is $1.99 \times 10^{-8} / (4.57 \times 10^{-6} \times 7.50 \times 10^{-1} \times (1-1.23 \times 10^{-3})) = 5.81 \times 10^{-3}$.

Pivotal event ‘failure to achieve maximum braking’
Because the analysis failed to identify occurrences where the aircraft overran the runway after a take-off was rejected below $V_1$ due to inappropriate aircraft handling by the flight crew, the conditional probability of ‘failure to achieve maximum braking’ is 0.

Pivotal event ‘flight crew fails to maintain control’ (take-off not rejected)
The conditional probability that the ‘flight crew fails to maintain control’ if the take-off is not rejected and the aircraft handling by the flight crew is inappropriate is $4.64 \times 10^{-8} / (4.57 \times 10^{-6} \times (1-7.50 \times 10^{-1})) = 4.06 \times 10^{-2}$.
Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: Aircraft handling by flight crew inappropriate.
6 ESD4 - Aircraft directional control related system failure

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft directional control related system failure

6.1 Definitions

Aircraft directional control related system failure
An aircraft directional control system failure is a failure of any of the aircraft’s systems that severely affects the directional controllability of the aircraft during the take-off roll. Included are failures of the aileron and aileron controls, rudder and rudder controls, tyres, and nose wheel steering. Directional control problems as a result of asymmetric thrust due to an engine failure are covered in ESD 9.

Flight crew rejects take-off
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take-off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway remaining. At a certain point, the amount of runway available may not be sufficient to bring the aircraft to a complete stop. For this reason a decision speed \( V_1 \) is calculated before each take-off. The decision speed \( V_1 \) is the maximum speed at which the take-off can be safely aborted.
and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$ the take-off can be safely rejected, at speeds above $V_1$ the take-off should be continued. Typical $V_1$ values for large commercial jet aircraft vary from 125 to 160 knots. The actual $V_1$ depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some operators and aircraft manufactures have defined a speed up to which a take-off should be rejected for all observed failures. At speeds between this speed and the take-off decision speed $V_1$, the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

$V > V_1$

The event $V > V_1$ describes a situation where the rejected take-off is initiated at a speed higher than the decision speed $V_1$. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$ the take-off can be safely rejected, at speeds above $V_1$ the take-off should be continued. Typical $V_1$ values for large commercial jet aircraft vary from 125 to 160 knots. The actual $V_1$ depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient.

Failure to achieve maximum braking

Immediately following the decision to reject a take-off, the flight crew must start reducing the speed of the aircraft. Particularly in the case of a high speed rejected take-off, braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

Flight crew fails to maintain control

Either after a rejected take-off with a speed lower than $V_1$ or during take-off with a loss of traction and steering capability, the crew may not be able to maintain control of the aircraft. This event describes a situation where the flight crew has lost control of the aircraft, i.e. the aircraft’s lateral movements are not in accordance with the flight crew’s intentions.
Runway overrun
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

6.2 Quantification
According to the definition used for this ESD, directional control related systems are those reported under ATA codes 2710-2722 (aileron and rudder), 3244-3245 (tyre) and 3250-3251 (nose wheel steering). A data sample of Service Difficulty Reports (see Appendix A for a description of this sample) was used to determine the probability of a directional control related system failure during take-off and the likelihood of a rejected take-off in the event of a system failure. The analysis was limited to air carrier operations from 1985 through 2003. Overall exposure is 216 million flights.

According to the SDR database, there were 14,254 directional control related system failures, i.e. a frequency of $6.60 \times 10^{-5}$ per flight. In 7,475 cases this resulted in a rejected take-off. The conditional probability of a rejected take-off in the event of a directional control related system failure is 0.52.

To estimate the frequency of occurrence of the end states, a data sample of accidents and incidents from the Airclaims database was analysed. The sample was restricted to accidents and incidents involving western-built aircraft heavier than 5,700 kg MTOW in commercial operations. Data from 1985 through 2005 was used, representing a total of 399 million flights.
The data sample contains 9 take-off overrun accidents resulting from directional control system failures and subsequent take-off rejection. In 2 cases the take-off was aborted at a speed below \( V_1 \), in 7 cases the take-off was aborted at a speed above \( V_1 \). The data sample contains 4 veer-off accidents resulting from directional control system failures during the take-off roll. For these veer-off accidents the available data was insufficient to determine whether the decision to reject the take-off was taken before or after the aircraft ran off the side of the runway. For the purpose of this ESD, it is assumed that all veer-offs occurred after the crew had decided to reject the take-off. The estimated probabilities for the end states are the following:

- Runway overrun (\( V > V_1 \)): \( 1.75 \cdot 10^{-8} \)
- Runway veer-off: \( 1.00 \cdot 10^{-8} \)
- Runway overrun (\( V < V_1 \)): \( 5.01 \cdot 10^{-9} \).

The conditional probability of \( V > V_1 \) in the event of a directional control related system failure and decision to reject the take-off is \( 1.75 \cdot 10^{-8} / (6.60 \cdot 10^{-5} \times 0.52) = 5.10 \cdot 10^{-4} \).

The conditional probability of ‘flight crew fails to maintain control’ in the event of a directional control related system failure and the decision to reject the take-off at a speed below \( V_1 \) is \( 1.00 \cdot 10^{-8} / (6.60 \cdot 10^{-5} \times 0.52 \times (1-5.10 \cdot 10^{-4})) = 2.92 \cdot 10^{-4} \).

The conditional probability of ‘failure to achieve maximum braking’ in the event of a directional control related system failure and the decision to reject the take-off at a speed below \( V_1 \) is \( 5.01 \cdot 10^{-9} / (6.60 \cdot 10^{-5} \times 0.52 \times (1-5.10 \cdot 10^{-4}) \times (1-2.92 \cdot 10^{-4})) = 1.46 \cdot 10^{-4} \).

The conditional probability of ‘aircraft stops on runway’ in the event of a directional control related system failure and the decision to reject the take-off at a speed below \( V_1 \) is \( 6.60 \cdot 10^{-5} \times 0.52 \times (1-5.10 \cdot 10^{-4}) \times (1-2.92 \cdot 10^{-4}) \times (1-1.46 \cdot 10^{-4}) = 3.43 \cdot 10^{-5} \).

The conditional probability of ‘aircraft continues take-off’ in the event of a directional control related system failure and a decision to continue the take-off is \( 6.60 \cdot 10^{-5} \times (1-0.52) = 3.17 \cdot 10^{-5} \).
Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft directional control related system failure

- Aircraft directional control related system failure
  - Loss of traction and steering capability
    - Flight crew rejects take-off
      - Flight crew fails to maintain control
        - Failure to achieve maximum braking
          - Runway overrun
            - Unrecovered loss of control
              - Runway veers off
                - Aircraft stops on runway
                  - 3.43 x 10^5
                - Runway veers off
                  - 5.01 x 10^5
                - Aircraft continues takeoff
                  - 3.17 x 10^5
              - Unrecovered loss of control
                - Runway veers off
                  - 1.75 x 10^6
                - Runway veers off
                  - 1.00 x 10^6
            - 2.92 x 10^4
        - 5.10 x 10^4
      - 5.20 x 10^1
    - 6.60 x 10^8
- no
- yes

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7 ESD5 – Incorrect configuration

Accident type: uncontrolled collision with ground.  
Flight phase: take-off.  
Initiating event: Incorrect configuration.

7.1 Definitions

Incorrect configuration
The initiating event is defined as an occurrence where the flight crew commences the take-off while the aircraft is not properly configured for take-off. The cause of an incorrect configuration can be either a system failure or the crew has not set the correct configuration. Setting the required aircraft configuration for take-off includes several systems. An incorrect setting of either one of those systems will generate a take-off configuration warning, unless the warning is inhibited. Aircraft manufacturers sometimes choose to inhibit take-off configuration warnings at speeds above 80 kts (typically) in order to avoid the risk of high speed rejected take-offs. Incorrect configuration includes the following:
- Thrust not set to take-off thrust
- Thrust reverser not stowed
- Parking brake not released
- Flaps not in take-off position
• Spoilers/speed brakes not stowed
• Stabiliser trim not within green band
• Main landing gear not aligned
• Rudder trim not centred
• Flight control system not properly set (e.g. yaw damper not switched on)

Take-off configuration warning
Modern aircraft are equipped with a take off configuration warning system. This system warns the flight crew of an inappropriate aircraft configuration as soon as the throttles are advanced to take-off thrust. Examples of inappropriate aircraft configurations are: speed brakes not properly stowed, stabiliser trim out of range, and incorrect flap setting. Absence of a take-off configuration warning if the aircraft is not properly configured for take-off can be caused by a failure of the take-off configuration warning system, inhibition of the take-off configuration warning, or absence of a take-off configuration warning system.

Flight crew rejects take-off
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway remaining. At a certain point, the amount of runway available may not be sufficient to bring the aircraft to a complete stop. For this reason a decision speed $V_1$ is calculated before each take-off. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$ the take-off can be safely rejected, at speeds above $V_1$ the take-off should be continued. Typical $V_1$ values for large commercial jet aircraft vary from 125 to 160 knots. The actual $V_1$ depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some operators and aircraft manufactures have defined a speed up to which a take-off should be rejected for all observed failures. At speeds between this speed and the take-off decision speed $V_1$, the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

$V > V_1$
The event $V > V_1$ describes a situation where the rejected take-off is initiated at a speed higher than the decision speed $V_1$. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining
runway. At a speed below V_1 the take-off can be safely rejected, at speeds above V_1 the take-off should be continued. Typical V_1 values for large commercial jet aircraft vary from 125 to 160 knots. The actual V_1 depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient.

**Failure to achieve maximum braking**
Immediately following the decision to reject a take-off, the flight crew must start reducing the speed of the aircraft. Particularly in the case of a high speed rejected take-off, braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

**Flight crew rejects take-off**
This event describes whether or not the flight crew rejects the take-off after receiving a take-off configuration warning.

From the database of air safety reports (see Appendix A) it appears that flight crews sometimes do not reject the take-off if they receive a take-off configuration warning. If a warning occurs after V_1, the standard operating procedures require the flight crew to continue the take-off. A momentary warning is sometimes considered irrelevant by the flight crew. Sometimes warnings are considered nuisance, e.g. warning related to centring of the main landing gear when the aircraft is lined-up with too much engine power. There are also cases where the flight crew corrects the situation on the spot without rejecting the take-off, e.g. if the parking brake is still set.

We assume for modelling purpose that the events in which the flight crew continues take-off with incorrect configuration (flaps) is covered by the sequence through pivotal event ‘aircraft stalls after rotation’. We assume that the sequence of events, following a ‘no’-outcome of the pivotal event ‘flight crew rejects take-off’ is covering situations where the crew continues take-off after having corrected the configuration problem or if the warning occurs after V_1 or momentarily. As a result of this assumption, the end state ‘aircraft continues take-off’ represents the situation that the aircraft is able to safely complete the take-off phase and climb out (i.e. incorrect configuration does not result in loss of control).
**Runway overrun**
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**Aircraft stops on runway**
This represents a situation where the take-off is aborted and the aircraft comes to a full stop before reaching the end of the runway.

**Aircraft continues take-off**
Based on the definitions above, the end state ‘aircraft continues take-off’ represents the situation that the aircraft is able to safely complete the take-off phase and climb out. Thus either the incorrect configuration does not result in loss of control or the incorrect configuration has been corrected by the flight crew ‘on the roll’.

**Aircraft stalls after rotation**
An aircraft is stalled if the maximum lift which can be developed by the wing is not sufficient to support the weight of the aircraft. If the aircraft’s flaps are not properly configured for take-off, or if the stabiliser trim is not properly set, a stall may develop after rotation.

**Flight crew fails to regain control**
This pivotal event refers to the ability of the flight crew to regain control of the aircraft after stall onset. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is in general affected by human factors (fatigue etc), training, aircraft system failures, weather conditions, available altitude for recovery manoeuvre etc.

**Collision with ground**
This end state refers to a possible outcome of an aircraft taking off with incorrect configuration. The aircraft impacts terrain (ground, water) or obstacles, which results in injuries, fatalities or (substantial) damage to the aircraft.
Aircraft continues flight
This end state refers to the possible outcome of a take-off with incorrect configuration: the flight crew continues the flight to destination airport, returns to the departure airport or diverts the aircraft to another airport.

7.2 Quantification

7.2.1 Data sources
The following data sources have been used to quantify events in this ESD:
• ADREP and Airclaims database of accidents and incidents;
• ASR databases (various airlines, European and non-European).

7.2.2 Results

ADREP and Airclaims data
A query was run in the ADREP and Airclaims databases to identify accidents and incidents related to take-off with incorrect configuration. The time span was set to 1990-2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators, and accidents/incidents during test flights and training flights are excluded. The number of flights associated with this query is 452 million flights. (1990-2005).

According to ADREP and Airclaims, there have been 24 accidents and incidents that are related to loss of control after take-off with incorrect configuration.
• In 16 of these 24 occurrences the flight crew rejected the take-off. In 6 occurrences this happened at a late stage in the take-off and resulted in a runway overrun. In 10 occurrences the flight crew rejected the take-off and stopped on the runway.
• In 3 events the flight crew did not receive a take-off configuration warning and were subsequently unable to rotate or lift-off at rotation speed. In all 3 cases the crew then failed to maintain control and collided with the ground (crash landed at the end of the runway).
• In 3 events the flight crew did not respond to the take-off configuration warning, and were subsequently unable to rotate or lift-off at rotation speed. In all 3 events the crew then failed to maintain control and collided with the ground (crash landed at the end of the runway).
• In 2 occurrences the crew took off with an incorrect take-off configuration, but were able to continue flight tot destination.
ASR database of various airlines
We have analysed Air Safety Report (ASR) databases for events involving a take-off with incorrect configuration and/or take-off configuration warnings. The ASR databases come from different airlines and cover 9 million flights between 1998 and 2004. All data concerns commercial operations with ‘western’ aircraft of more than 5700 kg maximum take-off weight.

We have analysed the databases for occurrences involving a take-off configuration warning and/or incorrect take-off configuration in the years 2000 and 2001. The corresponding number of flights for these two years is 2.44 million. A total of 550 occurrences were identified. Table 4 shows the number of occurrences of a take-off configuration warning per associated system, the percentage of take-off configuration warnings across the different systems that were incorrectly configured, and the corresponding frequency of occurrence per flight.

Table 4: Take-off configuration warning generated by incorrect take-off configuration of various systems

<table>
<thead>
<tr>
<th>Number of occurrences</th>
<th>Rate per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>Propulsion system</td>
<td>34</td>
</tr>
<tr>
<td>Thrust reverser</td>
<td>1</td>
</tr>
<tr>
<td>Parking brake</td>
<td>10</td>
</tr>
<tr>
<td>Flap system</td>
<td>38</td>
</tr>
<tr>
<td>Spoiler</td>
<td>22</td>
</tr>
<tr>
<td>Stabilizer trim</td>
<td>40</td>
</tr>
<tr>
<td>Speedbrakes</td>
<td>21</td>
</tr>
<tr>
<td>Landing gear</td>
<td>25</td>
</tr>
<tr>
<td>Flight control system</td>
<td>2</td>
</tr>
<tr>
<td>Rudder</td>
<td>0</td>
</tr>
<tr>
<td>Unknown system</td>
<td>69</td>
</tr>
<tr>
<td>Take-off warning system</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>269</td>
</tr>
</tbody>
</table>

*Total flights: 2.44·10^6*

In 494 of the 550 reported take-off configuration warnings (89.82 %), the take-off was rejected. This corresponds to a frequency of 2.02·10^{-4} per flight.

7.3 Summary of results

Incorrect configuration
According to Table 4, the frequency of occurrence of incorrect aircraft configuration during the take-off roll is 2.25·10^{-4} per flight.
Take-off configuration warning
According to ADREP and Airclaims data, out of a total sample of 452 million flights, there have been 6 events where the flight crew did not receive a take-off warning or the take-off warning was ignored without further action by the flight crew. The corresponding probability of occurrence of ‘take off warning not effective’ is $1.33 \times 10^{-8}$ per flight, or a conditional probability of $1.33 \times 10^{-8} / 2.25 \times 10^{-4} = 5.90 \times 10^{-5}$. All these cases ended as a ‘collision with ground’.

Flight crew rejects take-off
According to ASR data, in 494 of the 500 reported take-off configuration warnings the take-off was rejected. The conditional probability of a rejected take-off in the event of an effective configuration warning is 0.898.

$V > V_1$
According to ADREP and Airclaims data, in a total sample of 452 million flights there have been 6 high speed ($V > V_1$) rejected take-offs as a result of a take-off configuration warning. All these occurrences led to a runway overrun. The probability of a runway overrun after a high-speed rejected take-off after is configuration warning is $1.33 \times 10^{-8}$ per flight. The conditional probability of $V>V_1$ in the event of a rejected take off is $1.33 \times 10^{-8} / (2.25 \times 10^{-4} \times (1- 5.90 \times 10^{-5}) \times 0.898) = 6.57 \times 10^{-5}$.

Runway overrun after rejected take-off above $V_1$.
According to ADREP and Airclaims data, in a total sample of 452 million flights there have been 6 high speed ($V > V_1$) rejected take-offs as a result of a take-off configuration warning. All these occurrences led to a runway overrun. The probability of a runway overrun after a high-speed rejected take-off following a configuration warning is $1.33 \times 10^{-8}$ per flight.

Runway overrun after rejected take-off below $V_1$.
According to ADREP and Airclaims, out of a total sample of 452 million flights there have been no occurrences of a runway overrun following an aborted take-off at speed below $V_1$ if the reason for the abort was a take-off configuration warning. The probability of occurrence is estimated to be 0.

Failure to achieve maximum braking.
Because the probability of a runway overrun following an aborted take-off at speed below $V_1$ is estimated to be 0 (see previous section), the conditional probability of ‘failure to achieve maximum braking’ in the event of a rejected take-off at speeds below $V_1$ is also estimated to be 0.
Aircraft stops on runway.
The frequency of occurrence of the end state ‘aircraft stops on the runway’ can be calculated from the previous events. The probability is estimated to be $2.25 \times 10^{-4} \times (1-5.90 \times 10^{-5}) \times 0.898 \times (1-6.57 \times 10^{-5}) \times 1 = 2.02 \times 10^{-4}$ per flight.

Aircraft continues take-off.
The frequency of occurrence of the end state ‘aircraft continues take-off’ can be calculated from the previous events. The probability is estimated to be $2.25 \times 10^{-4} \times (1-5.90 \times 10^{-5}) \times 0.102 = 2.29 \times 10^{-5}$ per flight.

Aircraft stalls after rotation.
According to ADREP and Airclaims data, out of a total sample of 452 million flights, there have been 6 events where the flight crew did not receive a take-off warning or the take-off warning was ignored without further action by the flight crew. All these events resulted in a loss of control and collision with the ground. The corresponding conditional probability of occurrence of ‘aircraft stall after rotation’ is assumed to be 1.

Flight crew fails to regain control.
According to ADREP and Airclaims data, out of a total sample of 452 million flights, there have been 6 events where the flight crew did not receive a take-off warning or the take-off warning was ignored without further action by the flight crew. All these events resulted in a loss of control and collision with the ground. The conditional probability of ‘flight crew fails to regain control’ in the event of ‘aircraft stalls after rotation’ is assumed to be 1.

Collision with ground.
According to ADREP and Airclaims data, out of a total sample of 452 million flights, there have been 6 events where the flight crew did not receive a take-off warning or the take-off warning was ignored without further action by the flight crew. All these events resulted in a loss of control and collision with the ground. The corresponding probability of occurrence of ‘collision with ground’ is $1.33 \times 10^{-8}$ per flight.
Accident type: uncontrolled collision with ground. 
Flight phase: take-off. 
Initiating event: Incorrect configuration.
8 ESD6 - Aircraft takes off with contaminated wing

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft takes off with contaminated wing.

8.1 Definitions

Take-off is defined as: from the application of take-off power, through rotation and to an altitude of 35 ft above the runway elevation.

In the ESD the initiating event, pivotal events and end states are defined as follows.

Aircraft takes off with contaminated wing

Aircraft wing, horizontal stabiliser, tail and/or flight control surfaces (i.e. ailerons, elevator, trim, rudder) are contaminated with frost, ice, slush or snow, as the aircraft commences take-off. An event in which the contaminated wing results for instance in engine problems due to ice/snow ingestion, is considered in the scope of this ESD. Occurrences in which ice, snow or slush from the runway or landing gear enters the engine(s) and causes problems are excluded from this initiating event but are included in ESD 9.

Aircraft stalls after rotation

An aircraft is stalled if the maximum lift which can be developed by the wing is not sufficient to support the weight of the aircraft. The lift which is developed by a wing depends on the angle of attack (the relative angle of the impinging air to the wing chord) and the airspeed. The higher the angle of attack and the higher the speed, the greater the amount of lift developed so long as the airflow over the wing is smooth and adheres to its contour surface. If the airflow separates from the surface, the lift produced by the wing diminishes. The airflow starts to separate from any wing if its angle of attack reaches a critical value, typically 15 - 18 degrees. As the angle of attack is increased further, it will reach a value at which maximum lift is developed, after which higher angles of attack will produce a rapid decay in lift. Even a small amount of snow or ice on
the wing surface influences the smooth flow of air over the surface contour. Changes in the contour shape and roughness of the surface will cause the airflow to begin to separate from the wing at a lower angle of attack than normal and cause a reduction in the lift which will normally be developed by a wing at a given angle of attack and a given airspeed. Both the maximum lift which can be developed and the angle of attack at which it will be developed will be reduced significantly. The extent and way that performance will be affected depends on the position of the contaminant on the wing as well as on the nature of the contaminant.

**Flight crew fails to regain control**
This pivotal event refers to the ability of the flight crew to regain control of the aircraft after stall onset. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is in general affected by human factors (fatigue etc), training, aircraft system failures, weather conditions, available altitude for recovery manoeuvre etc.

**Collision with ground**
This end state refers to a possible outcome of an aircraft taking off with a contaminated wing. The aircraft impacts terrain (ground, water) or obstacles, which results in injuries, fatalities or (substantial) damage to the aircraft. The degree of damage is determined by the impact angle, impact speed, and the characteristics of the terrain.

**Aircraft continues flight**
This end state refers to the possible outcome of a take-off with contaminated wing: the flight crew continues the flight to destination airport, returns to the airport of departure or diverts the aircraft to another airport. While in flight, the aircraft may encounter difficulties associated with the contaminated wing, such as the ingestion of snow or ice by the engines, or controllability problems. An example is the accident of a Scandinavian Airlines MD-81 in 1991, which experienced ice ingestion in both engines from contaminated wings, resulting in a dual engine failure and a forced landing. Such a situation is described in the integrated ESD model by a transition from one ESD (e.g. ESD 6) to another (e.g. ESD 18).

### 8.2 Quantification

#### 8.2.1 Data sources
The following data sources have been used to quantify events in this ESD:
- NLR Air Safety Database (ADREP, Airclaims, ECCAIRS)
- NTSB database
- ASR databases (various airlines)
NLR Air Safety Database
A query was run in the NLR Air Safety Database to search for accidents and incidents related to take-off with contaminated wing. The time span was set to 1990-2003. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators and accidents/incidents during test flights and training flights are excluded. The number of flights associated with this query is 387 million flights.

The NLR Air Safety Database contains 5 accidents and 3 incidents related to a take-off with contaminated wing. In 3 occurrences engine problems occurred in take-off or during initial climb as a result of ice or snow ingestion from the contaminated wing. In all events de-icing was not effective: in 3 cases de-icing was not done, in 4 cases de-icing was not properly done (e.g. missing parts of aircraft surface), and in one occurrence the hold-over time was exceeded. As a result of the take-off with contaminated wing 4 flights ended in a collision with terrain, in one occurrence a rejected take-off was initiated above rotation speed ($V_r$), in one event a forced landing was made after a double engine flame-out. Two of the 8 flights continued and landed safely (they returned to the airport).

This data cannot be used for quantification of the initiating event because it does not include occurrences where a take-off was made with a contaminated wing but without further consequences.

Table 5 summarises the results of the accident and incident data analysis.

Table 5: Results of accident/incident analysis of take-off with contaminated wing (NLR Air Safety Database, 1990-2003)

<table>
<thead>
<tr>
<th>Consequences</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rejected take-off</td>
<td>1</td>
</tr>
<tr>
<td>Stall and collision with ground</td>
<td>4</td>
</tr>
<tr>
<td>Double engine failure and forced landing</td>
<td>1</td>
</tr>
<tr>
<td>Continue flight (return to airport)</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

*Source: NLR Air Safety Database, 1990-2003; 387 million flights*
ASR database of various airlines

Air Safety Reports (ASR) databases from different airlines, covering 9 million flights between 1998 and 2004, were analysed for events involving a take-off with contaminated wing and de-icing problems. Only commercial flights with fixed-wing Western-built aircraft heavier than 5,700 kg MTOW are considered. Reported problems with de-icing range from communication problems between cockpit crew and de-ice crew, collision between aircraft and de-icing vehicle, incorrect de-icing (e.g. incomplete de-icing or incorrect de-icing fluid used) and take-off with contaminated wing.

Nine occurrences of aircraft taking off with contaminated wing were found in the ASR databases. In one of these occurrences the hold-over time was exceeded, in 3 events the aircraft was not de-iced and in 5 events the de-icing of the aircraft was not done properly, i.e. parts of the aircraft remained covered with snow or ice. As a consequence one of the 9 flights experienced engine problems in take-off due to snow ingestion, after which the crew aborted the take-off. In one event the crew experienced pitch control problems in flight and diverted. In one event the aircraft was damaged by ice from the wing that struck the tail structure. In the other 6 occurrences the flight crew did not report any effects of the contaminated wing. In all 9 events the flight crew maintained control of the aircraft and landed safely. Table 6 shows the results of the ASR databases analysis of take-offs with contaminated wing.

Table 6: Take-off with contaminated wing (ASR database 1998-2004)

<table>
<thead>
<tr>
<th>Consequences</th>
<th>Number of events</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rejected take-off</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Continue flight or return to airport</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>1.00·10^{-6}</td>
</tr>
</tbody>
</table>

Source: ASR database 1998-2004, 9 million flights

The ASR database was queried for reports on de-icing problems. Many reported problems with respect to de-icing were not relevant for ESD 6 because it concerned for instance communication problems with the de-icing crew or collision between the de-icing vehicle and the aircraft. We found 108 reports about events in which de-icing was not performed or in which it was detected that ice or snow was still present on the aircraft structure after de-icing was performed and aircraft was cleared for flight. In 98 of these cases the flight crew reported that they requested a new de-icing to remove the remaining snow or ice deposits, while in 11 cases no further information was available. In the ASR databases we found 5 occurrences in which the hold-over time was exceeded. In 3 cases the aircraft returned to the gate for de-icing, while in 2 cases the aircraft took off, although it was not reported whether the aircraft structure
or wings were actually contaminated with snow/ice. It is assumed that in these cases the aircraft’s wing was not contaminated.

Table 7: De-icing problems (ASR database 1998-2004)

<table>
<thead>
<tr>
<th>Aircraft de-icing</th>
<th>Number of events</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hold over time exceeded</td>
<td>6</td>
<td>6.67·10⁻⁷</td>
</tr>
<tr>
<td>Aircraft not de-iced</td>
<td>6</td>
<td>6.67·10⁻⁷</td>
</tr>
<tr>
<td>Aircraft not properly de-iced</td>
<td>118</td>
<td>1.31·10⁻⁵</td>
</tr>
</tbody>
</table>

*Source: ASR database 1998-2004, 9 million flights*

8.2.2 Discussion

Accident databases do not contain a representative sample of incidents to reliably estimate the frequency of a take-off with contaminated wing, which did not result in a loss of control. On the other hand, the database contains a representative sample of loss of control accidents as a result of a contaminated wing. The probability of an unrecoverable loss of control and collision with ground after take-off with contaminated wing can therefore be reliably estimated with accident databases. For the frequency estimation of the Initiating Event we will use the ASR database, because these data are a more representative collection of incidents than accident databases. The ASR databases represent a selection of airlines, which means that the ASR database does not present the whole picture of de-icing problems and take-offs with contaminated wing. We assume that all events in which the flight crew reported incorrect or improper de-icing were followed up by a second de-icing as is mentioned in the vast majority of the reports.

8.2.3 Quantification results

Aircraft takes off with contaminated wing

The frequency of the Initiating Event “aircraft takes off with contaminated wing” is estimated from Table 6 as 1.00·10⁻⁶ per flight.

Aircraft stalls after rotation

The frequency of a stall with contaminated wing is 1.03·10⁻⁸ per flight (Table 5). Dividing this number by the frequency of the initiating event (1.00·10⁻⁶ per flight), yields the conditional probability that an aircraft stall after rotation, given a take-off with contaminated wing. This conditional probability is 1.03·10⁻². The probability that aircraft does not stall after take-off with contaminated wing is (1-1.03·10⁻²).
Flight crew fails to regain control
Given a take-off with contaminated wing and subsequent stall the conditional probability that the flight crew fails to regain control is 1. Although the conditional probability of a failure to regain control after stall is based on a few flights only, it is regarded to be a reliable estimate because those stalls will occur just after take-off and at low altitude which makes recovery impossible.

Collision with ground
The probability of an aircraft colliding with terrain as a result of a take off with contaminated wing and subsequent loss of control is estimated from table 1 as $1.03 \cdot 10^{-8}$ per flight.

Aircraft continues flight
The probability that an aircraft takes off with contaminated wing, does not stall and continues flight safely is estimated as $1.00 \cdot 10^{-6} \times (1-1.03 \cdot 10^{-2}) = 9.90 \cdot 10^{-7}$ per flight.

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft takes off with contaminated wing.
9 ESD 7 – Aircraft weight and balance outside limits during take-off

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: aircraft weight and balance outside limits.

9.1 Definitions

Aircraft weight and balance outside limits
This pivotal event describes situation where the aircraft’s centre of gravity or the aircraft’s weight differ from the flight crew’s expectations to such an extent that the flight crew has to take additional action to try to maintain control of the aircraft, such as the application of significantly different trim settings or large pitch control inputs. This can be due to:

- Cargo loose or shifted
- Wrong number of passengers
- Loadsheet incorrect
- Incorrect loading
- Weight limits incorrect/exceeded

The initiating event does not include situations in which the aircraft is ‘extremely nose heavy on rotation’ or where ‘extra nose up trim is required on take-off’ because these are not likely to result in an aircraft stall. These events are included in the initiating event of ESD 10.

Aircraft stalls after rotation
One of the possible consequences of weight and balance problems is that the aircraft stalls after rotation. An aircraft is stalled if the airflow separates from the wing surface resulting in a drastic reduction in lift. The maximum lift which can be developed by the stalled wing is not sufficient to support the weight of the aircraft.
Flight crew fails to regain control
After the aircraft stalls after rotation, the crew might be able to regain control. If not, the result is an unrecovered loss of control and a collision with the ground.

9.2 Quantification

Initiating event

Air Safety Report Database
Air safety report (ARS) databases from different airlines covering 9.5 million flights between 1997 and 2004 were analysed. The data sample included air safety reports from Western-built aircraft, heavier than 5700 kg MTOW in commercial operations. Initial search in the database resulted in 1179 occurrences related to the initiating event “aircraft weight and balance outside limits” in 9.5 million flights. This search included keywords like load, loadsheet, weight, gravity, balance, and considered all flight phases other than parked or cruise.

Using the classification of the source data it appears that 390 of the 1179 occurrences are related to the take-off flight phase. Analysis of these 390 occurrences shows that 285 are possibly relevant for ESD 7. These 285 can be classified as follows:
- 89 in which it is explicitly mentioned that the aircraft felt nose heavy on rotation;
- 45 in which it is explicitly mentioned that the aircraft felt tail heavy on rotation;
- 20 with an overweight take-off;
- 93 with incorrect loadsheet information;
- 22 load shifts; and
- 16 of which the context is not exactly clear.

To quantify the initiating event, the following is assumed:
- Occurrences with nose-heavy and overweight aircraft behaviour cannot lead to an aircraft stall. It is more likely that these result in e.g. a runway overrun. These occurrences are considered not applicable to ESD 7;
- Obviously, occurrences with a tail-heavy aircraft behaviour are relevant for this ESD;
- Load shifts during take-off means that loads are shifting in aft direction. Therefore, these occurrences are considered relevant for ESD 7;
- The occurrences with incorrect loadsheet information and with the unknown context could apply both to nose heavy and tail heavy aircraft behaviour but this is not explicitly stated. Therefore, these occurrences are divided 2:1 (using the 89:45 division of nose heavy and tail heavy occurrences) over not applicable and applicable to ESD 7.
With this, \(45+22+109/3 = 103\) occurrences are applicable. With 9.5 million flights this leads to a probability of the initiating event of \(1.08 \cdot 10^{-5}\) per flight.

**CAP 701**

In the first 11 months in 1998, CAA-UK’s Safety Data Department received 52 aircraft loading error Mandatory Occurrence Reports (MORs) [CAA, 2000]. Analysis indicated the following five main causal factors as follows:

Table 8: Number of occurrences per causal factor (CAP 701)

<table>
<thead>
<tr>
<th>Main causal factor</th>
<th>Number of occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loadsheet incorrect</td>
<td>29</td>
</tr>
<tr>
<td>Centre of gravity incorrect / outside limits</td>
<td>17</td>
</tr>
<tr>
<td>Cargo loose or shifted</td>
<td>10</td>
</tr>
<tr>
<td>Passenger load involved</td>
<td>8</td>
</tr>
<tr>
<td>Weight limits incorrect / exceeded</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70</strong></td>
</tr>
</tbody>
</table>

Note that the total of 70 factors exceeds the 52 MORs. This means that some of the MORs included more than one causal factor.

The number of flights in this period related to the MORs is determined as follows:

Table 9: Number of flights in this period related to the MORs

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of occurrences in 1998</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK Airline (Passenger) Aeroplanes &gt;5700kg MTOW</td>
<td>877,100</td>
</tr>
<tr>
<td>UK Airline (Cargo) Aeroplanes &gt;5700kg MTOW</td>
<td>37,800</td>
</tr>
<tr>
<td>UK Airline Aeroplanes &lt;5700kg MTOW</td>
<td>31,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>945,900</strong></td>
</tr>
</tbody>
</table>

From the total for 1998 it is estimated that the number of flights in the period January-November 1998 amounts to 867,075.

For the 52 occurrences in the period January – November 1998, this corresponds with a frequency of \(5.99 \cdot 10^{-5}\) per flight for the initiating event. [CAA, 2000] does not specify the flight phase during which the events occurred.

**STEADES**

IATA STEADES data shows that from July 2004 to June 2005, there were 118 High-Medium Risk Air Safety Reports (ASRs) relating to hold loading [IATA, 2005] and 293 Low-Minimal
Risk ASRs  Of the 118 high-medium risk occurrences, 52% was related to incorrect loading and 27% to unrestrained items in the hold. The incorrect loading occurrences are divided as follows: incorrect positioning of cargo (50%), excess loading (24%) and other (26%).

The corresponding exposure for the STEADES data totals 2.7·10^6 flights, resulting in a frequency of 4.37·10^{-5} per flight when considering the 118 high/medium risk ASRs and 1.7·10^{-4} when considering all 457 ASRs.

Note that in [IATA, 2005] it is not explicitly mentioned if the ASRs were encountered during take-off or during approach.

Combining information
Further analysis of load and balance events shows a fair consistency between CAP 701, STEADES and Air Safety Database data:

Table 10: Comparison of the different estimates of load and balance events

<table>
<thead>
<tr>
<th>Load and balance events</th>
<th>CAA-UK MORS</th>
<th>STEADES</th>
<th>Air Safety Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unrestrained cargo</td>
<td>5.99·10^{-5}</td>
<td>4.37·10^{-5}</td>
<td>1.08·10^{-5}</td>
</tr>
<tr>
<td>Excess loading</td>
<td>1.15·10^{-5}</td>
<td>1.18·10^{-5}</td>
<td></td>
</tr>
<tr>
<td>CG incorrect</td>
<td>6.91·10^{-6}</td>
<td>5.5·10^{-6}</td>
<td></td>
</tr>
</tbody>
</table>

Although the CAA data and STEADES do not specify the flight phase, it is expected that the majority of weight and balance problems will manifest itself during or immediately after take-off.

For the purpose of this model, a frequency of 1.08·10^{-5} will be assumed for the initiating event ‘aircraft weight and balance outside limits’.

Accidents
In the Air Safety Database, 10 weight and balance related take-off accidents have been found on 387 million flights. Scope of the search is as follows:

- Western built aircraft;
- Maximum Take-Off Weight above 5,700 kg;
- Jets and turbo prop aircraft (excluding piston engines);
- Commercial operations;
In the Air Safety Database, 10 accidents have been found caused by weight and balance problems during take-off. In 5 of these accidents, the aircraft crashed because it was too heavy or because the centre of gravity was too far aft. The other 5 accidents resulted in an overrun off the runway because of a forward centre of gravity or because of too much weight. These latter 5 accidents are subject of ESD 10. Given that the 5 applicable accidents relate to 387 million flights this means an accident frequency of $1.29 \times 10^{-8}$ per flight.

**Pivotal events**

No occurrences have been found of stalling aircraft during take-off (because of weight and balance problems) that could be controlled by the crew such that continuation of the flight was possible. Because of the close proximity to the ground, it is highly unlikely that such a recovery is possible. Therefore it is assumed that if an aircraft stalls, the flight crew is not able to regain control. The pivotal event “flight crew fails to regain control” is estimated to be 1.

Given the result of the pivotal event “flight crew fails to regain control”, quantification of the pivotal event “aircraft stalls after rotation” can be achieved by dividing the accident frequency by the frequency of the initiating event. The result is $1.19 \times 10^{-3}$.
10 ESD 8 – Aircraft encounters a performance decreasing wind shear after rotation

Scenario type: loss of control.
Phases: take-off.
Initiating event: aircraft encounters a performance decreasing windshear after rotation.

(1) Windshear is an abrupt change in wind direction and velocity. This ESD represents a situation where the aircraft encounters a performance decreasing windshear (decreasing headwind, increasing tailwind or a downdraft), e.g. as a result of a microburst.

10.1 Definitions

Aircraft encounters a performance decreasing wind shear after rotation
Wind shear is an abrupt change in wind direction and velocity. A type of wind shear that is particularly dangerous for air transport is a downburst or microburst. The aircraft may encounter performance increasing and decreasing effects. Wind shear poses the greatest danger to aircraft during takeoff and landing, if the aircraft is close to the ground and has little time or room to maneuver. During takeoff, an aircraft is near stall speed and thus is very vulnerable to wind shear [NASA, 1992].

This event includes situations where the aircraft encounters an increase in tailwind or a decrease in headwind after rotation (performance *decreasing* wind shear), but turbulence, e.g. due to wake vortex is not included. The qualification “after rotation” is taken in a wide sense - it includes also the (initial) climb.

Flight crew fails to detect wind shear
There are various possibilities for the flight crew to detect wind shear during take-off. Already before take-off the crew can detect thunderstorms ahead and they may decide not to take-off yet or request a different departure route. In other situations, during take-off and climb, the crew
monitors indicated airspeed and rates of climb. Rapid changes can be an indication of a wind shear encounter. With autopilot and autothrust engaged pitch deviations and unusual thrust settings are the primary cues for early wind shear onset as airspeed deviations are effectively compensated for. Alternative detection means can be other pilots’ reports, ground-based wind shear alert systems using ground-based radar or lidar, and on-board wind shear detection systems. Most, but not all, large commercial aircraft are equipped with an on-board wind-shear detection system. In the case of ground-based systems the crew will be alerted by ATC. For the purpose of this ESD, flight crew fails to detect wind shear is defined as a situation where the aircraft encounters wind shear but this goes undetected by the flight crew.

**Flight crew fails to perform wind shear escape manoeuvre**

Details of the wind-shear escape manoeuvre may vary among different aircraft types and different operators. A typical wind shear escape manoeuvre in take-off will include the following:

**On ground:**
- When the decision is made to continue the take-off:
- Set emergency thrust (disregard engine overlimit alerts).
  At $V_r$:
- Rotate initially to 15 degrees nose-up.
- Increase pitch attitude to lift off within the remaining distance, if necessary even to an attitude at which a tailstrike will occur.
- When airborne, do not change aircraft configuration.
- If the resulting flight path is still unacceptable, increase pitch until speed is just above the stick shaker actuation.

**Airborne:**
- Pull take-off/go-around (TOGA) triggers
- Disengage autopilot and autothrust
- Set emergency thrust
- Increase pitch to 15 degrees nose up (immediately after take-off it is not necessary to decrease pitch to 15 degrees unless the stick shaker becomes active)
- Maintain wings level unless absolutely required for obstacle clearance

For the purpose of this ESD, ‘flight crew fails to perform wind shear escape manoeuvre’ is defined as a failure of the flight crew to perform the prescribed escape manoeuvre, either by mistake or on purpose when the crew decides that it is not necessary because control can be maintained without following the procedure.
Pivotal Event Flight crew fails to maintain control
This pivotal even refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc.

10.2 Quantification
Airclaims and ADREP data are used to quantify the end states of this ESD, whereas airlines safety reports are used to quantify the initiating event.

A query was run to search for accidents and incidents related to wind shear during take-off. The time span was set to 1990-2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, and Embraer. Aircraft manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators and accidents/incidents during test flights and training flights were excluded. The number of flights associated with this query is 452 million flights for the ADREP and Airclaims databases and 9 million flights for the airlines safety reports.

Airclaims and ADREP data
Airclaims and ADREP data only show one accident in which an aircraft encountered wind shear immediately after rotation, forcing the aircraft into the ground. Two other incidents are reported in which the aircraft had a tail strike after rotation. In one of those incidents the cause was dedicated to wind shear and in the other there was a lot of crosswind, but this was not explicitly indicated as the cause of the tail strike. In both situations, the aircraft continued the flight. In these 3 accidents/incidents, no mention has been made regarding detection of wind shear or an attempt to avoid it.

Airlines safety reports
Air safety report (ARS) databases from different airlines covering 9.5 million flights between 1997 and 2004 were analysed. The data sample included air safety reports from Western-built aircraft, heavier than 5700 kg MTOW in commercial operations. A query was performed on keywords like wind shear, downdraft, microburst, and updraft and for the flight phases take-off and (initial) climb. This query resulted in 514 occurrences, all of which were analysed with the objective to quantify the frequencies of the events:

- Aircraft encounters a performance decreasing wind shear after rotation;
- Flight crew fails to detect wind shear; and
- Flight crew fails to perform wind shear escape manoeuvre.
Analysis is sometimes difficult because the narratives of the occurrences do not always provide sufficient information to draw any conclusions, and sometimes no additional information is given at all. For this analysis, the following is considered:

- If the wind shear warning was false, the occurrence is considered to be “not applicable”;
- In some occurrences, wind shear was detected before take-off, leading to a rejected take-off or to no take-off roll at all. These occurrences are also “not applicable”.
- The analysis distinguishes between cases with and without explicit wind shear warning. If there is no wind shear warning, a wind shear encounter can be detected as rapid changes in airspeed or rate of climb.
- The crew can react on wind shear (warnings) in various ways. The analysis identifies wind shear encounters in which the crew performs any recovery action and occurrences in which it is explicitly stated that standard operating procedures are followed, including e.g. applying maximum or firewall thrust and pushing the TO/GA switch, which is a subset of “any recovery action”.

These considerations lead to the following results:

### Table 11: Number of wind shear occurrences per flight phase

<table>
<thead>
<tr>
<th></th>
<th>Take-off</th>
<th>(Initial) climb</th>
<th>Take-off + (initial) climb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applicable to ESD 8</td>
<td>114</td>
<td>204</td>
<td>318</td>
</tr>
<tr>
<td>Sufficient information</td>
<td>108</td>
<td>187</td>
<td>295</td>
</tr>
<tr>
<td>Wind shear is detected</td>
<td>106 of 108</td>
<td>182 of 187</td>
<td>288 of 295</td>
</tr>
<tr>
<td>Wind shear warning</td>
<td>72 of 106</td>
<td>118 of 182</td>
<td>190 of 288</td>
</tr>
<tr>
<td>Crew avoidance/control actions</td>
<td>72 of 108</td>
<td>114 of 187</td>
<td>186 of 295</td>
</tr>
<tr>
<td>Wind shear escape manoeuvre</td>
<td>50 of 72</td>
<td>74 of 118</td>
<td>124 of 190</td>
</tr>
</tbody>
</table>

**Initiating event**

Using the results of the analysis of airlines safety reports, the frequency of the initiating event can be determined as follows:

- 318 applicable occurrences;
- With an exposure of 9 million flights, this leads to a frequency of $3.53 \times 10^{-5}$ per take-off.

**Flight crew fails to detect wind shear**

The results show that the wind shear was detected in 288 out of 295 occurrences. The conditional probability of ‘flight crew fails to detect wind shear’ in the event of a wind shear encounter after rotations is $7/297 = 2.37 \times 10^{-2}$. 
Flight crew fails to perform wind shear escape manoeuvre
According to the definition of this pivotal event, we consider cases where the flight crew fails to perform the full wind shear escape manoeuvre. According to the results, in 143 of 288 occurrences, the flight crew did not perform the wind shear escape manoeuvre, an estimated probability of $4.97 \cdot 10^{-1}$.

Collision with the ground
Airclaims and ADREP data showed only one accident in 452 million flights, resulting in a probability of a collision with the ground given that the aircraft encounters wind shear after rotation of $2.21 \cdot 10^{-9}$ per take-off.

Flight crew fails to maintain control
There are two situations that lead to the pivotal event “flight crew fails to maintain control:
- Flight crew fails to detect wind shear – this is estimated to happen with a probability of $2.37 \cdot 10^{-2} \times 3.53 \cdot 10^{-5} = 8.37 \cdot 10^{-7}$ per take-off; and
- Flight crew fails to perform wind shear escape manoeuvre – this is estimated to happen with a probability of $4.97 \cdot 10^{-1} \times (1-2.37 \cdot 10^{-2}) \times 3.53 \cdot 10^{-5} = 1.71 \cdot 10^{-5}$ per take-off.

In total, the probability that the crew gets into a situation in which they have to maintain control is $1.79 \cdot 10^{-5}$ per take-off.

The outcome is either a collision with the ground or the aircraft continues flight. The probability that the crew indeed fails to maintain control resulting in a collision with the ground already is estimated as $2.21 \cdot 10^{-9}$ per take-off. This means that the conditional probability that the crew fails to maintain control in the event of a wind shear encounter after rotation is $2.21 \cdot 10^{-9} / 1.79 \cdot 10^{-5} = 1.23 \cdot 10^{-4}$.

Aircraft continues flight
There are two end states “aircraft continues flight”. The probability of ‘aircraft continues flight’ if the crew succeeds in maintaining control after an undetected wind shear or without performing a wind shear escape manoeuvre is $(1-1.23 \cdot 10^{-4}) \times 1.79 \cdot 10^{-5} = 1.79 \cdot 10^{-5}$. The probability of ‘aircraft continues flight’ after successfully performing a wind shear escape manoeuvre is $(1-4.97 \cdot 10^{-1}) \times (1-2.37 \cdot 10^{-2}) \times 3.53 \cdot 10^{-5} = 1.73 \cdot 10^{-5}$. 
Scenario type: loss of control.
Phases: take-off.
Initiating event: aircraft encounters a performance decreasing windshear after rotation.

- Aircraft encounters a performance decreasing windshear after rotation
  - yes
    - Flight crew fails to detect windshear
    - Flight crew fails to perform windshear escape manoeuvre
    - Aircraft continues flight
  - no
    - Flight crew fails to maintain control
    - Unrecovered loss of control
    - Collision with ground

Risk probabilities:
- 3.53 \times 10^{-5}
- 1.23 \times 10^{-4}
- 2.21 \times 10^{-9}
- 1.79 \times 10^{-5}
- 1.73 \times 10^{-5}
- 4.97 \times 10^{-1}
- 2.37 \times 10^{2}
- 1.23 \times 10^{-4}
- 2.37 \times 10^{-2}
- 1.23 \times 10^{-4}
11 ESD9 - Single engine failure during take-off

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: single engine failure.

11.1 Definitions

**Single engine failure**
For the purpose of this ESD, a single engine failure is defined as any failures of one of the systems that correspond with the ATA codes between 6100 and 6197 or between 7100 and 8097.

**Flight crew rejects take-off**
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway remaining. At a certain point, the amount of runway available may not be sufficient to bring the aircraft to a complete stop. For this reason a decision speed \( V_1 \) is calculated before each take-off. The decision speed \( V_1 \) is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below \( V_1 \) the take-off can be safely rejected, at speeds above \( V_1 \) the take-off should be continued. Typical \( V_1 \) values for large commercial jet aircraft vary from 125 to 160 knots. The actual \( V_1 \) depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some operators and aircraft manufactures have defined a speed up to which a take-off should be
rejected for all observed failures. At speeds between this speed and the take-off decision speed $V_1$, the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft, in particular with respect to the aircraft’s flight- or ground path. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc.

Failure to achieve maximum braking
Immediately following the decision to reject a take-off, the flight crew must start reducing the speed of the aircraft. Particularly in the case of a high speed rejected take-off, braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

11.2 Quantification

Initiating event
The database of Service Difficulty Report (SDR) (see Appendix A) was used to estimate the probability of occurrence of the initiating event. It is assumed that an engine failure can consist of failures that correspond with the ATA codes between 6100 and 6197 or between 7100 and 8097. According to the data sample there were 8,745 engine related failures during take-off on a total of 216 million flights. The estimated probability of occurrence is $4.05 \times 10^{-5}$ per flight.

Pivotal event flight crew rejects take-off
Of the 8,745 engine failures during take-off that were reported in the SDR database, 6,999 resulted in a rejected take-off and 1,746 resulted in continuation of the take-off. Based on these results, the conditional probability of ‘flight crew rejects take-off’ in the event of an engine failure is estimated to be $8.00 \times 10^{-1}$. 
End states
To estimate the probability of runway overruns and veer-offs that are caused by engine failures during take-off, the Airclaims accident and incident database was analysed. Only large Western-built jets and turboprops in commercial operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group conducted a total of 399 million flights. Results of the analysis are presented in Table 12.

Table 12: Probability per flight for the different end states

<table>
<thead>
<tr>
<th>Type of occurrence</th>
<th>Abort speed</th>
<th>Number of occurrences</th>
<th>Frequency per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overrun</td>
<td>V &gt; V₁</td>
<td>15</td>
<td>3.76·10⁻⁸</td>
</tr>
<tr>
<td>Veer-off</td>
<td>V &lt; V₁</td>
<td>3</td>
<td>7.52·10⁻⁹</td>
</tr>
<tr>
<td>Overrun</td>
<td>V &lt; V₁</td>
<td>4</td>
<td>1.00·10⁻⁸</td>
</tr>
<tr>
<td>Veer-off</td>
<td>V &gt; V₁</td>
<td>2</td>
<td>5.01·10⁻⁹</td>
</tr>
</tbody>
</table>

Pivotal events
The conditional probability of an abort speed above V₁ in the event of an engine failure during take-off is estimated to be $3.76\cdot10^{-8} / (4.05\cdot10^{-5} \times 8.00\cdot10^{-1}) = 1.16\cdot10^{-3}$.

The conditional probability of failure to maintain control in the event of a rejected take-off due to an engine failure is $7.52\cdot10^{-9} / (4.05\cdot10^{-5} \times 8.00\cdot10^{-1} \times (1-1.16\cdot10^{-3})) = 2.32\cdot10^{-4}$.

The conditional probability of ‘failure to achieve maximum braking’ in case of a rejected take-off below V₁ as a result of an engine failure is $1.00\cdot10^{-8} / (4.05\cdot10^{-5} \times 8.00\cdot10^{-1} \times (1-1.16\cdot10^{-3}) \times (1-2.32\cdot10^{-4}) = 3.09\cdot10^{-4}$.

The conditional probability of ‘flight crew fails to maintain control’ in case the take-off is continued with an engine failure is $5.01\cdot10^{-9} / (4.05\cdot10^{-5} \times (1-8.00\cdot10^{-1})) = 6.19\cdot10^{-4}$. 
Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: single engine failure.

1. Single engine failure
   - Loss of power and directional control problems
     - Flight crew rejects take-off
       - $V > V_s$
         - $1.16 \times 10^{-3}$
           - Runway overrun
         - $2.32 \times 10^{-4}$
           - Unrecovered loss of control
             - Runway veer-off
       - Flight crew fails to maintain control
         - Failure to achieve maximum braking
           - $3.09 \times 10^{-4}$
             - Runway overrun
           - $3.23 \times 10^{-5}$
             - Aircraft stops on runway
       - Flight crew fails to maintain control
         - Unrecovered loss of control
           - Runway veer-off
           - $5.01 \times 10^{-8}$
             - Aircraft continues take-off

2. $4.05 \times 10^{-5}$
   - yes
     - no
12 ESD10 - Pitch control problems

Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: pitch control problem.

12.1 Definitions

Pitch control problem
For the purpose of this ESD, a pitch control problem can arise from a pitch control system malfunction or difficulties related to the aircraft’s weight and balance. Only weight and balance problems that may lead to a failure to rotate the aircraft are considered here. Weight and balance problems that lead to overrotation and a subsequent risk of a wing stall are considered in ESD 7.

Flight crew rejects take-off
A rejected take-off is defined as “failure to complete a take-off manoeuvre after take-off power has been applied”. If, during the take-off run, a situation arises that potentially compromises a safe take-off and climb, the flight crew may elect to reject the take-off. The decision whether or not to reject the take-off depends on the speed of the aircraft and the amount of runway remaining. At a certain point, the amount of runway available may not be sufficient to bring the aircraft to a complete stop. For this reason a decision speed $V_1$ is calculated before each take-off. The decision speed $V_1$ is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below $V_1$
the take-off can be safely rejected, at speeds above \( V_1 \) the take-off should be continued. Typical \( V_1 \) values for large commercial jet aircraft vary from 125 to 160 knots. The actual \( V_1 \) depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient. Some operators and aircraft manufactures have defined a speed up to which a take-off should be rejected for all observed failures. At speeds between this speed and the take-off decision speed \( V_1 \), the take-off should be rejected only in case of an engine failure and conditions affecting the safe handling of the aircraft. Different policies exist among the operators regarding these take-off rejection criteria. The speed up to which a take-off should be rejected for all observed failures varies between 70-100 knots with a typical value in the order of 80 knots.

**Aircraft fails to rotate and lift-off**

This describes the situation where, when the aircraft reaches rotation speed \( V_R \), the aircraft cannot be rotated and fails to lift off. This pivotal event describes a situation where the flight crew does not abort the take-off, but continues the take-off attempt (i.e. engine remain at high power) until the aircraft overruns the runway.

\( V > V_1 \)

The event \( V > V_1 \) describes a situation where the rejected take-off is initiated at a speed higher than the decision speed \( V_1 \). The decision speed \( V_1 \) is the maximum speed at which the take-off can be safely aborted and the aircraft can be brought to a complete stop at the remaining runway. At a speed below \( V_1 \) the take-off can be safely rejected, at speeds above \( V_1 \) the take-off should be continued. Typical \( V_1 \) values for large commercial jet aircraft vary from 125 to 160 knots. The actual \( V_1 \) depends on aircraft type, aircraft weight, wind, air density, temperature, and runway gradient.

**Flight crew fails to maintain control**

This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc.

**Failure to achieve maximum braking**

Immediately following the decision to reject a take-off, the flight crew must start reducing the speed of the aircraft. Particularly in the case of a high speed rejected take-off, braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP).
Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

Runway overrun
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

12.2 Quantification

Initiating event
The Service Difficulty Report (SDR) database (see Appendix A) has been used to determine the contribution of pitch control system failures to the initiating event. According to the SDR database, there have been 389 failures of ATA series 2730 (elevator) and 2740 (stabilizer) during take-off, in a total of 216 million flights. This results in a frequency of $1.80 \cdot 10^{-6}$ per flight.

To determine the contribution of weight and balance problems to the initiating event, the Air safety database was analysed. See also ESD 7. Initial search in the database resulted in 1179 occurrences related to the initiating event “aircraft weight and balance outside limits” in 9.5 million flights. This search included keywords like load, loadsheet, weight, gravity, balance, and considered all flight phases other than parked or cruise.
Using the classification of the source data it appears that 390 of the 1179 occurrences are related to the take-off flight phase. Analysis of these 390 occurrences shows that 285 are possibly applicable to ESD 10. These 285 can be classified as follows:

- 89 in which it is explicitly mentioned that the aircraft felt nose heavy on rotation;
- 45 in which it is explicitly mentioned that the aircraft felt tail heavy on rotation;
- 20 with an overweight take-off;
- 93 with incorrect loadsheet information;
- 22 load shifts; and
- 16 of which the context is not exactly clear.

To quantify the initiating event, the following is assumed:

- Only occurrences with nose-heavy and overweight aircraft behaviour are relevant for this initiating event.
- The occurrences with incorrect loadsheet information and with the unknown context could apply both to nose heavy and tail heavy aircraft behaviour but this is not explicitly stated. Therefore, these occurrences are divided 2:1 (using the 89:45 division of nose heavy and tail heavy occurrences) over applicable and not applicable to ESD 10.

With this, $89 + 20 + 93 \times \frac{2}{3} = 182$ occurrences are applicable. With 9.5 million flights this leads to a contribution to the probability of the initiating event of $1.91 \times 10^{-5}$ per flight.

The total probability of the initiation event is estimated to be $1.80 \times 10^{-6} + 1.91 \times 10^{-5} = 2.09 \times 10^{-5}$ per flight.

Pivotal event ‘flight crew rejects take off’

Analysis of the 389 pitch control system failures that are reported in the SDR database shows that 313 pitch control system failures resulted in a rejected take-off, while 76 pitch control system failures resulted in a continuation of the take-off.

Analysis of all 182 weight and balance related pitch control problems that are reported in the Air Safety Database shows that none of those resulted in a rejected take-off.

The conditional probability of a rejected take-off in the event of a pitch control problem can now be calculated. In one million flights, there will be an expected number of 1.80 pitch control related system failures, which will result in $1.80 \times (313/389) = 1.45$ rejected take offs. In those same one million flights, there will be an expected number of 19.1 weight and balance related pitch control problems, resulting in no rejected take off.
In total, for the one million flights under consideration, there are 20.90 pitch control problems and 0.869 rejected take-offs. The conditional probability of a rejected take-off in the event of a pitch control problem is \( \frac{1.45}{20.90} = 6.93 \cdot 10^{-2} \) per flight.

**Runway overruns**

A query in the ADREP and Airclaims databases has been performed to find runway overruns that are caused by weight and balance problems (centre of gravity too much forward) or by pitch control system failure (stabilizer or elevator). The scope of the query was flights from 1990 to 2005, Western-built aircraft with a MTOW of over 5700 kg in commercial operations. This set has an exposure of 452 million flights. The following accidents could be identified:

**Table 13: Number of occurrences per accident type**

<table>
<thead>
<tr>
<th>Accident type</th>
<th>Number of occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overrun with RTO, ( V_{RTO} &gt; V_1 )</td>
<td>3</td>
</tr>
<tr>
<td>Overrun with RTO, ( V_{RTO} &lt; V_1 )</td>
<td>1</td>
</tr>
<tr>
<td>Overrun with RTO, ( V_{RTO} ) unknown</td>
<td>3</td>
</tr>
<tr>
<td>Overrun without RTO</td>
<td>1</td>
</tr>
</tbody>
</table>

Most of these accidents are related to weight and balance problems, either too much weight or a centre of gravity that is more forward than calculated. In one additional accident, the aircraft had pitch control problems (overweight), lifted off, and hit a building at the extended runway centreline. This is considered outside the scope of this ESD.

Pitch control problems are often only discovered if the aircraft is already at rotation speed, i.e. at a late stage of the take-off. If the crew decides to reject the take-off, this will be with a speed close to \( V_1 \). In the narratives of 3 accidents it is not explicitly stated whether the RTO speed is above or below \( V_1 \). Considering the division of the accidents with known RTO speeds (3 higher and 1 lower than \( V_1 \)) it is decided to divide the 3 accidents as follows: 2 with an RTO speed higher than \( V_1 \) and 1 lower than \( V_1 \). With 452 million flights, this gives the following results:

**Table 14: Probability per flight for each end state**

<table>
<thead>
<tr>
<th>End state</th>
<th>Number of occurrences</th>
<th>Probability of occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overrun with RTO, ( V_{RTO} &gt; V_1 )</td>
<td>5</td>
<td>( 1.11 \cdot 10^{-8} ) per flight</td>
</tr>
<tr>
<td>Overrun with RTO, ( V_{RTO} &lt; V_1 )</td>
<td>2</td>
<td>( 4.42 \cdot 10^{-9} ) per flight</td>
</tr>
<tr>
<td>Aircraft fails to rotate and lift-off</td>
<td>1</td>
<td>( 2.21 \cdot 10^{-9} ) per flight</td>
</tr>
</tbody>
</table>
Runway veer-off
One of the possible outcomes of pitch control problems is a runway veer-off, which is the result of the crew not maintaining control after a rejected take-off. In the list of accidents that has been analysed, two runway veer-offs are found. However, in these 2 situations, the crew did maintain control and steered the aircraft after the RTO on purpose to the side of the runway. Therefore, these two situations are counted as runway overruns, not as runway veer-offs (see also the definition of a runway overrun). Considering also that pitch control problems are not necessarily leading to directional control problems, it is assumed here that the probability of a runway veer-off after pitch control problems and a RTO is 0. With this, the conditional probability of the pivotal event ‘flight crew fails to maintain control’ is 0.

\[ V > V_1 \]
The conditional probability that \( V > V_1 \) in the event of pitch control problems and a continued take off is \( 1.11 \cdot 10^{-8} / (2.09 \cdot 10^{-5} \times 6.93 \cdot 10^{-2}) = 7.66 \cdot 10^{-3} \) per flight.

Failure to achieve maximum braking
The conditional probability of a failure to achieve maximum braking in the event of pitch control problems and a rejected take-off below \( V_1 \) is \( 4.42 \cdot 10^{-9} / (2.09 \cdot 10^{-5} \times 6.93 \cdot 10^{-2} \times (1 - 7.66 \cdot 10^{-3})) = 3.08 \cdot 10^{-3} \) per flight.

Aircraft fails to rotate and lift-off
The conditional probability that the aircraft fails to rotate and lift off in the event of a continued take-off with pitch control problems is \( 2.21 \cdot 10^{-9} / (2.09 \cdot 10^{-5} \times (1 - 6.93 \cdot 10^{-2})) = 1.14 \cdot 10^{-4} \).

Aircraft stops on runway
The conditional probability that the aircraft stops on the runway is \( 2.09 \cdot 10^{-5} \times 6.93 \cdot 10^{-2} \times (1 - 7.66 \cdot 10^{-3}) \times (1 - 3.08 \cdot 10^{-3}) = 1.43 \cdot 10^{-6} \).

Aircraft continues flight
The conditional probability that the aircraft continues flight after pitch control problems during take-off is \( 2.09 \cdot 10^{-5} \times (1 - 6.93 \cdot 10^{-2}) \times (1 - 1.14 \cdot 10^{-4}) = 1.94 \cdot 10^{-5} \).
Accident type: uncontrolled collision with ground.
Flight phase: take-off.
Initiating event: pitch control problem.

Pitch control problem
\[ 2.09 \times 10^{-5} \]

Flight crew rejects take-off
\[ 6.93 \times 10^{-2} \]
\[ 7.66 \times 10^{-3} \]

\[ V > V_1 \]

Runway overrun
\[ 1.11 \times 10^{-8} \]

Failure to achieve maximum braking
\[ 3.08 \times 10^{-3} \]

Runway overrun
\[ 4.42 \times 10^{-9} \]

Aircraft stops on runway
\[ 1.43 \times 10^{-6} \]

Aircraft continues flight
\[ 1.94 \times 10^{-5} \]

Aircraft fails to rotate and lift-off
\[ 1.14 \times 10^{-4} \]
13 ESD11 - Fire onboard aircraft

Accident type: fire/explosion.
Flight phase: take-off, initial climb, en route, approach, landing.
Initiating Event: fire onboard aircraft.

13.1 Definitions

Fire onboard aircraft
This initiating event describes a situation where a combustible substance on-board the aircraft is burning. The combustible material can be part of the aircraft’s payload, (e.g. cargo), systems e.g. (fuel, oil, hydraulics) or interior (plastics etc). Indicators of a fire are (visible) flames, but also visible smoke and a burning smell. Smoke and a burning smell may be generated even before there is a real fire (e.g. smouldering plastics may generate smoke), but the difference between smouldering and burning is often quite ambiguous. Cases where meals were overheated causing a burning smell in the cabin were not considered to be cases of ‘fire onboard aircraft’.

Flight crew fails to detect smoke/fire
Possible indicators of a fire are visible flames, visible smoke, burning smell, or an alert by fire detection system. Most aircraft types are equipped with fire detection systems for the engines and cargo areas. Modern aircraft also may display messages indicating that systems are overheating. Detection capabilities are limited however, and fire detection systems are notorious for the number of false warnings they generate. Small fires that die-out automatically may go unnoticed, only to be detected after the flight during maintenance inspection.

Flight crew fails to extinguish fire
In most commercial transport aircraft there are three types of fire extinguishers:
- Engine fire extinguishers, remotely controlled from the cockpit
• Cargo bay fire extinguishers, remotely controlled from the cockpit
• Portable fire extinguishers, to be used for battling fire in the cockpit or the aircraft cabin.

Apart from these extinguishers there may be indirect ways in which the flight crew can extinguish fires, such as shutting off the fuel lines to a burning engine. This pivotal event refers to any situation where the fire is extinguished, either directly or indirectly, through actions of the flight crew.

Fire propagates
The pivot event “Fire propagates” is defined as the situation in which the fire propagates to such an extent that the flight is hampered by the fire. This could either be a failure of the flight control system, a structural failure of the aircraft, or incapacitation of the crew.

Flight crew fails to maintain control
In case of a flight control system failure, aircraft structural failure or flight crew incapacitation, the flight crew may still be able maintain control and safely land the aircraft. This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc.

13.2 Quantification
For quantification of this Event Sequence Diagram the Accident and Incident Database System (AIDS) of the FAA was used. For this ESD, incidents and accidents from Part 121 flights in the period 1990 to 2000 are selected. This selection corresponds to 100,860,778 departures.

Initiating event
The data sample from the FAA AIDS database contains 370 cases of genuine fires, which corresponds with a frequency of 3.67·10⁻⁶ fires per flight. Details are presented in Table 15. Only ‘genuine’ fires were considered, cases where meals were overheated causing a burning smell in the cabin were not considered to be ‘genuine’ fires.

The most frequent type of fire is an engine fire: about 50 % of the occurrences are engine fires. Electrical fires are the next most frequent type of fire. Other types of fire are less frequent. In only 3 cases (0.81 %) the fire was not detected during the flight. In 216 (58.4 %) cases in the data sample, the crew were able to extinguish the fire.
Table 15: Fire on-board aircraft

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of occurrences</th>
<th>Frequency per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>184</td>
<td>1.82·10^{-6}</td>
</tr>
<tr>
<td>Electrical fires</td>
<td>106</td>
<td>1.05·10^{-6}</td>
</tr>
<tr>
<td>APU</td>
<td>20</td>
<td>1.98·10^{-7}</td>
</tr>
<tr>
<td>Cargo</td>
<td>9</td>
<td>8.92·10^{-8}</td>
</tr>
<tr>
<td>Lavatory</td>
<td>9</td>
<td>8.92·10^{-8}</td>
</tr>
<tr>
<td>Air conditioning</td>
<td>18</td>
<td>1.78·10^{-7}</td>
</tr>
<tr>
<td>Cabin fire</td>
<td>23</td>
<td>2.28·10^{-7}</td>
</tr>
<tr>
<td>Fuel tank</td>
<td>1</td>
<td>9.91·10^{-9}</td>
</tr>
</tbody>
</table>

Accidents

Table 16 and Table 17 provide an overview of all fatal loss of control accidents that were caused by fire on-board the aircraft. Only ‘western-built’ aircraft heavier than 5,700 kg MTOW in commercial operations between 1985 and 2005 were considered. A distinction is made between large jet aircraft (more than 19 passengers) and small jet aircraft and turboprops. There have been 7 cases of loss of control accidents due to fire for large jet aircraft. In the time-frame under consideration, this group conducted a total of 309 million flights. The corresponding accident frequency is 2.26·10^{-8} per flight. There have been 4 cases of loss of control for small jet aircraft and turboprops. In the time frame under consideration this group conducted a total of 107 million flights. The corresponding accident frequency is 3.74·10^{-8} per flight. If no distinction is made between large jet aircraft and small jet aircraft and turboprops, the accident frequency is 2.64·10^{-8}.

Table 16: Fatal accidents of western-built jet aircraft in commercial operations in the period 1985-2003, more than 19 seats, loss of control caused by fire

<table>
<thead>
<tr>
<th>Date</th>
<th>Aircraft type</th>
<th>Operator</th>
<th>Location</th>
<th>Cause of loss of control</th>
</tr>
</thead>
<tbody>
<tr>
<td>31/03/86</td>
<td>Boeing 727</td>
<td>Mexicana</td>
<td>Mexico</td>
<td>Structural failure</td>
</tr>
<tr>
<td>28/11/87</td>
<td>Boeing 747</td>
<td>SAA</td>
<td>Mauritius</td>
<td>Exact cause unknown</td>
</tr>
<tr>
<td>11/07/91</td>
<td>DC-8</td>
<td>Nationair</td>
<td>Jeddah, Saudi-Arabia</td>
<td>Structural failure</td>
</tr>
<tr>
<td>11/05/96</td>
<td>DC-9</td>
<td>Valujet</td>
<td>Miami, USA</td>
<td>Flight control system</td>
</tr>
<tr>
<td>17/07/96</td>
<td>Boeing 747</td>
<td>TWA</td>
<td>New York, USA</td>
<td>Structural failure</td>
</tr>
<tr>
<td>02/09/98</td>
<td>MD-11</td>
<td>Swissair</td>
<td>Nova Scotia, Canada</td>
<td>Crew incapacitation</td>
</tr>
<tr>
<td>25/07/00</td>
<td>Concorde</td>
<td>Air France</td>
<td>Paris, France</td>
<td>Structural failure</td>
</tr>
</tbody>
</table>
Table 17: Fatal accidents of western-built jet- and turboprop aircraft in commercial operations in the period 1985-2003, 19 seats or less, loss of control caused by fire

<table>
<thead>
<tr>
<th>Date</th>
<th>Aircraft type</th>
<th>Operator</th>
<th>Location</th>
<th>Cause of loss of control</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/06/85</td>
<td>Learjet 24</td>
<td>Euralair International</td>
<td>France (en route)</td>
<td>Flight crew incapacitation</td>
</tr>
<tr>
<td>20/01/95</td>
<td>Dassault Falcon 20</td>
<td>Unijet</td>
<td>Paris, France</td>
<td>Structural failure</td>
</tr>
<tr>
<td>12/07/95</td>
<td>DHC-6 Twin Otter</td>
<td>Airlines of PNG Papua New Guinea</td>
<td>Exact cause unknown</td>
<td></td>
</tr>
<tr>
<td>18/06/96</td>
<td>Fairchild Metro II</td>
<td>Propair</td>
<td>Montreal, Canada</td>
<td>Structural failure</td>
</tr>
</tbody>
</table>

Analysis of FAA’s AIDS database failed to find any cases of structural failure, flight control system failure or flight crew incapacitation where the flight crew managed to maintain control. It is therefore assumed that in the event of a fire which causes a structural failure, a flight control system failure or flight crew incapacitation, the probability for the flight crew to maintain control of the aircraft is 0.

Accident type: fire/explosion.
Flight phase: take-off, initial climb, en route, approach, landing.
Initiating Event: fire onboard aircraft.
14 ESD12 - Flight crew spatially disoriented

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: flight crew member spatially disoriented.

14.1 Definitions
Spatial orientation refers to a person’s ability to perceive motion, position and attitude in relation to the surrounding environment. This capability depends upon the reception, integration and interpretation of sensory inputs from visual, vestibular, muscular and skin receptors. [Antuñano & Mohler, 1992].

Spatial disorientation occurs when a pilot has inadequate visual information or fails to attend to or properly interpret available information regarding the airplane’s pitch and bank. Instead, a disoriented pilot relies on cues that are often misleading. The most hazardous illusions that lead to spatial disorientation result from ambiguous information received from motion sensing organs located in each inner ear. The sensory organs of the inner ear detect angular accelerations in the pitch, yaw, and roll axes and gravity and linear accelerations. During flight, the inner ear organs may be stimulated by motion of the aircraft alone or along with head and body movement [NTSB, 2003].

Quantification of ESD 12 is based on the assumption that spatial disorientation refers to disorientation with respect to the attitude (pitch, roll and yaw) of the aircraft only. Disorientation with respect to aircraft’s position and altitude are excluded. ESD 12 describes a loss of control accident as a result of spatial disorientation. In this type of accident the pilot’s perception of aircraft attitude relative to the surface of the earth and the gravitational vertical plays a role, not his perception of position with respect to the surface of the earth. Situational
awareness regarding the aircraft position and altitude are relevant in the context of a potential collision with terrain and are covered in ESD 35. Events where the flight crew lost situational awareness and landed on a wrong runway, taxied along the wrong route, lined-up the wrong runway etc., are covered by ESD 32.

It is often difficult to prove with certainty that spatial disorientation affected the pilot. However, in many accidents, weather conditions in combination with the aircraft trajectory (e.g. ‘graveyard spin’) are strong indications that the flight crew was spatially disoriented.

In the ESD the initiating event, pivotal events and end states are defined as follows.

**Flight crew member spatially disoriented**
The Initiating Event is defined as the situation that a flight crew member suffers spatial disorientation, i.e. has inadequate visual information or fails to attend to or properly interpret available information regarding the airplane’s pitch, roll or yaw angle or rate of rotation.

**Flight crew fails to maintain control**
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc. In this ESD the failure of the flight crew to maintain control refers to a situation where a flight crew spatial disorientation event occurs. It is then pivotal in the sequence of events whether any member of the flight crew detects the disorientation and gives over or takes-over control in time to maintain control of the aircraft.

**Collision with ground**
This end state refers to a possible outcome of a flight crew spatial disorientation event and includes any sort of collision with terrain (ground, water) or obstacles that results in injuries or fatalities or substantial damage to the aircraft.

**Aircraft continues flight**
This end state refers to the possible outcome of a flight crew spatial disorientation event when the flight crew continues the flight to the destination airport or diverts the aircraft to another airport. This includes occurrences where the non-affected pilot takes over control and occurrences where the pilot(s) succeed(s) in overcoming the disorientation.
14.2 Quantification

14.2.1 Data sources

The following data sources have been used for quantifying the events in this ESD:

- NLR Air Safety Database;
- ASRS database;
- NTSB database.

**NLR Air Safety Database**

A query was run in the NLR Air Safety Database to search for accidents and incidents related to spatial disorientation. The time span was set to 1970 to 2003. Aircraft types include jet and turboprop aircraft with a maximum take-off mass of more than 5700 kg in commercial operations. Only ‘Western-built aircraft’ are considered, i.e. aircraft from manufacturers such as Airbus, Boeing, McDonnell-Douglas, Lockheed, Fokker, Embraer etc. Aircraft from manufacturers located in Eastern Europe (such as Let, Antonov, Tupolev and Ilyushin) and China are excluded. The corresponding number of flights for this data sample is 750 million. The query resulted in 28 accidents.

The data sample was further analysed to determine causal factors. The data sample was not suitable to estimate the frequency of occurrence of spatial disorientation events as it includes only accidents. Minor occurrences and incidents involving spatial disorientation without further consequences are not captured in the data sample.

Results of the accident data analysis are summarised in Table 18. In 24 of 28 accidents the aircraft collided with the ground, in 4 cases the aircraft made a hard landing. 23 accidents were fatal. In all 28 accidents the flight crew failed to maintain control, although in at least three cases it is known or suspected that the crew detected the condition of spatial disorientation, but failed to correct the situation or take-over control from the disoriented pilot.

The weather conditions at the time of the accident are often not detailed. About a third of the accidents occurred at night. In 7 occurrences visual reference with the horizon and terrain was obscured or lost due to (heavy) rain showers. In 8 occurrences visual reference was not available because aircraft was flying in(to) clouds at the time of spatial disorientation. In 2 cases fog was present during the accident.

Table 18 also shows the distribution of spatial disorientation accidents across different flight phases. About 90% of the spatial disorientation accidents occur in the approach, landing, missed approach and climb flight phase, which is understandable given that these flight phases are
typically the flight phases during which pilots manually fly the aircraft part of the flight. These flight phases include also manoeuvring, which means accelerations, turns, descents, climbs) which can be conducive to spatial disorientation.

Table 18: Results from data analysis of spatial disorientation related accidents

<table>
<thead>
<tr>
<th></th>
<th>Number of occurrence</th>
<th>Percentage of occurrences</th>
<th>Accidents per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total accident sample</td>
<td>28</td>
<td>100%</td>
<td>3.73·10^{-8}</td>
</tr>
<tr>
<td>Fatal accidents</td>
<td>23</td>
<td>82%</td>
<td>3.07·10^{-8}</td>
</tr>
<tr>
<td>Non-fatal accidents</td>
<td>5</td>
<td>18%</td>
<td>6.67·10^{-9}</td>
</tr>
<tr>
<td>Flight crew response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detect spatial disorientation</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Take over control</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintain control</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consequence</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collision with ground</td>
<td>24</td>
<td>86%</td>
<td>3.20·10^{-8}</td>
</tr>
<tr>
<td>Hard landing</td>
<td>4</td>
<td>14%</td>
<td>5.33·10^{-9}</td>
</tr>
<tr>
<td>Weather conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rain</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Night</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clouds</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fog</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft system failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADI failure</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flight phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climb</td>
<td>8</td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td>En route</td>
<td>3</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>Missed approach</td>
<td>5</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td>9</td>
<td>32%</td>
<td></td>
</tr>
<tr>
<td>Landing</td>
<td>3</td>
<td>11%</td>
<td></td>
</tr>
</tbody>
</table>

Source: NLR Air Safety Database

ASRS and NTSB database
The ASRS database was queried for incidents on spatial disorientation, illusion or vertigo. The data sample was restricted to commercial Part 121 operations. Aircraft types include jet, and turboprop aircraft with a maximum take-off weight of more than 5700 kg, operated in commercial operations. Only ‘Western-built aircraft’ are considered, i.e. aircraft from manufacturers such as Airbus, Boeing, McDonnell-Douglas, Lockheed, Fokker, Embraer etc.
Aircraft from manufacturers located in Eastern Europe (such as Let, Antonov, Tupolev and Ilyushin) and China are excluded. The time span was selected as 1990 to 2004. The number of flights corresponding to this time span and Part 121 operations is 143.5 million [NTSB, 2005].

The ASRS query resulted in 12 pilot reports of in-flight spatial disorientation. All occurrences were classified as incidents and none of them resulted in a collision with terrain. Table 19 shows the results of the analysis of these occurrences. In 9 of the 12 events the flight crew reported that they were manually flying the aircraft, in 3 cases information on whether the crew was manually flying or flying on autopilot was not available. In the majority of the occurrences the pilot(s) recognised the spatial disorientation, but did not hand over control. In all cases the flight crew was able to maintain control, relaying on their instruments. In one case the aircraft developed a high bank angle before the flight crew recognised the spatial disorientation and unusual attitude, after which they regained control. The consequences of the loss of spatial orientation are listed in Table 19. Most events of spatial disorientation occurred in the approach phase (7), followed by climb phase (3). This result matches the distribution across flight phases that we found in the NLR Air Safety Database query.

In addition to the NLR Air Safety Database and ASRS database a query was run in the NTSB database to search for incidents related to spatial disorientation, vertigo or illusions. The query was limited to Part 121 commercial operations between 1990 and 2004. Of the data sample returned by the NTSB database query one incident was relevant for this study and has been included in the results in Table 19.
Table 19: ASRS incident data on spatial disorientation occurrences

<table>
<thead>
<tr>
<th></th>
<th>Number of occurrences</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial disorientation event</td>
<td>12^4</td>
<td>8.36·10^-8</td>
</tr>
</tbody>
</table>

**Flight crew response**

- Detect spatial disorientation: 8
- Takeover control: 0
- Maintain control: 11
- Momentary loss of control: 1
- Flight crew manual flying: 9
- Manual flying or autopilot status unknown: 3

**Consequence (end state)**

- Continue flight: 12
- Hard landing: 1
- Altitude bust: 4

**Weather conditions**

- Rain: 1
- Night: 7
- Clouds: 5
- Fog: 0

**Aircraft systems**

- Instrument failure: 1

**Flight phase**

- Climb: 3
- En route: 2
- Missed approach: 1
- Approach: 6
- Landing: 0

**Percentage**

- Climb: 25%
- En route: 17%
- Missed approach: 8%
- Approach: 50%

*Source: NTSB and ASRS database.*

**14.2.2 Summary**

**Quantification Initiating Event**

The best estimate that we currently can derive from accident and incident data yields a frequency of in-flight spatial disorientation of 8.36·10^-8 per flight. This number is based on ASRS data, which is a voluntary reporting system. The data reliability is poor and a degree of underreporting is suspected.

---

^3 All events were classified as incidents

^4 The small sample size does not allow conclusions that are statistically significant.
Quantification Pivotal Event ‘Flight crew fails to maintain control’
Given spatial disorientation the conditional probability of a flight crew failing to maintain control is $3.83 \cdot 10^{-1}$. This number is derived from the frequency of spatial disorientation occurrences and the frequency of spatial disorientation events resulting in a collision with ground. The frequency of spatial disorientation was determined using ASRS data which has limited reliability.

End state ‘collision with ground’
The probability of a ground collision as result of spatial disorientation is $3.20 \cdot 10^{-8}$.

End state ‘aircraft continues flight’
The probability of a continued flight after a spatial disorientation event is estimated as $8.36 \cdot 10^{-8} \times (1 - 3.83 \cdot 10^{-1}) = 5.16 \cdot 10^{-8}$ per flight.

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: flight crew member spatially disoriented.

![Diagram of accident sequence]
15 ESD13 - Flight control system failure

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: flight control system failure.

Flight control system failure

Controllability problems → Flight crew fails to maintain control (1) → Unrecovered loss of control → Collision with ground

Aircraft continues flight

yes

no

(1) Maintaining control is influenced by factors such as type of failure, crew response to the system failure, training, aircraft handling by crew etc

15.1 Definitions

Flight control system failure
For the purpose of this ESD, a flight control system failure is defined as a failure of any of the following systems:

- Aileron system  ATA 2710-2719
- Rudder system  ATA 2720-2729
- Elevator system  ATA 2730-2739
- Stabilizer system  ATA 2740-2749
- Other  ATA 2700-2709 & ATA 2750-2797

Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc.

15.2 Quantification
The database of Service Difficulty Reports (SDR) (see Appendix A) has been used to determine the number of flight control system failures. A failure of any of the following systems was considered to be a ‘flight control system’ failure:
The data sample contained a total number of 7,789 flight control system failures during the flight phases (initial) climb, en-route, descent, approach and landing. The corresponding number of flights is 215,800,000. The results are presented in Table 20. The estimated probability of a flight control system failure is $3.61 \times 10^{-5}$ per flight.

<table>
<thead>
<tr>
<th>System</th>
<th>ATA code</th>
<th>Number of SDRs</th>
<th>Number of failures per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aileron</td>
<td>2710 – 2719</td>
<td>454</td>
<td>$2.10 \times 10^{-6}$</td>
</tr>
<tr>
<td>Rudder</td>
<td>2720 – 2729</td>
<td>512</td>
<td>$2.37 \times 10^{-6}$</td>
</tr>
<tr>
<td>Elevator</td>
<td>2730 – 2739</td>
<td>545</td>
<td>$2.53 \times 10^{-6}$</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>2740 – 2749</td>
<td>510</td>
<td>$2.36 \times 10^{-6}$</td>
</tr>
<tr>
<td>Other</td>
<td>2700 – 2709 &amp; 2750 – 2797</td>
<td>5768</td>
<td>$2.67 \times 10^{-5}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2700 – 2797</strong></td>
<td><strong>7789</strong></td>
<td><strong>$3.61 \times 10^{-5}$</strong></td>
</tr>
</tbody>
</table>

Airclaims database
The number of collisions with the ground due to flight control system failures has been determined from the Airclaims database. The time span was set to 1985-2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators, and accidents/incidents during test flights and training flights were excluded. The number of flights associated with this query is 309 million flights. (1985-2005).

The analysis identified 11 loss-of-control accidents that were initiated by flight control system failures. The estimated frequency of occurrence is $3.56 \times 10^{-8}$ per flight.

The estimated conditional probability of occurrence of a failure of the flight crew to maintain control in the event of a flight control system failure is $3.56 \times 10^{-8} / 3.61 \times 10^{-5} = 9.86 \times 10^{-4}$. 
Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: flight control system failure.

1. Flight control system failure
2. Controllability problems
3. Flight crew fails to maintain control
4. Unrecovered loss of control
5. Collision with ground
6. Aircraft continues flight

Probabilities:
- Flight control system failure: $3.61 \times 10^5$
- Controllability problems: $9.89 \times 10^4$
- Collision with ground: $3.56 \times 10^8$
- Aircraft continues flight: $3.61 \times 10^5$
16 ESD14 - Flight crew incapacitation

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event flight crew incapacitation.

16.1 Definitions
In the ESD the initiating event, pivotal events and end states are defined as follows.

Initiating Event Flight crew incapacitation
Incapacitation is the inability of any required flight crew member (i.e. captain, first officer or flight engineer) to perform prescribed flight duties as a result of reduced medical fitness. In medical literature distinction is made between impairment and incapacitation, but in this study it is assumed that flight crew incapacitation covers both incapacitation and impairment of a flight crew member. Incapacitation or impairment events related to cabin crew are excluded.

In general, flight crew incapacitation can be health related, hypoxia or caused by asphyxiation. ESD 14 covers flight crew incapacitation due to a health related factor or hypoxia. Flight crew incapacitation due to asphyxiation is covered in ESD 11 (in-flight fire). Accordingly, the frequency of occurrence of flight crew incapacitation in this ESD pertains to flight crew incapacitations as a result of health related problems or hypoxia.

Pivotal Event Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions etc. In this ESD the failure of the flight crew to maintain control refers to a situation where a flight crew incapacitation event occurs. It is then pivotal in the sequence of events whether the affected or unaffected flight crew member detects the incapacitation, gives over or takes over control in time to maintain control of the aircraft.
End State Collision with ground
This end state refers to a possible outcome of a flight crew incapacitation event: the aircraft impacts terrain (ground, water) or obstacles, which results in injuries, fatalities or (substantial) damage to the aircraft.

End State Aircraft continues flight
This end state refers to the possible outcome of a flight crew incapacitation: the flight crew continues the flight to destination airport or diverts the aircraft to another airport due to medical emergency (flight crew incapacitation).

In some occurrences in which a flight crew member became incapacitated or impaired the other pilot took over control of the aircraft or the incapacitated/impaired pilot was replaced by a relief pilot. This situation is classified as ‘aircraft continues flight’.

16.2 Quantification

16.2.1 Data sources
To quantify the events in the ESD multiple data sources have been used:
- NLR Air Safety Database;
- Occurrence data from an airline;
- Medical research (see references).

16.2.2 Results
There have been relatively few recent studies on-flight crew incapacitation. Some studies in this area are relatively old (1970s and 1980s), which may not represent the situation today with respect to current medical knowledge, medical examinations, medical regulations etc. A relevant data source providing quantitative data is a study conducted into in-flight medical incapacitation of U.S. airline pilots (1993-1998) [DeJohn, et al., 2004]. The study deals with medical related incapacitation and impairments, including incapacitation as a result of hypoxia, and excludes incapacitation as a result of asphyxiation. For quantification of the frequency of flight crew incapacitation events, operator data is the most reliable source. Other sources, including [DeJohn et al, 2004] and [Martin-Saint-Laurent et al., 1990] admittedly suffer from underreporting and therefore cannot be used for quantification of the initiating and pivotal event.
European operator data

Airline occurrence data from a European operator\(^5\) contains five flight crew incapacitation events in the time span 1997 to 1998. The corresponding number of flights in this period is 107,000, which yields a frequency of an incapacitation event of \(4.67 \cdot 10^{-5}\) per flight.

**Literature**

Two important studies on flight crew incapacitation are [DeJohn et al., 2004] and [Martin-Saint-Laurent et al., 1990]. [DeJohn et al., 2004] estimates the probability of an accident related to flight crew incapacitation. Two of 217 accidents in the study’s data sample are related to medical incapacitation, which yields \(3.7 \cdot 10^{-8}\) as probability of an accident per flight as result of medical incapacitation. No passenger fatality occurred in the accidents as a result of flight crew incapacitation in the data sample, however there were some occurrences with passenger injuries as a result. An in-flight crew incapacitation was considered an accident when the affected pilot died in-flight. In 5 of 7 cases where flight safety was considered severely impaired, the unaffected pilot took over the controls. In 2 cases the affected pilot remained in control, which resulted in an accident.

Different categories of medical incapacitation are distinguished (see Table 21). Loss of consciousness, gastrointestinal, neurological, cardiac and urological are the most frequent categories. Consequences of in-flight incapacitations are listed in Table 22. Continuation of flight and diversion were the most frequently observed ‘consequence’ of a flight crew incapacitation event in [DeJohn et al., 2004].

**Table 21: Categories of health related flight crew incapacitation [DeJohn et al., 2004]**

<table>
<thead>
<tr>
<th>Category</th>
<th>Number of events in data sample</th>
<th>Percentage of events in data sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of consciousness</td>
<td>9</td>
<td>23 %</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>6</td>
<td>15 %</td>
</tr>
<tr>
<td>Neurological</td>
<td>6</td>
<td>15 %</td>
</tr>
<tr>
<td>Cardiac</td>
<td>5</td>
<td>13 %</td>
</tr>
<tr>
<td>Urological</td>
<td>3</td>
<td>8 %</td>
</tr>
<tr>
<td>Hypoxia</td>
<td>2</td>
<td>5 %</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>8</td>
<td>21 %</td>
</tr>
<tr>
<td>Total health related incapacitations</td>
<td>39</td>
<td>100 %</td>
</tr>
</tbody>
</table>

---

\(^5\) The data itself is confidential. The airline conducts worldwide commercial operations with large (> 5,700 kg MTOW) Western-built jet aircraft.
Table 22: Consequences of flight crew incapacitation [DeJohn et al., 2004]

<table>
<thead>
<tr>
<th>Consequence given flight crew incapacitation</th>
<th>Number of events in data sample</th>
<th>Rate per incapacitation event ¹ ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision with ground</td>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>Diversion</td>
<td>22</td>
<td>0.44</td>
</tr>
<tr>
<td>Continue flight</td>
<td>26</td>
<td>0.52</td>
</tr>
<tr>
<td>Fatal passenger</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fatal crew</td>
<td>4</td>
<td>0.08</td>
</tr>
</tbody>
</table>

¹ more than one medical event per flight is possible (e.g. hypoxia)
² total of 50 incapacitation/impairment events

According to [Martin-Saint-Laurent et al., 1990], seven out of ten incapacitations occurred in cruise flight, two in approach, and one on ground. The data sample of this study ranges from 1968 to 1988.

According to [James, 1991], 58% of incapacitation incidents are related to gastrointestinal problems. This information is based on a survey among airline pilots.

NLR Air Safety Database

In the NLR Air Safety Database a query was run to search for accidents and incidents related to flight crew incapacitation. The time span was set to 1970-2003. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturer from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. The number of flights associated with this query is 750 million flights.

The NLR data sample is not representative to estimate the conditional probability of an accident given flight crew incapacitation, because the data sample is skewed towards accidents. Operator data provides better quality information to estimate the frequency of in-flight incapacitation.

The query in the NLR Air Safety Database yields 118 incidents and accidents related to pilot incapacitation. In the majority of the 118 accidents and incidents no information was available to be able to make a distinction between incapacitation and impairment. Therefore all occurrences were classified as a flight crew incapacitation event.
In 14 of the 118 incidents and accidents related to pilot incapacitation only crew fatalities occurred. In 4 of these 118 occurrences both crew and passenger fatalities occurred, while in one occurrence only passenger fatalities occurred.

Taking into account the number of flights corresponding to the data sample, the following rates are derived:

- Pilot incapacitation occurrence (accident or incident) is $1.6 \times 10^{-7}$ per flight.
- Pilot incapacitation occurrence with fatalities amongst passengers or crew is $2.5 \times 10^{-8}$ per flight.
- Pilot incapacitation occurrence with fatalities amongst passengers is $6.7 \times 10^{-9}$ per flight.

Table 23 and Figure 7 show the distribution of the flight crew incapacitation by flight phase, as found in the NLR Air Safety Database.

Table 23: Distribution of flight crew incapacitation across flight phases (NLR Air Safety Database)

<table>
<thead>
<tr>
<th>Flight phase of incapacitation event</th>
<th>Number of events in data sample</th>
<th>Percentage of events in data sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>4</td>
<td>3 %</td>
</tr>
<tr>
<td>Take-off</td>
<td>1</td>
<td>1 %</td>
</tr>
<tr>
<td>Climb</td>
<td>13</td>
<td>11 %</td>
</tr>
<tr>
<td>Cruise and descent</td>
<td>91</td>
<td>77 %</td>
</tr>
<tr>
<td>Approach</td>
<td>6</td>
<td>5 %</td>
</tr>
<tr>
<td>Landing</td>
<td>1</td>
<td>1 %</td>
</tr>
<tr>
<td>Unknown</td>
<td>2</td>
<td>2 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>118</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Flight Crew Incapacitation by Flight Phase

The consequences of the incapacitation occurrences found in the NLR Air Safety Database are listed in Table 24. Data in Table 24 on diversion and continuation of flight are not reliable due to the fact that the NLR Air Safety Database has a bias towards accidents. It therefore does not contain a representative sample of incidents to estimate frequency of diversion.

Table 24: Consequences of flight crew incapacitation/impairment (NLR Air Safety Database)

<table>
<thead>
<tr>
<th>Consequence given flight crew incapacitation.</th>
<th>Number of events</th>
<th>Rate per incapacitation event ²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision with ground</td>
<td>7</td>
<td>0.06</td>
</tr>
<tr>
<td>Diversion</td>
<td>32+28¹)</td>
<td>0.51</td>
</tr>
<tr>
<td>Continue flight</td>
<td>23+28¹)</td>
<td>0.43</td>
</tr>
<tr>
<td>Fatal passenger</td>
<td>5</td>
<td>0.04</td>
</tr>
<tr>
<td>Fatal crew</td>
<td>18</td>
<td>0.15</td>
</tr>
</tbody>
</table>

¹) Category ‘Unknown consequence’ is equally divided between ‘diversion’ and ‘continue flight’.
²) 118 incapacitation events in total

In the NLR Air Safety database relatively more accidents than incidents involving flight crew incapacitation are found compared to [DeJohn et al., 2004]. In the NLR data sample 18 of 118 occurrences involve fatalities (i.e. the event is classified as an accident), while according to
[DeJohn et al., 2004] 2 of 47 flights in which incapacitation or impairment occurred resulted in an accident. We have calculated the accident probability as result of flight crew incapacitation with the NLR Air Safety Database data sample, in combination with the frequency of flight crew incapacitation from operator data.

The NLR Air Safety Database contains a representative, reliable, set of accidents with which the probability of collision with ground given flight crew incapacitation is estimated as follows. Seven cases of collision with ground after pilot incapacitation occurred in 750 million flights, which is a frequency $9.33 \times 10^{-9}$ per flight. Taking into account the probability of flight crew incapacitation ($4.67 \times 10^{-5}$) from operator data, the probability of collision with ground given pilot incapacitation then becomes: $(9.33 \times 10^{-9})/4.67 \times 10^{-5} = 2.00 \times 10^{-4}$. This result yields a probability of $1-2.00 \times 10^{-4} = 0.9998$ for a diversion or continuation of flight after pilot incapacitation.

**Note**

Simulator studies have been conducted in which a subtle incapacitation was simulated [Chapman, 1984]. In 8 of 500 simulator flights it resulted in an accident when incapacitation occurred in critical stage of flight, occasionally together with system failure. When subtle incapacitation occurred without system failures 2 out of 800 simulator flights resulted in accident. In other words one accident occurred in 400 simulated incapacitations ($2.50 \times 10^{-3}$ per incapacitation). This result is one order of magnitude higher than our estimate, but our estimate includes flight crew impairment and is not limited to complete incapacitation.

**Accident type:** uncontrolled collision with ground.
**Flight phase:** initial climb, en route, approach and landing.
**Initiating Event:** flight crew incapacitation.
17 ESD15 - Anti-ice/de-ice system not operating

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: anti-ice/de-ice system not operating.

17.1 Definitions
This ESD describes a loss of control due to ice accretion on the aircraft’s outside structure and/or control surfaces. Such ice accretion can occur if the aircraft’s anti-icing or de-icing system is not operating while the aircraft flies in icing conditions or if the icing conditions are so severe that they exceed the certification envelope of the aircraft. Icing of the pitot-static system is not covered in this ESD. If the pitot-heat is for example not turned on, ice build-up may cause erratic airspeed indications. This type of event is covered by ESD 16 ‘Flight instrument failure’. Excluded from this ESD are control problems due to ice inside the aircraft’s structure. This can occur if trapped water (e.g. resulting from a blocked drain) or other fluids freezes and jams the flight control system. These types of occurrences are covered by ESD 13 ‘Flight control system failure’.

In the ESD the Initiating Event, Pivotal Events and End States are defined as follows.

Ice accretion on aircraft in flight
This event refers to ice accretion on the aircraft’s outside structure, i.e. fuselage, wing, tail, and flight control surfaces. Even if anti-ice/de-ice systems are operating ice accretion may occur. The icing conditions may be so severe that they exceed the ‘certification envelope’ of the aircraft. Other phenomena like ice bridging or ice accretion on parts of the aircraft that can not be de-iced may contribute to controllability and performance problems.

Flight crew fails to respond appropriately to ice accretion
This pivotal event refers to the flight crew action following flight into icing conditions. When ice accretion occurs, the flight crew’s awareness of icing conditions, the detection of ice accretion on the aircraft and adequate awareness of associated risks will influence the flight
crew response. Appropriate response is to avoid or exit icing conditions and to operate the anti-ice/de-ice systems.

**Flight crew fails to maintain control**
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft after performance and controllability has degraded due to ice accretion on the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control of the aircraft is in general affected by human factors, aircraft system failures, weather conditions, operating procedures, available altitude for a recovery manoeuvre etc. The flight crew may experience controllability problems or aircraft performance degradation (e.g. reduced rate of climb, speed drop) as a result of ice accretion, which may be overcome by descending or exiting icing conditions.

In some occurrences ice accretion causes a temporary loss of control which is then restored by the flight crew. In this ESD such occurrences are classified ‘flight crew maintains control’ leading to end state ‘aircraft continues flight’ as opposed to an unrecovered loss of control.

**Collision with ground**
This end state refers to a possible outcome of an aircraft flying in icing conditions while the anti-ice/de-ice systems do not operate: the aircraft impacts terrain (ground, water) or obstacles, which results in injuries, fatalities or (substantial) damage to the aircraft.

**Aircraft continues flight**
This end state refers to the situation that the flight crew continues the flight to the destination airport, returns to the airport of departure or diverts to another airport.

If ice accretion on the aircraft structure leads to ice or snow ingestion in the engine and subsequently causes an engine failure and potentially controllability or performance problems, the occurrence is regarded as leading to end state ‘aircraft continues flight’. In the Master Logic Diagram that combines all ESDs this occurrence will then link to ESD 9 which describes a (potential) loss of control after an engine failure.

**17.2 Quantification**

**NLR Air Safety Database**
A query was run in the NLR Air Safety Database to search for loss of control accidents and incidents related to ice accretion on the aircraft structure. The time span was set to 1990-2003. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of
more than 5,700 kg in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators, and accidents/incidents during test flights and training flights are excluded.

In a number of investigation reports on loss of control accidents due to in-flight ice accretion, reference was made to previous, related, accidents and incidents. Several of these referenced accidents and incidents complemented the NLR Air Safety Database query results. The reports are listed in the reference section of this report.

The number of flights associated with this query is 387 million flights. The dataset contains 45 accidents and incidents related to a (temporary) loss of control in flight as result of ice accretion on the aircraft. The distribution of occurrences across flight phases is shown in Figure 8.

Figure 8: Distribution of accidents/incidents related loss of control as result of ice accretion on aircraft [NLR Air Safety Database 1990-2003]

**Operation of anti-ice/de-icing system while in icing conditions**

The data sample of 45 accidents and incidents was analysed to determine whether the flight crew operated the anti-ice/de-icing systems of the aircraft in icing conditions. It was found that
in 15 events the anti-ice/de-ice system was not activated and in 3 events the system was inoperative. In 14 occurrences it is not known whether the crew had activated the system. In 12 occurrences the crew operated the anti-ice/de-ice system, but still a (temporary) loss of control occurred. In 2 occurrences the ice accretion was so severe that the de-ice/anti-ice systems could not cope with the icing conditions.

**Flight crew response in case of ice accretion**

In all 45 accidents and incidents some degree of ice accretion on the aircraft occurred. In 25 occurrences (56%) the flight crew failed to respond appropriately to the ice accretion on the aircraft, while in 18 (40%) events the flight crew response was considered appropriate (e.g. activate de-icing/anti-icing systems or exit icing conditions). In two cases (4%) the data contains no information on the crew response. In 8 of the 25 inappropriate response cases an unrecovered loss of control and subsequent collision with terrain occurred. In 17 of the 25 inappropriate response cases the flight crew continued flight. In all 20 events in which the flight crew response to the ice accretion was appropriate, the flight continued.

The ability of the flight crew to maintain control of the aircraft following ice accretion is summarised in Table 25.

Table 25: Flight crew response to ice accretion

<table>
<thead>
<tr>
<th>If flight crew response to ice accretion is inappropriate:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision with terrain</td>
<td>8</td>
</tr>
<tr>
<td>Aircraft continues flight</td>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>If flight crew response to ice accretion is appropriate:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision with terrain</td>
<td>0</td>
</tr>
<tr>
<td>Aircraft continues flight</td>
<td>20</td>
</tr>
</tbody>
</table>

45 incidents and accidents related to in-flight ice accretion.

**ASR databases of various airlines**

Air Safety Report (ASR) databases from different airlines were analysed for events involving anti-/de-icing systems and icing problems. The ASR database covers 9 million flights in a period between 1998 and 2004. The ASR database contains 177 occurrences where either ice accretion on the aircraft was reported or (part) of the aircraft’s anti/de-ice system failed while the aircraft was flying in icing conditions. This corresponds to a frequency of $1.97 \times 10^{-5}$ per flight.
17.3 Results

Initiating event ‘ice accretion on aircraft in flight’
Based on the analysis of ASR data, the estimated probability of occurrence of in-flight ice accretion is $1.97 \cdot 10^{-5}$ per flight.

End states ‘collision with ground’
According to the analysis of the Air Safety Database there have been 8 loss of control and subsequent collision with ground accidents due to ice accretion in 387 million flights. The estimated probability of this end state is $2.07 \cdot 10^{-8}$ per flight.

End state ‘aircraft continues flight’ when crew has failed to respond appropriately
According to the analysis of the Air Safety Database there have been 17 occurrences in 387 million flights where the flight crew failed to respond appropriately to in-flight ice accretion, but control of the aircraft was not lost. The estimated probability of this end state is $4.39 \cdot 10^{-8}$ per flight.

Flight crew ‘fails to respond appropriately’ to ice accretion
The conditional probability that the flight crew fails to respond appropriately to ice-accretion on the aircraft is \( (2.07 \cdot 10^{-8} + 4.39 \cdot 10^{-8}) / 1.97 \cdot 10^{-5} = 3.28 \cdot 10^{-3} \).

Flight crew ‘fails to maintain control’
The conditional probability of the flight crew failing to maintain control after inappropriate response to ice accretion is \( 2.07 \cdot 10^{-8} / (1.97 \cdot 10^{-5} \times 3.28 \cdot 10^{-3}) = 3.20 \cdot 10^{-1} \).
18 ESD16 - Flight instrument failure

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: flight instrument failure.

18.1 Definitions

Flight instrument failure
For the purpose of this ESD, a flight instrument failure is defined as a failure of the flight instrument(s) to correctly display airspeed, altitude or attitude of the aircraft. In the case of dual instruments and/or if a standby instrument is available, even a failure of only one of the instruments to correctly display is considered to be a ‘flight instrument failure’.

Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control is affected by human factors (fatigue, training etc), aircraft system failures, weather conditions, etc.

18.2 Quantification
The probability of occurrence of the initiating events is estimated by analysing the Service Difficulty Report (SDR) database (see Appendix A). Query 1 below has been used to count the flight instrument failures during initial climb, en route, approach and landing. Instrument failures during take-offs without a rejected take-off are included as well. It is assumed that flight instrument failures can consist of failures that correspond with the ATA codes described in Table 26 and Query 1. This data corresponds to a total of 216 million flights.
Table 26: ATA codes defining “flight instruments”

<table>
<thead>
<tr>
<th>ATA code</th>
<th>Description</th>
<th>Number of SDRs</th>
<th>Rate per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>3414</td>
<td>Airspeed/Mach indicator</td>
<td>133</td>
<td>$6.16 \times 10^{-7}$</td>
</tr>
<tr>
<td>3416</td>
<td>Altimeter, barometric / encoder</td>
<td>308</td>
<td>$1.43 \times 10^{-6}$</td>
</tr>
<tr>
<td>3417</td>
<td>Air Data Computer</td>
<td>445</td>
<td>$2.06 \times 10^{-6}$</td>
</tr>
<tr>
<td>3420</td>
<td>Attitude and direction data system</td>
<td>248</td>
<td>$1.15 \times 10^{-5}$</td>
</tr>
<tr>
<td>3421</td>
<td>Attitude gyro and indicator system</td>
<td>282</td>
<td>$1.31 \times 10^{-5}$</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>1416</td>
<td>$6.56 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Query 1:

c15 Year Between “1985” And “2003”
c35 Air Carrier or General Aviation “A”
c40 ATA code 3414 Or 3416 Or 3417 Or 3420 Or 3421
c314a 1st occurrence Not Like “aborted takeoff”
c330 Stage of operation code Not Like "in" And Not Like "nr" And Not Like "tx" And Not Like "uk"
c604 Aircraft wing type code Not Like “g”

A query was run in the ADREP and Airclaims databases to search for accidents and incidents related to flight instrument failures. The time span was set to 1990-2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators, and accidents/incidents during test flights and training flights are excluded. The number of flights associated with this query is 452 million flights (1990-2005). Six accidents were identified (Table 27) resulting in an estimated probability of occurrence of $1.33 \times 10^{-8}$ per flight.
Table 27: World-wide flight instrument failure accidents between 1990 and 2003

<table>
<thead>
<tr>
<th>Date</th>
<th>A/C type</th>
<th>Airline</th>
<th>Location</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/06/92</td>
<td>B737-204</td>
<td>COPA</td>
<td>Panama</td>
<td>Attitude</td>
</tr>
<tr>
<td>02/06/96</td>
<td>B757-200</td>
<td>Birgenair</td>
<td>Dominican Republic</td>
<td>Speed</td>
</tr>
<tr>
<td>02/10/96</td>
<td>B757-23A</td>
<td>Aeroperu</td>
<td>Peru</td>
<td>Speed / Altitude</td>
</tr>
<tr>
<td>10/10/97</td>
<td>DC9-32</td>
<td>Austral Lineas Aeras</td>
<td>Uruguay</td>
<td>Speed</td>
</tr>
<tr>
<td>18/03/98</td>
<td>SAAB 340</td>
<td>Formosa Airlines</td>
<td>Taiwan</td>
<td>Instrument failure</td>
</tr>
<tr>
<td>2212/99</td>
<td>B747-2B5F</td>
<td>Korean Airlines</td>
<td>Stansted</td>
<td>Attitude</td>
</tr>
</tbody>
</table>

The conditional probability of ‘flight crew fails to maintain control’ in the event of a flight instrument failure is estimated to be $1.33 \times 10^{-8} / 6.56 \times 10^{-6} = 2.02 \times 10^{-3}$.

Accident type: uncontrolled collision with ground.
Flight phase: initial climb, en route, approach and landing.
Initiating Event: flight instrument failure.
19 ESD17 - Aircraft encounters adverse weather

Accident type: structure overload
Flight phase: initial climb, en route, and approach.
Initiating Event: aircraft encounters adverse weather.

19.1 Definitions

Aircraft encounters adverse weather
For the purpose of this ESD, an adverse weather encounter is defined as an encounter with severe turbulence that results in occupant injuries, an aircraft upset or structural damage to the aircraft as a result of overstress of the aircraft’s structure.

Ultimate design load exceeded
This event is defined as an occurrence where the ultimate design load of the aircraft is exceeded as a direct result of the aircraft’s encounter with adverse weather. This occurrence will result in an in-flight break-up of the aircraft.

Flight crew fails to maintain control
An encounter with adverse weather may result in an unusual aircraft attitude. This pivotal event describes whether the flight crew is able to maintain control of the aircraft in the event of an adverse weather encounter.

Personal injury
One or more occupants receive minor, serious or fatal injuries as a direct result of the aircraft’s encounter with adverse weather. An encounter with adverse weather may result in injuries to passengers or crew when people fall to the ground, hit the aircraft’s ceiling or are hit by loose objects such as service trolleys.
19.2 Quantification
A query was run in the ADREP and Airclaims databases to search for accidents and incidents related to adverse weather. The time span was set to 1990-2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators and accidents/incidents during test flights and training flights are excluded. The number of flights associated with this query is 452 million flights (1990-2005).

Initiating event
According to the dataset, there have been 324 accidents and incidents involving encounters with adverse weather. The corresponding probability of occurrence of an adverse weather encounter is 324 / 4.52·10^8 = 7.16·10^{-7} per flight.

End states
Table 28 shows the resulting number of occurrences for the various events and end states of the ESD. The dataset contained no accidents in which the ultimate design load was exceeded resulting in an in flight break-up. In 2 occurrences the flight crew failed to maintain control and the aircraft subsequently collided with the ground. The remaining 322 adverse weather encounters resulted in personal injury.

Table 28: Results of analysis of adverse weather related accidents ADREP and Airclaims (1990-2005, 452 million flights)

<table>
<thead>
<tr>
<th>End state</th>
<th>Number of occurrences</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>In flight break-up</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Collision with ground</td>
<td>2</td>
<td>4.42·10^{-9}</td>
</tr>
<tr>
<td>Personal injury</td>
<td>322</td>
<td>7.12·10^{-7}</td>
</tr>
</tbody>
</table>

Pivotal event
Based on the results of this analysis, the conditional probability that the ultimate design load is exceeded when an aircraft encounters adverse weather is 0.

Based on the results of this analysis, the conditional probability that the flight crew fails to maintain control if adverse weather is encountered is 4.42·10^{-9} / 7.16·10^{-7} = 6.17·10^{-3}. 

110
Accident type: structure overload
Flight phase: initial climb, en route, and approach.
Initiating Event: aircraft encounters adverse weather.

- Aircraft encounters adverse weather
- Ultimate design load exceeded
- Flight crew fails to maintain control
- Unrecovered loss of control
- Collision with ground
- Personal injury
- In flight break-up

Probabilities:
- 7.16 \times 10^7
- 6.17 \times 10^3
- 4.42 \times 10^9
- 7.12 \times 10^7
20 ESD18 - Single engine failure in flight

20.1 Definitions

Single engine failure
Single engine failure is defined as a significant loss of thrust from one of the aircraft’s propulsion systems. Single engine failures also include cases where the engine detaches from the aircraft. Engine fires are not included here but are incorporated in ESD11. Only engine failures during climb, en-route or approach are considered. Engine failures during the take-off roll are addressed in ESD 9, engine failures in the landing roll in ESD 28.

Dual engine failure
Dual engine failure is defined as a significant loss of thrust from two of the aircraft’s propulsion systems.

Flight crew fails to restore engine power
Failure of the flight crew to restore the amount of thrust from the propulsion system to similar values as before the occurrence of the initiating event.
Flight crew shutdown wrong engine
Event in which, after the occurrence on a single engine failure, the flight crew accidentally shut down an engine that is performing adequately, whereas the intention of the crew is to secure the suspected faulty engine.

Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control following an engine failure. The asymmetric thrust that results from the engine failure limits the control authority and may result, possibly in combination with other circumstances such as crosswind, in a failure to maintain control.

Aircraft unable to reach airport
Occurrence in which the aircraft, given an absence of thrust, is not able to reach a suitable airfield for landing and position itself correctly for a successful landing on one of the airfield’s runways.

20.2 Quantification
To derive the probability of a single engine failure, operational data from a large western European airline has been used. This airline operates western-built jet aircraft in worldwide commercial operations. The data set consists of 286,753 flights from the year 2001. This set contains 79 occurrences of an engine failure. There were no dual engine failures. The set did not include cases where the flight crew was able to restore engine power. The corresponding engine failure probability is estimated to be 79/286,753 = 2.75 · 10^{-4} per flight.

To estimate the frequency of accidents/incidents due to engine failures the Airclaims accident and incident databases was analysed. The data sample included large western-built jets and turboprops in commercial operations between 1985 and 2005, representing 399 million flights. Business jets were excluded. The data set contains 151 relevant occurrences of engine failures. The distribution of these events over the different end states is given in the table below.

Table 29: Engine failure related probabilities per flight for different end states

<table>
<thead>
<tr>
<th>End state</th>
<th>Number of occurrences</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power loss, collision with ground</td>
<td>8</td>
<td>2.01 · 10^{-8}</td>
</tr>
<tr>
<td>Total power loss, aircraft lands off runway</td>
<td>27</td>
<td>6.77 · 10^{-8}</td>
</tr>
<tr>
<td>Total power loss, aircraft continues landing</td>
<td>4</td>
<td>1.00 · 10^{-7}</td>
</tr>
<tr>
<td>Single engine failure, collision with ground</td>
<td>69</td>
<td>1.73 · 10^{-7}</td>
</tr>
<tr>
<td>Single engine failure, aircraft continues landing</td>
<td>43</td>
<td>1.08 · 10^{-7}</td>
</tr>
</tbody>
</table>
Based on these results, the probability of a total power loss is \( \frac{39}{3.99 \times 10^8} = 9.77 \times 10^{-8} \) per flight. The 39 occurrences of total power loss include one case in which the flight crew secured the wrong engine. The corresponding conditional probability of a ‘dual engine failure’ given a single engine failure is \( \left( \frac{38}{3.99 \times 10^8} \right) / 2.75 \times 10^{-4} = 3.46 \times 10^{-4} \).

Since there were no cases observed in which the flight crew restored power, the conditional probability that the flight crew fails to restore power in the event of a single engine failure is 1.00.

The conditional probability that the flight crew shuts down the wrong engine in the event of a single engine failure is \( \left( \frac{1}{3.99 \times 10^8} \right) / (2.75 \times 10^{-4} \times (1-3.46 \times 10^{-4})) = 9.10 \times 10^{-6} \).

The conditional probability that the flight crew fails to maintain control given a total power loss is \( \frac{8}{39} = 2.05 \times 10^{-1} \).

The conditional probability that the aircraft is unable to reach an airport in the event of a total power loss where the flight crew is able to maintain control is \( \frac{27}{39 - 8} = 8.71 \times 10^{-1} \).

In the event of a single engine failure resulting into asymmetric thrust, the conditional probability that the flight crew fails to maintain control is \( \left( \frac{69}{3.99 \times 10^8} \right) / (2.75 \times 10^{-4} - 9.77 \times 10^{-8}) = 6.29 \times 10^{-4} \).
21 ESD19 - Unstable approach

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: unstable approach.

21.1 Definitions

Unstable approach
An approach is considered unstable if any of the following criteria is not met:

- Correct glide path;
- Only small changes in heading/pitch;
- Speed between $V_{ref}$ and $V_{ref} + 20$ knots;
- Correct landing configuration;
- Sink rate is no greater than 1000 feet per minute;
- Power setting appropriate for the aircraft configuration;
- All briefings and checklists have been conducted;

Approach type specific:
- ILS approaches: within one dot of the glide slope and localizer;
- Cat. II or III ILS approach: within the expanded localizer band;
- Circling approach: wings should be level on final at 300 feet.
Flight crew fails to initiate missed approach
If during the approach to the landing runway a certain situation exists or arises, which would make the continuation of the approach and consecutive landing “unsafe”, the flight crew should initiate a missed approach. Generally speaking, during a missed approach the flight crew advance the throttle to go-around power, the flap setting is reduced (typically to 20 degrees) and the aircraft is rotated to 15 degrees pitch attitude. The aircraft climbs to a predefined altitude from where a new approach is initiated, or the aircraft diverts to an alternate airport. The purpose of the missed approach is to reject flying into unsafe conditions or under unsafe circumstances and to enable the flight crew to carry out a new approach and landing under safer circumstances.

Aircraft touchdown fast or long
A long touchdown is a situation where the aircraft contacts the runway far beyond the runway threshold. A long touchdown itself is not always hazardous. Particularly if small aircraft land on a long runway, a long touchdown does not create a risk. However, a long touchdown is more hazardous if the runway is relatively short and/or slippery.

A fast touchdown occurs if the aircraft lands with a speed that is significantly higher than the reference touchdown speed. A fast touchdown itself is not always hazardous. Particularly if small aircraft land on a long runway, a fast touchdown does not create a risk. However, a long touchdown is more hazardous if the runway is relatively short and/or slippery.

Collision with ground
This end states describes a situation where the aircraft collides with the ground during an unstabilised approach. Included are runway undershoots were the aircraft collides with the ground short of the runway. Undershoot accidents are sometimes difficult to classify because the available information is not always sufficient to distinguish this type of accident from approach CFIT accidents. We decided to classify undershoot accidents where the point of impact is ‘just short’ of the runway threshold (up to several hundreds of meters), as unstable approach & loss of control cases, and accidents where the point of impact is relatively further from the runway threshold (more than a few hundred metres) as CFIT (ESD 35).

Runway overrun
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed
at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**Runway veer-off**
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**Aircraft continues landing roll damaged**
This end state describes a situation where the aircraft is damaged as a result of a hard landing but remains on the runway. ‘Damage’ includes landing gear failures, damage to propellers and airframe overstress. Tail strikes are not included because these are rarely the result of a hard landing.

**Failure to achieve maximum braking**
Immediately following touchdown, the flight crew must start reducing the speed of the aircraft. On most large aircraft, a ‘positive’ touchdown is required to make sure the aircraft switches to ground logic, which will automatically deploy lift dumpers (if available and armed) and will ensure a proper functioning of the autobrake system. Braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

**Collision with ground**
This event describes a situation where control is lost during the execution of a missed approach.
21.2 Quantification

Initiating event
To estimate the probability of occurrence of an unstable approach, an analysis was made of all landings between 1998 and 2001 of a large European airline that operates globally. Out of a total of 312,044 flights, 1642 approaches did not meet the stabilised approach criteria. The estimated probability of the initiating event is $5.26 \cdot 10^{-3}$ per flight.

End states
The probability of occurrence of the end states was estimated from the Airclaims accident and incident database. Only large Western-built jets and turboprops in commercial operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group conducted a total of 399 million flights.

Table 30: Probability of occurrence of the end states

<table>
<thead>
<tr>
<th>End state</th>
<th>Number of occurrences</th>
<th>Frequency per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable approach, loss of control</td>
<td>128</td>
<td>$3.21 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>Unstable approach, overrun</td>
<td>79</td>
<td>$1.98 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>Unstable approach, hard landing, veer-off</td>
<td>15</td>
<td>$3.76 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>Unstable approach, hard landing, damage</td>
<td>26</td>
<td>$6.52 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>Unstable approach, hard landing, no damage</td>
<td>5</td>
<td>$1.25 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>Loss of control during missed approach</td>
<td>20</td>
<td>$5.01 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>Fuel exhaustion during missed approach</td>
<td>3</td>
<td>$7.52 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

Pivotal events
According to [Roelen et al., 2002], the conditional probability of ‘failure to execute a missed approach’ in the event of an unstable approach is $2.18 \cdot 10^{-2}$. This estimate is based on expert judgement. A total of 4 experts were interviewed. The results of the experts were averaged by assigning equal weights to all of them. The experts were informed that all questions concerned a “Schiphol class airport”.

The conditional probability that ‘flight crew fails to maintain control’ if the approach is unstable and a missed approach is not executed is $3.21 \cdot 10^{-7} / (5.26 \cdot 10^{-3} \times 2.18 \cdot 10^{-2}) = 2.80 \cdot 10^{-3}$.

The conditional probability that the ‘aircraft lands long or fast’ if the approach in not stable and a missed approach is not executed is $1.98 \cdot 10^{-7} / (5.26 \cdot 10^{-3} \times 2.18 \cdot 10^{-2} \times (1-2.80 \cdot 10^{-3})) = 1.73 \cdot 10^{-3}$. 

The conditional probability of a ‘touchdown with excessive sinkrate’ if the approach is not stable and a missed approach is not executed is \((3.76 \cdot 10^{-8} + 6.52 \cdot 10^{-8} + 1.25 \cdot 10^{-8}) / (5.26 \cdot 10^{-3} \times 2.18 \cdot 10^{-2} \times (1-2.80 \cdot 10^{-3}) \times (1-1.73 \cdot 10^{-3})) = 1.01 \cdot 10^{-3}.

The conditional probability that a hard landing after an unstabilised approach results in a structural failure is \((3.76 \cdot 10^{-8} + 6.52 \cdot 10^{-8}) / (5.26 \cdot 10^{-3} \times 2.18 \cdot 10^{-2} \times (1-2.80 \cdot 10^{-3}) \times (1-1.73 \cdot 10^{-3}) \times 1.01 \cdot 10^{-3}) = 8.91 \cdot 10^{-1}.

The conditional probability that a hard landing after an unstabilised approach results in a structural failure and the ‘flight crew fails to maintain control’ is \(3.76 \cdot 10^{-8} / (5.26 \cdot 10^{-3} \times 2.18 \cdot 10^{-2} \times (1-2.80 \cdot 10^{-3}) \times (1-1.73 \cdot 10^{-3}) \times 1.01 \cdot 10^{-3} \times 8.91 \cdot 10^{-1}) = 3.66 \cdot 10^{-1}.

The conditional probability that the ‘flight crew fails to maintain control’ if a missed approach is executed is \(5.01 \cdot 10^{-8} / (5.26 \cdot 10^{-3} \times (1-2.18 \cdot 10^{-2})) = 9.74 \cdot 10^{-6}.

The conditional probability that there is ‘insufficient fuel available for the next approach’ when a missed approach is executed is \(7.52 \cdot 10^{-9} / (5.26 \cdot 10^{-3} \times (1-2.18 \cdot 10^{-2}) \times (1-9.74 \cdot 10^{-6})) = 1.46 \cdot 10^{-6}.

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: Unstable approach.
22 ESD 21 – Aircraft weight and balance outside limits during approach

Accident type: uncontrolled collision with ground.  
Flight phase: approach.  
Initiating Event: aircraft weight and balance outside limits.

22.1 Definitions

If the aircraft’s weight and balance are outside limits, there is a possibility that, although the aircraft was controllable during the preceding part of the flight, controllability becomes difficult during the approach phase. The change in aircraft configuration that is required for the approach, particularly the selecting of landing flaps, causes a redistribution of the airflow and associated changes in the aerodynamic moment.

This event sequence diagram deals with a similar problem as ESD 7, in which also “aircraft weight and balance outside limits” is the initiating event. However, in ESD 21, the approach phase is considered and the “aircraft stall” pivotal event is combined with the “flight crew fails to maintain control” pivotal event.

Aircraft weight and balance outside limits

This initiating event considers the following situations:

- Centre of gravity (CG) incorrect / outside limits
- Cargo loose or shifted
- Wrong number of passengers
- Loadsheet incorrect
- Weight limits incorrect/exceeded
This means that also situations are accounted for where weight and balance is not strictly “outside limits”, but it is different than the crew expected.

Not considered for this event are overweighed landings, problems with lateral fuel balance and jettison of fuel during descent.

Flight crew fails to regain control
The crew might not be able to regain control of the aircraft if there are problems during approach because of weight and balance problems. The result is an unrecovered loss of control and a collision with the ground.

22.2 Quantification

Initiating event
The initiating event “Aircraft weight and balance outside limits” in ESD 21 is similar to the initiating event of ESD 7, except for the difference in flight phase. Some occurrences that are counted for ESD 7 are also relevant for ESD 21:

- Some weight and balance occurrences are noticed during take-off and are not corrected during the flight, e.g. shifted cargo that cannot be corrected during flight; The flight continues, so that the problem still exists during approach;
- Some weight and balance problems are noticed during take-off and are corrected during the flight, e.g. new loading information is retrieved after take-off and this is accounted for in the remaining flight phases, including approach, or overweight during take-off is solved by means of burning fuel during the flight;
- Weight and balance occurrences did not originate during take-off but during approach, e.g. cargo that starts shifting during descent or approach, or a centre of gravity problem that is notified when extending the flaps during approach.

The sources [IATA, 2005] and [CAA, 2000] do not distinguish between weight and balance problems in the various flight phases. The information in the NLR Air Safety Database includes the flight phase in which the problem occurred. When considering the classification “approach” used in the database, 18 occurrences can be related to relevant weight and balance problems, like loose or shifted cargo and wrong information regarding the load of the aircraft. These 18 occurrences are assumed to be new occurrences that did not appear during take-off but only during approach. For example, it is often explicitly mentioned that cargo shifted during approach. Considering 9.5 million flights, these 18 occurrences result in a frequency of 1.89·10⁻⁶ per approach for the initiating event of ESD 21. This is approximately a factor 20 lower than the frequency of the initiating event of ESD 7 (i.e. 3.70·10⁻⁵ per take-off). The reason for the difference could be that problems that occur during take-off can be solved during the flight such
that there are no problems during approach anymore. For example, in often happens that new (and better) loadsheet information is received after take-off and problems with weight can be solved by burning more fuel (or dumping it).

**Accidents**
In the NLR Air Safety Database, 2 accidents that were caused by weight and balance problems in the approach phase have been found on 387 million flights. These flights include:
- Western built aircraft;
- Weight above 5700 kg; and
- Jets and turbo prop aircraft (excluding piston engines).
- Commercial operations
- Time frame 1990-2003
This means an accident frequency of $5.16 \times 10^{-9}$ per flight.

**Pivotal event**
Quantification of the pivotal event “flight crew fails to regain control” can be achieved by dividing the accident frequency ($5.16 \times 10^{-9}$ per flight) with the frequency of the initiating event ($1.89 \times 10^{-6}$ per flight), resulting in:
- Yes: $2.73 \times 10^{-3}$
- No: 0.99727

Accident type: uncontrolled collision with ground.
Flight phase: approach.
Initiating Event: aircraft weight and balance outside limits.
23 ESD23 - Aircraft encounters wind shear during approach

Aircraft encounters wind shear on approach/landing
Wind shear is an abrupt change in wind direction and velocity. A type of wind shear that is dangerous for air transport is a downburst or microburst. The aircraft may encounter performance increasing and decreasing effects. Wind shear poses the greatest danger to aircraft during takeoff and landing, if the aircraft is close to the ground and has little time or room to maneuver. This event includes situations where the aircraft encounters an increase in tailwind or a decrease in headwind during approach and landing (performance decreasing wind shear), but turbulence, e.g. due to wake vortex is not included.

Flight crew fails to detect wind shear
There are various possibilities for the flight crew to detect wind shear during approach and landing. Rapid changes in indicated airspeed or rates of vertical speed can be an indication of a wind shear encounter. With autopilot and autothrust engaged pitch deviations and unusual thrust settings are the primary cues for early wind shear onset as airspeed deviations are effectively compensated for. Other detection means can be other pilots’ reports, ground-based wind shear alert systems using ground-based radar or lidar, and on-board wind shear detection systems.
Most, but not all, large commercial aircraft are equipped with an on-board wind shear detection system. In the case of ground-based systems the crew will be alerted by ATC. For the purpose of this ESD, flight crew fails to detect wind shear is defined as a situation where the aircraft encounters wind shear but this goes undetected by the flight crew.

**Flight crew fails to execute escape manoeuvre successfully**

Details of the wind shear escape manoeuvre may vary among different aircraft types and different operators. A typical wind shear escape manoeuvre in approach and landing will include the following:

- Pull take-off/go-around (TOGA) triggers;
- Disengage autopilot and autothrust;
- Set emergency thrust;
- Increase pitch to 12 degrees nose up; and
- Maintain wings level unless absolutely required for obstacle clearance.

For the purpose of this ESD, ‘flight crew fails to perform wind shear escape manoeuvre’ is defined as a failure of the flight crew to perform the prescribed escape manoeuvre, either by mistake or on purpose if the crew decides that it is not necessary because control can be maintained without following the procedure.

Sometimes a go-around manoeuvre is initiated by the flight crew if a wind shear is encountered during the approach. Strictly speaking a go-around manoeuvre differs from the wind shear escape manoeuvre. Configuration changes (such as reducing flap setting) that are normally made during the go-around are not recommended during the wind shear escape manoeuvre and the go-around is conducted with go-around thrust rather than emergency thrust. For the purpose of this ESD however, a go-around manoeuvre which helps the aircraft to successfully escape wind shear is regarded as a ‘successful escape manoeuvre’.

Depending on the strength of the wind shear/downdraft, the altitude of encounter, the response of the flight crew and aircraft performance, the aircraft may hit the ground during the wind shear escape manoeuvre. If the flight crew initiates a wind shear escape manoeuvre during which they hit the ground (e.g. tree tops or the runway), but maintain control and continue safe flight, the event is classified as a successful wind shear escape manoeuvre.

**Aircraft touchdown with excessive sink rate**

Whether or not the sink rate during touchdown is considered to be ‘excessive’, resulting in a hard landing, is determined by the captain. If the captain decides that the landing was ‘hard, an entry will be made in the aircraft’s tech log. As an indication, a touchdown during which the
vertical deceleration exceeds 1.9 g will usually be considered as a touchdown with excessive sink rate.

In some accidents the wind shear caused the aircraft to develop an excessive sink rate resulting in the aircraft touching down short of the runway. These events are also considered to be included in this pivotal event.

**Structural failure**
Structural failure refers to the situation that the aircraft suffers a mechanical (overstress) structural failure after touching down with excessive sink rate (a hard landing). A structural failure can be any failure of the aircraft structure and components. In these circumstances a structural failure often includes:
- failure of landing gear (collapse, torn off);
- damage to wing (tip) damage after contact with ground (runway, approach lights, trees etc);
- damage of tail section (over-rotation, if pilots try to arrest sink rate and pitch up).

**Failure to maintain control**
This pivotal event refers to the ability of the flight crew to maintain (directional) control on the runway after a hard landing that results in some kind of structural failure. Particularly in the event of landing gear failures, directional control may be difficult to maintain.

**Runway veer-off**
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.
Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’.

**Aircraft continues landing roll damaged**
The aircraft suffered damage during a hard landing but stays on the runway during the landing roll-out.

**Aircraft continues landing roll**
The aircraft continues the landing roll-out on the runway.
**Aircraft touchdown fast or long**

A long touchdown is a situation where the aircraft contacts the runway far beyond the runway threshold. A long touchdown itself is not always hazardous. Particularly if small aircraft land on a long runway, a long touchdown does not create a risk. However, a long touchdown is more hazardous if the runway is relatively short and/or slippery.

A fast touchdown occurs if the aircraft lands with a speed that is significantly higher than the reference touchdown speed. A fast touchdown itself is not always hazardous. Particularly if small aircraft land on a long runway, a fast touchdown does not create a risk. However, a fast touchdown is more hazardous if the runway is relatively short and/or slippery.

For the purpose of this ESD, ‘aircraft touchdown fast or long’ is defined as a situation where the combination of touchdown speed and touchdown point is such that the aircraft cannot be brought to a full stop before reaching the end of the runway, even when making full use of all available deceleration devises such as wheel brakes, lift dumpers and thrust reversers.

**Runway overrun**

A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

### 23.2 Quantification

#### 23.2.1 Data sources

The following data sources have been used to quantify events in this ESD:

- ADER
- Airclaims;
- ASR databases (various airlines).

#### 23.2.2 Results

**ADREP and Airclaims database**

A query was run in the ADREP and Airclaims databases to search for accidents and incidents related to wind shear encounters during approach and landing. The time span was set to 1990-
2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer. Airframe manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators, and accidents/incidents during test flights and training flights are excluded. The number of flights associated with this query is 452 million flights (1990-2005).

A total of 42 accidents and incidents related to wind shear encounters in the approach-landing flight phase were found. Table 31 shows the results of the analysis of this data sample. Figure 9 shows a mapping of these 42 accidents to the different scenarios in ESD 23. The figure shows the absolute number of occurrences observed of each pivotal event and end state, based on this accident data sample.

In 26 of 42 occurrences the flight crew detected wind shear. In 11 of these 26 cases the flight crew successfully executed a wind shear escape manoeuvre. In 15 occurrences the flight crew detected wind shear but failed to execute a wind shear escape manoeuvre successfully.

In 31 of 42 occurrences the flight crew did not detect the wind shear or did not escape the wind shear successfully: There were 15 unsuccessful wind shear escape manoeuvres, 9 events in which the wind shear encounter was not detected and 7 events in which it was not clear whether the crew detected wind shear. Out of those 31 events, there were 28 events in which the aircraft touched down with excessive sink rate (i.e. a hard landing) and 3 events in which the aircraft touched fast or long.
Table 31: Results of analysis of wind shear related accidents NLR Air Safety Database (1990-2005, 452 million flights)

<table>
<thead>
<tr>
<th>Event</th>
<th>Number of occurrences</th>
<th>Rate per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft encounters wind shear during approach/landing</td>
<td>42</td>
<td>9.29·10⁻⁸</td>
</tr>
<tr>
<td>Flight crew fails to detect wind shear</td>
<td>16</td>
<td>0.38⁶</td>
</tr>
<tr>
<td>Flight crew fails to execute wind shear escape manoeuvre successfully</td>
<td>15</td>
<td>0.58¹</td>
</tr>
<tr>
<td>Aircraft touchdown excessive sink rate</td>
<td>28</td>
<td>0.90¹</td>
</tr>
<tr>
<td>Aircraft touchdown fast or long</td>
<td>3</td>
<td>1.00¹</td>
</tr>
<tr>
<td>Structural failure</td>
<td>21</td>
<td>0.75¹</td>
</tr>
<tr>
<td>Failure to maintain control (followed by runway veer off)</td>
<td>7</td>
<td>0.33¹</td>
</tr>
<tr>
<td>Failure to apply maximum braking (followed by overrun)</td>
<td>3</td>
<td>1.00¹</td>
</tr>
</tbody>
</table>

**End states**

<table>
<thead>
<tr>
<th>End states</th>
<th>Number of occurrences</th>
<th>Rate per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway veer-off</td>
<td>7</td>
<td>1.55·10⁻⁸</td>
</tr>
<tr>
<td>Aircraft continues landing roll damaged</td>
<td>14</td>
<td>3.10·10⁻⁸</td>
</tr>
<tr>
<td>Aircraft continues landing roll</td>
<td>7</td>
<td>1.55·10⁻⁸</td>
</tr>
<tr>
<td>Runway overrun</td>
<td>3</td>
<td>6.64·10⁻⁹</td>
</tr>
<tr>
<td>Aircraft continues flight</td>
<td>11</td>
<td>2.43·10⁻⁸</td>
</tr>
</tbody>
</table>

In 21 of 28 hard landings a structural failure occurred. The flight crew failed to maintain control of the aircraft and veered off the runway after a structural failure in 7 occurrences. In 14 cases the flight crew maintained control after structural failure and the aircraft continued the landing roll with structural damage. In 7 hard landings no structural failure occurred and the aircraft continued the landing roll.

In the 3 occurrences where the aircraft touched down fast or long the flight crew failed to apply maximum braking and overran the runway.

⁶ Conditional probability.
Flight crew fails to detect windshear.

Aircraft encounters windshear during approach/landing.

Accident type: uncontrolled collision with ground.
Flight phase: approach and landing.
Initiating Event: aircraft encounters windshear during approach/landing.

Figure 9: ESD quantified with NLR Air Safety Database (accidents and incidents, 1990-2005)

ASR database

Air Safety Reports (ASR) databases were analysed for events involving a wind shear encounter in the approach and landing flight phase. The ASR databases come from different airlines and cover 9 million flights between 1998 and 2004. The databases were queried for occurrences involving wind shear, a downdraft, or a microburst in the years 2000 and 2001. Only air safety reports involving Western-built aircraft heavier than 5700 kg MTOW in commercial operations were considered. The corresponding number of flights for these two years is 2.44 million.

Analysis of the data shows the following results:

- The data sample contains 578 occurrences of a wind shear encounter in the approach and landing phase. This corresponds to an estimated frequency of $2.37 \times 10^{-4}$ per flight. Because air safety reports are filed by flight crews, obviously in all of the 578 occurrences the wind shear encounter was detected by the flight crew.

- In 427 of 578 wind shear encounters the flight crew initiated a go-around or a wind shear recovery manoeuvre.

- Some of the wind shear warnings were considered false warnings. In 25 of 578 occurrences the wind shear warning was considered a false, spurious or nuisance alert. In 7 of these events a go-around was initiated nevertheless. In the remaining cases the aircraft continued

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7 In most ASRs a go-around was reported rather than a wind-shear escape manoeuvre.
the landing. This set of 7 events is part of the 427 reported occurrences involving a wind shear encounter followed by a go-around.

- In a number of events the aircraft encountered wind shear in the approach or landing, but the flight crew was able to maintain control and decided to continue the flight. In 151 of 578 reported wind shear encounters the flight crew decided to continue the approach. In 27 of these cases (17.9%) the wind shear resulted in a flap overspeed warning. In 13 of 151 events (8.6%) a hard landing was made. In one event the aircraft landed long but this did not result in a runway overrun.

Examples of instances in which the flight crew continued the approach or landing after a wind shear encounter, and landed uneventfully are:

- Aircraft was again stabilised before reaching 500 feet altitude (unstable approach criterion).
- Speed was adjusted by use of power and speed brakes.
- Wind shear was briefed and anticipated by the flight crew. Therefore the approach was continued with a stable flight path or after a stable approach was regained. This mostly refers to wind shear generated by obstacles on the ground and ‘normal’ wind shear close to the ground rather than wind shear associated with a microburst and thunderstorm cells.
- Wind shear alert during flare manoeuvre.
- Momentary wind shear alert.

23.2.3 Discussion
The ADREP and Airclaims data do not contain a representative sample of incidents to reliably estimate the frequency of a wind shear encounter, which did not result in a loss of control accident. On the other hand, ADREP and Airclaims data do contain a representative sample of loss of control accidents as a result of a wind shear encounter. The probability of the end states and conditional probabilities of pivotal events can therefore be reliably estimated with ADREP and Airclaims data. For the frequency estimation of the Initiating Event we will use the ASR database. The pivotal events ‘flight crew fails to detect wind shear’ and ‘flight crew fails to execute wind shear escape manoeuvre successfully’ will be quantified by using a combination of ASR and ADREP and Airclaims data.

23.3 Summary of results

Aircraft encounters wind shear on approach/landing
The frequency of occurrence of a wind shear encounter in the approach landing phase is estimated as \(2.37 \times 10^{-4}\) per flight (based on ASR data).
Flight crew fails to detect wind shear and Flight crew fails to execute escape manoeuvre successfully

The conditional probabilities of these events are estimated as follows:

- In 16 of 42 (38%) wind shear encounter related accidents the flight crew did not detect the wind shear, while in 15 of these 42 occurrences the flight crew failed to execute a wind shear escape manoeuvre (ADREP and Airclaims data).
- It is assumed that the relative contribution to the pivotal event ‘aircraft touchdown with excessive sink rate’ from both input events ‘flight crew fails to detect wind shear’ and ‘flight crew fails to execute wind shear escape manoeuvre successfully’ as found in accidents and incidents (ADREP and Airclaims data) is representative for all wind shear encounters.
- ASR data indicate that 151 of 578 (26%) wind shear encounters do not result in a successful wind shear escape manoeuvre.
- Combining this information results in the conclusion that, in the event of a wind shear encounter during approach and landing, the conditional probability that the flight crew fails to detect wind shear is 0.144 whereas the conditional probability that the event ‘flight crew fails to execute wind shear escape manoeuvre successfully’ is 0.135.

Aircraft touchdown with excessive sink rate (hard landing)

According to ASR data, in 151 of 587 (26%) of wind shear encounters the flight crew continued the approach or the wind shear escape manoeuvre was considered unsuccessful. In 13 of these 151 events the aircraft touched down with excessive sink rate. Hence, the conditional probability of this event is estimated as $8.60 \times 10^{-2}$. This probability is conditional on the sum of the yes-output of ‘flight crew fails to detect wind shear’ and ‘flight crew fails to execute wind shear escape manoeuvre successfully’. The no-output of the pivotal event ‘aircraft touchdown with excessive sink rate’ is 0.914.

Flight crew fails to maintain control

ADREP and Airclaims data show that out of 21 structural failures due to touchdowns with excessive sink rate that where the result of a wind shear encounter, 7 (33%) led to a runway veer-off and 14 (67%) resulted a ‘continued landing roll damaged’. Given the event that the aircraft has a structural failure the conditional probability of the flight crew failing to maintain control is 0.33.

Runway veer-off

According to ADREP and Airclaims data, out of a total sample of 452 million flights, there have been 7 runway veer-off accidents as result of a wind shear encounter and hard landing.
followed by structural damage and a failure of the flight crew to maintain control. The corresponding probability is $1.55 \times 10^{-8}$ per approach and landing.

**Structural failure**
The conditional probability of a structural failure is derived from the following equation:

$$2.37 \times 10^{-4} \times 0.26 \times 0.086 \text{ (excessive sink rate)} \times \text{structural failure} \times 0.33 \text{ (failure to maintain control)} = 1.54 \times 10^{-8} \text{ (veer-off).}$$

Hence, given the event that the aircraft touches down with an excessive sink rate, the conditional probability of a structural failure is $8.81 \times 10^{-3}$.

**Aircraft continues landing roll damaged**
According to ADREP and Airclaims data, out of a total sample of 452 million flights, there have been 14 cases of ‘aircraft continues landing roll’ damaged’ accidents as result of a wind shear encounter followed by a and hard landing and structural damage. The corresponding probability is $3.10 \times 10^{-8}$ per approach and landing.

**Aircraft continues landing roll**
The estimated probability that the aircraft continues the landing roll after a hard landing following a wind shear encounter in the landing is $5.25 \times 10^{-6}$ per flight. This probability follows by multiplication of the initiating event probability and the conditional probabilities of the intermediate pivotal events.

**Aircraft touchdown fast or long**
According to ADREP and Airclaims data, in a total sample of 452 million flights there have been 3 runway overrun accidents as a result of a fast and long landing following a wind shear encounter during approach and landing. The corresponding runway overrun probability is $6.63 \times 10^{-9}$ per approach and landing. The conditional probability of a fast or long landing can be calculated from previously calculated information:

$$2.37 \times 10^{-4} \times 0.26 \times 0.914 \times P(\text{touchdown fast or long}) = 6.63 \times 10^{-9}.$$  

The conditional probability of a fast or long touchdown is $1.18 \times 10^{-4}$.

**Runway overrun**
According to ADREP and Airclaims data, out of a total sample of 452 flights, there have been three cases of a runway overrun following a long and fast touchdown after a wind shear encounter. The estimated probability that the aircraft overruns the runway following a wind shear encounter and subsequent long/fast touchdown is $6.63 \times 10^{-9}$ per flight.
Aircraft continues landing roll
According to ASR data, there have been 137 cases in 2.44 million flights where the flight crew continued the approach after a wind shear encounter and landed without any further incident. Hence the estimated absolute probability of ‘aircraft continues landing roll’ $5.61 \times 10^{-5}$ per flight.

Aircraft continues flight
The probability that the aircraft continues flight after encountering wind shear and a successful escape manoeuvre is $2.37 \times 10^{-4} \times 0.874 \times 0.866 = 1.79 \times 10^{-4}$ per flight.

Accident type: uncontrolled collision with ground.
Flight phase: approach and landing.
Initiating Event: aircraft encounters windshear during approach/landing.
24 ESD25 – Aircraft handling by flight crew during flare inappropriate

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: Aircraft handling by crew during flare inappropriate

24.1 Definitions

**Aircraft handling by crew during flare inappropriate**
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 experience and judgement. For the purpose of this ESD, ‘aircraft handling by crew during flare inappropriate’ is defined as a flare that starts from a stabilised condition at the runway threshold but the manoeuvre itself is conducted inappropriately. A stabilised condition at the runway threshold is defined as a situation where the aircraft is not more than 10 ft above or below the prescribed height and not more than 10 kts faster or slower than the target (or bug-) speed.

**Aircraft touchdown fast or long**
For the purpose of this ESD, a fast or long touchdown is defined as an aircraft landing more than 2000 ft down from the runway threshold.

**Aircraft touchdown with excessive sink rate**
For the purpose of this ESD, a touchdown with excessive sink rate is defined as a touchdown were the vertical acceleration exceeds 1.85 g or the vertical speed is more than 1000 ft/minute.
Structural failure
The aircraft is damaged as a direct result of the hard landing. This includes failures of the landing gear and failures of the aircraft structure such as wing spars, fuselage frames and skin panels.

Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control is affected by human factors (fatigue, training, etc), aircraft system failures, weather conditions, etc.

Runway overrun
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

24.2 Quantification
To determine the frequency of inappropriate aircraft handling during the flare, a study of landing performances during ILS approaches conducted by NLR in 2006 was used [van Es & van der Geest, 2006]. This study analysed in-flight recorded data of 40,764 landings. The data was limited to two types of aircraft: Boeing 737-400 and Airbus A319/A320/A321. All data was obtained from a European airline. The flight data were obtained from the airline’s flight data monitoring program. The recording effort lasted for more than 7 months and covered winter, spring and summer time operations.
The point of crossing of the runway threshold is not directly captured by the flight data recorder but needs to be calculated from other parameters. To perform this calculation it was assumed that all approaches in the data sample were according to a 3-degree glideslope and that for all approaches the ILS Reference Datum Height that marks the height of the intersection of the glideslope beam with the runway threshold was 50 ft.

The aircraft touchdown point was calculated from the flight data by differentiation of the normal acceleration signal. The peak value in this differentiated normal acceleration was considered to indicate the point of touchdown. The longitudinal distance of the touchdown point relative to the runway threshold was calculated by integrating the recorded ground speed of the aircraft from the point of runway threshold crossing until touchdown.

The set contains 3 hard landings and 946 long landings that occurred in spite of a stabilised condition at the runway threshold (see definitions). There were no occurrences where the aircraft landed both hard and long after a stabilised condition at the runway threshold. The corresponding probability of inappropriate aircraft handling during the flare is estimated to be $949 / 40,764 = 2.33 \times 10^{-2}$ per flight.

To estimate the accident rates due to inappropriate aircraft handling during the flare, the Airclaims accident and incident database was analysed. Only large Western-built jets and turboprops in commercial operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group conducted a total of 399 million flights.

The data sample contained 47 hard landings which can be contributed to inappropriate aircraft handling during the flare and in which the aircraft remained on the runway. In 45 occurrences the hard landing resulted in a structural failure, in 2 cases there was no damage to the aircraft.

The data sample contained 12 cases of runway veer-off accidents that were the result of a structural failure following a hard landing that was caused by an inappropriate flare. In addition, the database contained 13 cases where a hard landing resulting from an inappropriate flare did not cause a structural failure but led to a loss off control and subsequent veer-off.

The data sample contained 9 overruns where the aircraft touched down long or fast due to an inappropriate flare. The results of the analysis are summarised in Table 32.
Table 32: A summary of the probabilities for the end states of ESD 25

<table>
<thead>
<tr>
<th>End state</th>
<th>Number of accidents</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway overrun</td>
<td>9</td>
<td>2.26·10^{-8}</td>
</tr>
<tr>
<td>Aircraft damaged</td>
<td>45+12</td>
<td>1.43·10^{-7}</td>
</tr>
<tr>
<td>Runway veer-off</td>
<td>13</td>
<td>3.26·10^{-8}</td>
</tr>
</tbody>
</table>

The conditional probability of a fast or long touchdown given inappropriate aircraft handling during the flare is 2.26·10^{-8} / 2.33·10^{-2} = 9.69·10^{-7} per flight.

The probability of a touchdown with excessive sink rate following an inappropriate flare is 3 / 40,764 = 7.36·10^{-5} per flight. The corresponding conditional probability that the aircraft touches down with an excessive sink rate given an inappropriate flare is 7.36·10^{-5} / (2.33·10^{-2} × (1-9.69·10^{-7})) = 3.16·10^{-3} per flight.

The conditional probability of a structural failure in the event of a touchdown with excessive sink rate due to an inappropriate flare is 1.43·10^{-7} / 7.36·10^{-5} = 1.94·10^{-3}.

The conditional probability that the flight crew fails to maintain control when the aircraft touches down with an excessive sink rate as a result of an inappropriate flare is 3.26·10^{-8} / (7.36·10^{-5} × (1 - 1.94·10^{-3})) = 4.44·10^{-4}.

The probability of end state “Aircraft continues landing roll” becomes: 2.33·10^{-2} × (1 - 9.69·10^{-7}) × (1-3.16·10^{-3})×1 = 2.32·10^{-2}.
**25 ESD26 - Aircraft handling by flight crew during landing roll inappropriate**

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: aircraft handling by flight crew during landing roll inappropriate.

25.1 Definitions

**Aircraft handling by flight crew during landing roll inappropriate**
This ESD describes the scenario in which a touchdown is made with a correct speed and sink rate, but due to an action by the crew during the landing roll, control of the aircraft is (temporarily) lost or maximum braking is not achieved. Included in this initiating event are off-centreline touchdowns. Inappropriate aircraft handling includes inappropriate use of rudder and aileron, inappropriate use of the steering tiller, delayed operation of deceleration devices such as lift dumpers, thrust reverser and wheel brakes and inappropriate differential braking. The occurrence of aquaplaning is also considered to be in the scope of this initiating event.

**Flight crew fails to maintain control**
This pivotal event refers to the ability of the flight crew to maintain (directional) control on the runway after touchdown.

**Failure to achieve maximum braking**
Immediately following touchdown, the flight crew must start reducing the speed of the aircraft. On most large aircraft, a ‘positive’ touchdown is required to make sure the aircraft switches to ground logic, which will automatically deploy lift dumpers (if available and armed) and will ensure a proper functioning of the autobrake system. Braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and
reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

**Runway overrun**

A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**Runway veer-off**

A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**25.2 Quantification**

**Initiating event**

To estimate the probability of an inappropriate aircraft handling during the landing roll, operational data from a large western European airline has been used. The data set consists of 286,753 flights from the year 2001. This set contains 61 reports of inappropriate pilot handling during the landing phase without technical or environmental reasons. In 58 cases, the report only reports an “exceedance” due to pilot handling. It is assumed that these 61 cases are due to inappropriate aircraft handling during the landing roll. The corresponding probability is estimated to be $61/286,753 = 2.13 \cdot 10^{-4}$ per flight.

**End states**

The Airclaims accident and incident database was analysed to estimate the probability of occurrence of the end states. Only large Western-built jets and turboprops in commercial
operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group conducted a total of 399 million flights.

The data sample contains 62 veer-off accidents that are attributed to inappropriate aircraft handling during landing or off-centreline touchdowns. The corresponding probability is $\frac{62}{3.99 \times 10^8} = 1.55 \times 10^{-7}$ per flight.

The data sample contains 59 runway overrun accidents that are attributed to inappropriate aircraft handling during the landing roll and/or the occurrence of aquaplaning. The corresponding probability is $\frac{59}{3.99 \times 10^8} = 1.48 \times 10^{-7}$ per flight.

**Pivotal events**

The conditional probabilities of the pivotal events can be estimated from the probability of occurrence of the initiating event and the end states.

The conditional probability of ‘flight crew fails to maintain control’ if aircraft handling during the landing roll is inappropriate is $\frac{1.55 \times 10^{-7}}{2.13 \times 10^{-4}} = 7.28 \times 10^{-4}$ per flight.

The conditional probability of ‘failure to achieve maximum braking’ if aircraft handling during the landing roll is inappropriate and the crew is able to maintain control is $\frac{1.48 \times 10^{-7}}{2.13 \times 10^{-4} \times (1-7.28 \times 10^{-4})} = 6.95 \times 10^{-4}$ per flight.

**Accident type: uncontrolled collision with ground.**
**Flight phase: landing.**
**Initiating Event: aircraft handling by flight crew during landing roll inappropriate.**
26 ESD27 - Aircraft directional control related system failure during landing

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: aircraft directional control related system failure.

26.1 Definitions

Aircraft directional control system failure
An aircraft directional control system failure is a failure of any of the aircraft’s systems that affects the directional controllability of the aircraft during the landing roll. Included are failures of the aileron and aileron controls, rudder and rudder controls, tyres, and landing gear. Directional control problems as a result of asymmetric thrust due to an engine failure are covered in ESD 28. Directional control problems as a result of thrust reverser failures are covered in ESD 29.

Flight crew fails to maintain control
As a result of the degraded directional control capabilities of the aircraft the crew may find it difficult to maintain control, particularly in conditions of crosswind and a slippery runway. This pivotal event is defined as an unrecovered loss of directional control during the landing roll.

Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.
26.2 Quantification
The main source of information was the database of Service Difficulty Reports (SDRs), see also Appendix A. The time period 1985-2003 was selected as representative of current aviation. The analysis was limited to air carrier operations, thereby excluding general aviation. Only events which resulted in precautionary procedures were included in the data sample. Finally, events which were the result of a false warning were excluded.

Table 33: Directional control problems during landing phase

<table>
<thead>
<tr>
<th>ATA code</th>
<th>ATA description</th>
<th>Nr of reports</th>
<th>Exposure (flights)</th>
<th>Failure rate (per flight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2710</td>
<td>Aileron control system</td>
<td>13</td>
<td>$2.16 \times 10^8$</td>
<td>$6.02 \times 10^{-8}$</td>
</tr>
<tr>
<td>2711</td>
<td>Aileron tab control system</td>
<td>2</td>
<td>$2.16 \times 10^8$</td>
<td>$9.27 \times 10^{-9}$</td>
</tr>
<tr>
<td>2720</td>
<td>Rudder control system</td>
<td>14</td>
<td>$2.16 \times 10^8$</td>
<td>$6.49 \times 10^{-8}$</td>
</tr>
<tr>
<td>2722</td>
<td>Rudder actuator</td>
<td>1</td>
<td>$2.16 \times 10^8$</td>
<td>$4.63 \times 10^{-9}$</td>
</tr>
<tr>
<td>3200</td>
<td>Landing gear</td>
<td>1437</td>
<td>$2.16 \times 10^8$</td>
<td>$6.56 \times 10^{-6}$</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1467</td>
<td>$2.16 \times 10^8$</td>
<td>$6.79 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

The probability of a directional control related system failure is estimated as $6.79 \times 10^{-6}$ per flight.

To estimate the probability of runway veer-offs that are caused by directional control related system failures, the Airclaims accident and incident database was analysed. Only large Western-built jets and turboprops in commercial operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group conducted a total of 399 million flights. A total number of 44 veer-offs were identified. The probability of a veer-off due to a directional control related system failure is estimated to be $1.10 \times 10^{-7}$ per flight.

The conditional probability of ‘flight crew fails to maintain control’ in the event of a directional control related system failure is estimated to be $1.10 \times 10^{-7} / 6.79 \times 10^{-6} = 1.62 \times 10^{-2}$ per flight.
27 ESD28 - Single engine failure during landing

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: single engine failure.

27.1 Definitions

Single engine failure
For the purpose of this ESD, a single engine failure is defined as any failures of one of the systems that correspond with the ATA codes between 6100 and 6197 or between 7100 and 8097.

Flight crew fails to maintain control
Because of the asymmetric thrust that is a result of the engine failure, the crew may find it difficult to maintain control, particularly in conditions of crosswind and a slippery runway. This pivotal event is defined as an unrecovered loss of directional control during the landing roll.

Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

Failure to achieve maximum braking
Immediately following touchdown, the flight crew must start reducing the speed of the aircraft. On most large aircraft, a ‘positive’ touchdown is required to make sure the aircraft switches to
ground logic, which will automatically deploy lift dumpers (if available and armed) and will ensure a proper functioning of the autobrake system. Braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available) are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

**Runway overrun**
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**27.2 Quantification**

**Initiating event**
The database of service difficulty reports (see Appendix A) has been used to estimate the probability of occurrence of landing roll-outs with an engine failure. All engine failures that occurred between an take-off (not rejected) and landing roll were considered. According to the SDR database, out of a total of 215,800,000 flights there have been 10,562 occurrences of landings with a single engine failure. The corresponding probability of occurrence is \(4.89 \times 10^{-5}\) per flight.

**End states**
To estimate the probability of runway overruns and veer-offs that are caused by landings with one-engine inoperable, the Airclaims accident and incident database was analysed. Only large Western-built jets and turboprops in commercial operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group conducted a total of 399 million flights.
According to the Airclaims database, there have been 3 veer-off accidents that were contributed to landing with one engine inoperable, and 2 overrun accidents. The corresponding probabilities are $7.52 \cdot 10^{-9}$ per flight for veer-off and $5.01 \cdot 10^{-9}$ for overrun.

**Pivotal events**

The probability of ‘flight crew fails to maintain control’ in the event of a landing with one engine inoperable is $7.52 \cdot 10^{-9} / 4.89 \cdot 10^{-5} = 1.54 \cdot 10^{-4}$.

The conditional probability of ‘failure to achieve maximum braking’ in the event of a landing with one engine inoperable is $5.01 \cdot 10^{-9} / (4.89 \cdot 10^{-5} \times (1-1.54 \cdot 10^{-4})) = 1.02 \cdot 10^{-4}$.
28 ESD29 - Thrust reverser failure

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: thrust reverser failure.

Thrust reverser failure
A thrust reverser is a system that redirects a jet engine’s airflow such that the resulting thrust force acts against the forward travel of the aircraft. On propeller driven aircraft reverse thrust is obtained by changing the pitch of the propeller blades to a negative angle, thereby directing airflow into the direction of travel. For the purpose of this ESD a thrust reverser failure is defined as a failure of system ATA 7830 reverser for aircraft with jet propulsion and a failure of system ATA 6120 propeller control for aircraft with propeller propulsion. Only technical malfunctions of the thrust reverser system are considered in this initiating event. Failures of the flight crew to correctly operate the thrust reverser system are covered in ESD 26.

Flight crew fails to maintain control
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control is affected by human factors (fatigue, training, etc), aircraft system failures, weather conditions, etc.

Failure to achieve maximum braking
Immediately following touchdown, the flight crew must start reducing the speed of the aircraft. On most large aircraft, a ‘positive’ touchdown is required to make sure the aircraft switches to ground logic, which will automatically deploy lift dumpers (if available and armed) and will ensure a proper functioning of the autobrake system. Braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available)
are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

**Runway overrun**
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**Runway veer-off**
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

**28.2 Quantification**
Thrust reverser failure frequencies were determined from the database of Service Difficulty Reports (SDRs), see Appendix A. The time period 1985-2003 was selected as representative of current aviation. The analysis was limited to commercial operations of large (> 5700 kg MTOW) aircraft. Only events which resulted in precautionary procedures were included in the data sample. Finally, events which were the result of a false warning were excluded. According to the SDR database there have been 92 failures of the thrust reverser system (ATA 7830) during the approach and landing phase in 2.05·10^8 corresponding flights. Only exposure data for aircraft equipped with thrust reversers is taken into account. This results in a frequency of 4.49·10^-7 thrust reverser failures per approach and landing for aircraft with jet engines.

According to the SDR database there have been 170 failures of the propeller control system (ATA 6120) during the approach and landing phase in 5.52·10^7 corresponding flights. Only
exposure data for aircraft equipped with propellers is taken into account. This results in a frequency of \(3.08 \times 10^{-6}\) propeller control system failures per approach and landing.

For the overall aircraft fleet that is represented in the SDR database, the frequency of thrust reverser or propeller control system failures is \(1.01 \times 10^{-6}\) per approach and landing.

End states “runway veer-off” and “runway overrun”
To quantify these end states, ADREP and Airclaims data are used. The time span was set to 1990-2005. Aircraft types include jet, turbofan and turboprop aircraft with a Maximum Take-off Weight of more than 5700 kg, operated in commercial operations (passenger and cargo flights). Aircraft manufacturers include ‘Western’ airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, and Embraer. Aircraft manufacturers from former USSR or Eastern-block countries (e.g. Tupolev, Let, Antonov) are excluded from the query. All operators of aforementioned aircraft types, irrespective of country of origin, are included. Military operators and accidents/incidents during test flights and training flights are excluded. The number of flights associated with this query is 452 million flights for the ADREP and Airclaims databases.

When selecting on “reverse”, Airclaims data show 100 accidents. Of these accidents, the following can be related to thrust reversers:
• 19 runway veer-offs;
• 6 runway overruns; and
• 4 veer-offs and overruns where the crew made a mistake in using the thrust reversers.
This latter category, however, is considered outside the scope of this ESD, but is considered to be part of ESD 26.

Since the Airclaims database does not necessarily cover all accidents that have occurred in the period 1990-2005, also ADREP data has been analysed.

As a result of a similar query, using the keyword “reverse” ADREP shows 232 occurrences. Note that this selection partly overlaps with the Airclaims selection. Analysis of these occurrences results in the following additional occurrences:
• 5 runway veer-offs; and
• 1 runway overrun.

This gives a total number of relevant occurrences of:
• 24 runway veer-offs; and
• 7 runway overruns.
This number of accidents can be related to 452 million flights. Although not all of these flights are equipped with thrust reversers and, if available, thrust reversers are not always used, it is assumed here that all of the 452 million flights are applicable. This leads to the following frequencies:

- Runway veer-off, due to a thrust reverser failure: $5.31 \times 10^{-8}$ per flight
- Runway overrun, due to a thrust reverser failure: $1.55 \times 10^{-8}$ per flight

The conditional probability of a failure to maintain control in the event of a thrust reverser failure is estimated to be $5.32 \times 10^{-8} / 1.01 \times 10^{-6} = 5.26 \times 10^{-2}$.

The conditional probability of failure to achieve maximum braking in the event of a thrust reverser failure and the flight crew maintains control is estimated to be $1.11 \times 10^{9} / (1.01 \times 10^{-6} \times (1-5.26 \times 10^{-2})) = 1.62 \times 10^{-2}$.

Accident type: uncontrolled collision with ground.
Flight phase: landing.
Initiating Event: thrust reverser failure.
29 ESD30 - Aircraft encounters unexpected wind

Accident type: uncontrolled collision with ground.
Flight phases: landing.
Initiating event: aircraft encounters unexpected wind.

29.1 Definitions

**Aircraft encounters unexpected wind**
The initiating event is defined as significant unexpected cross wind, gusting winds and/or turbulence. For the purpose of quantification, it is assumed that “unexpected cross wind” is defined as a situation where the cross wind speed encountered during landing is more than 15 knots and deviates more than 10 kts from the reported cross wind speed. Wake vortex encounters due to insufficient ATC separation are not taken into account. Wind shear is not regarded as ‘unexpected wind’, but is treated separately in ESD 23.

**Flight crew fails to maintain control**
This pivotal event refers to the ability of the flight crew to maintain control of the aircraft. This pivotal event does not necessarily imply a failure or error by the flight crew. The ability of the flight crew to maintain control is affected by human factors (fatigue, training, etc), aircraft system failures, weather conditions, etc.

**Failure to achieve maximum braking**
Immediately following touchdown, the flight crew must start reducing the speed of the aircraft. On most large aircraft, a ‘positive’ touchdown is required to make sure the aircraft switches to ground logic, which will automatically deploy lift dumpers (if available and armed) and will ensure a proper functioning of the autobrake system. Braking must start immediately using maximum braking power and all available deceleration devices: the lift-dumpers (if available)
are raised (manually or automatically), the brakes are applied (manually or automatically), and reverse thrust or propeller reverse is selected (if available). These actions must be conducted without delay and according to the standard operating procedures (SOP). Braking performance is strongly influenced by the runway conditions, if the runway is wet or flooded, or if it is covered with snow, slush or ice, tyre-to-ground friction is significantly reduced resulting in longer stopping distances.

Runway overrun
A runway overrun is a situation where the aircraft is not able to come to a full stop before reaching the end of the runway. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are also considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

Runway veer-off
A runway veer-off is a situation where the flight crew is not able to maintain directional control and the aircraft deviates to the side of the runway and veers off it. Occurrences where the aircraft cannot be brought to a halt before reaching the end of the runway but where flight crew deliberately steer the aircraft off the side of the runway in order to prevent a collision with obstacles located in line with the runway are considered to be ‘runway overruns’. The degree of damage is determined by the speed at which the aircraft leaves the runway, the veer-off angle, and the possible presence of obstacles such as ditches, fences, approach lights, buildings, etc.

29.2 Quantification
For the purpose of quantification, it is assumed that “unexpected cross wind” is defined as a situation where the cross wind speed encountered during landing is more than 15 knots and deviates more than 10 kts from the reported cross wind speed. According to [van Es et al., 2001], the probability that the encountered cross wind speed deviates more than 10 knots from the reported crosswind speed is 0.06 per flight. According to the same reference, the probability that the mean actual cross wind speed exceeds 15 knots is 0.02 per flight. Based on these numbers, the probability of an unexpected cross wind is estimated at $0.06 \times 0.02 = 1.20 \times 10^{-3}$ per flight.

To estimate the probability of encountering turbulence during the approach and landing, operational data from a large western European airline has been used. The data set consists of 286,753 flights from the year 2001. This set contains 3 turbulence encounters during the landing
phase. Wake vortex encounters due to insufficient separation by ATC were not taken into account. As a result, the probability is estimated to be \( \frac{3}{286753} = 1.05 \cdot 10^{-5} \) per flight.

On total, the probability of encountering unexpected wind is estimated to be \( 1.21 \cdot 10^{-3} \) per flight.

To estimate the probability of runway overruns and veeroffs that are caused by unexpected wind, the Airclaims accident and incident database was analysed. Only large Western-built jets and turboprops in commercial operations between 1985 and 2005 were considered. Business jets were excluded from the data sample. In the time frame under consideration, this group represented a total of 399 million flights. A total number of 23 veer-offs were identified, and 9 overruns. The probability of a veer-off due to unexpected wind in the landing is estimated to be \( 5.76 \cdot 10^{-8} \) per flight. The probability of an overrun due to unexpected wind in the landing is estimated to be \( 2.26 \cdot 10^{-8} \) per flight.

The conditional probability of flight crew fails to maintain control in the event of an unexpected wind encounter is estimated to be \( \frac{5.76 \cdot 10^{-8}}{1.21 \cdot 10^{-3}} = 4.76 \cdot 10^{-5} \).

The conditional probability of failure to achieve maximum braking in the event of an unexpected wind encounter is \( \frac{5.76 \cdot 10^{-8}}{(1.21 \cdot 10^{-3} \times (1-4.76 \cdot 10^{-5}))} = 1.86 \cdot 10^{-5} \).

**Accident type:** uncontrolled collision with ground.
**Flight phases:** landing.
**Initiating event:** aircraft encounters unexpected wind.

![Diagram](image-url)
30  ESD31 - Aircraft are positioned on collision course

Accident type: mid-air collision.  
Flight phases: initial climb, en-route and approach. 
Initiating event: aircraft are positioned on collision course.

(1) This pivotal event includes the execution of ‘see-and-avoid’ principle and the response to a Traffic Collision Avoidance System alert.

30.1 Definitions

Aircraft are positioned on collision course  
This event refers to a situation where two airborne aircraft are positioned such that their trajectories, if unaltered, will bring the aircraft closely together leading to a risk for collision.  
The initiating event “Aircraft are positioned on collision course” describes an aircraft proximity (Airprox) incident. An airprox is described by ICAO as ‘A situation in which, in the opinion of a pilot or Air Traffic Controller, the distance between aircraft as well as their relative positions and speeds have been such that the safety of the aircraft involved was or may have been compromised’. [CAA, 1997]. They are classified into four different categories, A through D, with classes A and B being “risk bearing” proximities.

ATC fails to detect and resolve conflict 
This event refers to any situation where action or inaction of the air traffic controller fails to resolve the collision risk that has been arisen due to the aircraft trajectories.
Flight crew fails to detect and resolve conflict
This event refers to any situation where action or inaction of the flight crew fails to resolve the collision risk that has been arisen due to the aircraft trajectories.

30.2 Quantification

Aircraft are positioned on collision course
The initiating event “Aircraft are positioned on collision course” is considered to be an aircraft proximity (airprox) incident. An airprox is described by ICAO as ‘A situation in which, in the opinion of a pilot or Air Traffic Controller, the distance between aircraft as well as their relative positions and speeds have been such that the safety of the aircraft involved was or may have been compromised’. [CAA, 1997]. They are classified into four different categories, A through D, with classes A and B being “risk bearing” proximities. In these cases it was assessed that the safety was not assured or that there was a risk of collision. The initiating event “Aircraft are positioned on collision course” is quantified by the number of risk bearing airproxes per flight. Figure 10 below shows the risk bearing airprox frequency for the UK [CAA, 2002], the Netherlands [LVNL, 2004], Germany [DFS, 2006] and Switzerland [Skyguide, 2004] as a frequency per flight.

![Figure 10: Frequency of airproxes in 4 European states](image)
By taking the average over the period 2000-2004, the frequency is estimated to be $9.20 \times 10^{-6}$ airproxes per flight. The average was taken by summation of all airproxes, summation of all accompanying movement data and then dividing the two numbers.

**Mid air collisions**

From 1985 through 2004, there have been 7 mid air collisions involving western-built large jet aircraft in commercial operations (see Table 34), and also 7 mid-air collisions involving western-built turboprop aircraft in commercial operations (see Table 35).

**Table 34: Midair collisions involving commercial jet aircraft**

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Aircraft 1 Type</th>
<th>Aircraft 2 Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-08-1986</td>
<td>Los Angeles, USA</td>
<td>Douglas DC9 Passenger</td>
<td>Piper PA28 Private</td>
</tr>
<tr>
<td>16-06-1987</td>
<td>Fuzhou, China</td>
<td>Boeing 737 Passenger</td>
<td>Jian-6 Military</td>
</tr>
<tr>
<td>22-12-1992</td>
<td>Tripoli, Libya</td>
<td>Boeing 727 Passenger</td>
<td>Mig 23 Military</td>
</tr>
<tr>
<td>12-11-1996</td>
<td>Delhi, India</td>
<td>Boeing 747 Passenger</td>
<td>Ilyushin 76</td>
</tr>
<tr>
<td>12-02-1999</td>
<td>Grenouillet, France</td>
<td>Airbus A320 Passenger</td>
<td>Grob G103 Glider</td>
</tr>
<tr>
<td>01-07-2002</td>
<td>Überlingen, Germany</td>
<td>Boeing 757 Cargo</td>
<td>Tupolev 154</td>
</tr>
<tr>
<td>26-12-2002</td>
<td>Windhoek, Namibia</td>
<td>Boeing 737 Passenger</td>
<td>Cessna 404 Private</td>
</tr>
</tbody>
</table>

**Table 35: Midair collisions involving turboprop aircraft**

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Aircraft 1 Type</th>
<th>Aircraft 2 Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-06-1986</td>
<td>USA</td>
<td>DHC-6 Twin Otter</td>
<td>Bell Jet Ranger</td>
</tr>
<tr>
<td>15-01-1987</td>
<td>Salt Lake City, USA</td>
<td>Swearingen Metro II</td>
<td>Mooney M20C Private</td>
</tr>
<tr>
<td>09-04-1990</td>
<td>Gadsen, USA</td>
<td>Embraer 120 Brasilia</td>
<td>Cessna 172 Private</td>
</tr>
<tr>
<td>09-12-1993</td>
<td>Dakar, Senegal</td>
<td>NAMC YS-11 Passenger</td>
<td>DHC-6 Twin Otter</td>
</tr>
<tr>
<td>09-12-1993</td>
<td>Dakar, Senegal</td>
<td>DHC-6 Twin Otter</td>
<td>NAMC YS-11 Passenger</td>
</tr>
<tr>
<td>01-05-1995</td>
<td>Sioux Lookout, Canada</td>
<td>Swearingen Metro 23</td>
<td>Piper PA-31</td>
</tr>
<tr>
<td>30-07-1998</td>
<td>Baie de Quiberon, France</td>
<td>Beech 1900 Passenger</td>
<td>Cessna 177 Private</td>
</tr>
</tbody>
</table>
Exposure data from the period 1985-2004 gives in total 416,360,000 flights in that period. It involves western-built aircraft, >5700 kg MTOW in commercial operations. Hence, the mid-air collision rate is $3.36 \times 10^{-8}$ per flight.

**ATC fails to detect and resolve the conflict**

In many Air Traffic Control centres the radar controllers are supported with a short-term conflict alerting system (STCA). This computer system monitors Secondary Surveillance Radar (SSR) data and alerts the controller if two aircraft are dangerously close to each other. Two aircraft are dangerously close if they are (potentially) going to collide within a certain time period that is less than the warning time. The warning time is set such that it is judged to be sufficient to resolve the conflict from the moment the warning is given. The STCA is a last-resort backup tool.

The UK Airprox Board (UKAB) investigates all proximities in UK airspace. To determine the probability of occurrence of ‘ATC fails to detect and resolve the conflicts’, a set of 414 UK Airproxes in the period 1999-2003 was analysed. The data set needed to be limited to cases where STCA was available. For cases where STCA was not available, the information was insufficient for quantification of the pivotal event. When we only consider class A or B airproxes and only those situations where STCA was available, 22 incidents remain. The results are presented in Table 36.

In 2 cases the traffic controller resolved the potential conflict before an STCA alert was given. In 35% of the remaining cases, no warning was given by the STCA. In 5% of the cases an alert was given, but the controller did not respond properly.

**Table 36: Impact of STCA on number of class A and B airproxes**

<table>
<thead>
<tr>
<th>STCA event description</th>
<th>Number of airproxes class A and B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acted before possible warning</td>
<td>2 (9%)</td>
</tr>
<tr>
<td>No STCA warning</td>
<td>7 (32%)</td>
</tr>
<tr>
<td>Warned and acted</td>
<td>12 (55%)</td>
</tr>
<tr>
<td>Inappropriate controller response</td>
<td>1 (5%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22 (100%)</strong></td>
</tr>
</tbody>
</table>

In 8 cases (36.4 %), the controller did not resolve the conflict (with or without the help of STCA). Hence, the conditional probability that the controller fails to resolve the conflict is $3.63 \times 10^{-1}$. This conditional probability only represents situations where STCA is available.
Flight crew fails to detect and resolve the conflict

Based on the frequencies of the Airproxes, the ATC failure to detect and resolve the conflict, and the frequency of mid-air collision, the probability that the flight crew fails to detect and resolve the conflict is calculated as $3.38 \times 10^{-8} / (9.20 \times 10^{-6} \times 0.36) = 1.02 \times 10^{-2}$. 

Table 37: Summary of the probabilities for the initiating and pivotal events

<table>
<thead>
<tr>
<th>Event</th>
<th>Probability (per flight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft are positioned on a collision course</td>
<td>$9.20 \times 10^{-6}$</td>
</tr>
<tr>
<td>ATC fails to detect and resolve conflict</td>
<td>$3.63 \times 10^{-1}$</td>
</tr>
<tr>
<td>Flight crew fails to detect and resolve conflict</td>
<td>$1.02 \times 10^{-2}$</td>
</tr>
<tr>
<td>Collision in mid-air</td>
<td>$3.38 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Accident type: mid-air collision.
Flight phases: initial climb, en-route and approach.
Initiating event: aircraft are positioned on collision course.
31. ESD32 - Incorrect presence on runway in use

Accident type: collision on ground.
Flight phases: taxi, take-off and landing.
Initiating event: incorrect presence of aircraft/vehicle on runway in use

31.1 Definitions

Incorrect presence of aircraft / vehicle on runway in use
According to a definition from ICAO, a runway incursion is any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft. For the purpose of this ESD, only the runway incursions are considered that could lead to a collision between two aircraft or an aircraft and a vehicle. ICAO uses a categorisation of runway incursions to denote the severity. For this study only class A and B incursions are taken into account, i.e. runway incursions where there was a significant potential for a collision.

ATC fails to resolve the conflict
Failure of Air Traffic Control to successfully provide corrective instructions to flight crew or vehicle driver in case of a runway incursion.

Flight crew or vehicle driver fails to resolve the conflict.
Failure of the flight crew or vehicle driver to successfully perform corrective actions in the absence of corrective ATC instructions.

31.2 Quantification
According to Eurocontrol’s mandatory incident reporting scheme, there have been 350 runway incursions reported in the ECAC area in 2002. This corresponds to 15,300,000 movements or 7,650,000 flights (one flight involves two movements) [EUROCONTROL, 2004]. Since the
A definition of a runway incursion includes any occurrence involving the incorrect presence of an aircraft, vehicle or person on the protected area of the runway, not all runway incursions are taken into account for this scenario. In the mandatory reporting scheme, runway incursions are classified A through D based on their severity. Of the above mentioned incursions, 5% were classified as class A (“Very serious”) and 30% as class B (“Significant risk”). For this ESD only class A and B runway incursions are taken into account denoting incursions with a significant potential for a collision. Hence, the probability of a runway incursion with a significant potential for a collision (class A and B) is estimated to be $1.60 \times 10^{-5}$ per flight. Such a runway incursion could involve two aircraft or an aircraft and a vehicle.

In 2001, the National Aerospace Laboratory NLR conducted a study to collect and analyse a selected number of air traffic management related accidents, which occurred in the period 1980 through 1999 and involved civil transport aircraft [van Es, 2001]. The accidents involved aircraft operated by commercial operators, including and limited to:

- Western-built aircraft,
- Freight operators and air carriers involved in public transport,
- Scheduled and non-scheduled flights,
- Freight, passenger, training and positioning flights,
- International and domestic flights,
- Turbojet, turboprop and piston-engine fixed-wing aircraft,
- Aircraft in the takeoff weight category of 5,700 kg or higher.

But excluding:

- Experimental/test flights;
- Accidents with helicopters; and
- Accidents caused by sabotage, terrorism and military actions.

According to this study, there were 25 runway incursion accidents in 70 million flights. The corresponding accident rate is $3.57 \times 10^{-7}$ per flight. This implies that 2.23% of all runway incursions with significant risk lead to an accident.

To analyse the causes and effects, a set of runway incursions on airports controlled by ATC from a western-European country in the period 1995-2001 has been studied. The set involved 259 runway incursions. From this set only incursions are considered where there was a possible collision. For example, unauthorised entries of a runway with no other traffic were excluded from the data sample. In total 170 runway incursion remained. It is assumed that this set is representative for class A and B runway incursions in the ECAC area.
In the analysis the two parties involved in the incursion and their flight phases are determined: landing aircraft, aircraft in take-off, taxiing aircraft (e.g. crossing the runway) or a vehicle (including a tow truck). The take-off phase is considered to start when the aircraft enters the runway to line-up for departure (authorised or not). The landing phase ends when the aircraft has left the runway. If it was not clear from the incident description if an aircraft entered the runway to take-off or to cross, it is assumed that the aircraft was crossing the runway, i.e. that the aircraft was taxiing.

Furthermore, it was determined who resolved the conflict: ATC or the flight crew. If ATC is notified by the crew or if ATC did not take any evasive action, but no collision occurred, the resolution of the conflict is contributed to the flight crew or vehicle driver.

Table 38: The number of runway incursions resolved by ATC or the flight crew per conflict type

<table>
<thead>
<tr>
<th>Type of conflict</th>
<th>ATC resolved conflict</th>
<th>Flight crew (or driver) resolved conflict</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing - Landing</td>
<td>2</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Landing - Take-off</td>
<td>39</td>
<td>10</td>
<td>49</td>
</tr>
<tr>
<td>Landing - Vehicle</td>
<td>30</td>
<td>12</td>
<td>42</td>
</tr>
<tr>
<td>Landing - Crossing</td>
<td>24</td>
<td>5</td>
<td>29</td>
</tr>
<tr>
<td>Take-off - Take-off</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Take-off - Vehicle</td>
<td>13</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Take-off - Crossing</td>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>112</strong></td>
<td><strong>58</strong></td>
<td><strong>170</strong></td>
</tr>
</tbody>
</table>

In this ESD, the risk is calculated from an aircraft perspective. Therefore, the above results are transformed into the number of times (per flight phase) an aircraft was involved in a runway incursion. In 102 cases (60%), the runway incursion involved two aircraft. In 68 (40%) runway incursions a vehicle and an aircraft were involved. In total, 272 aircraft were involved in 170 runway incursion situations. The probability of a class A or B runway incursion for a particular aircraft is: $272/170 \times 1.60 \times 10^{-5} = 2.58 \times 10^{-5}$ per flight. Similarly, the probability of an aircraft experiencing a collision due to a runway incursion is $272/170 \times 3.57 \times 10^{-7} = 5.71 \times 10^{-7}$ per flight.

Table 39: The number of runway incursions resolved by ATC or flight crew per flight phase

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>ATC resolved conflict</th>
<th>Flight crew (or driver) resolved conflict</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>25</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>Take-off</td>
<td>59</td>
<td>38</td>
<td>97</td>
</tr>
<tr>
<td>Landing</td>
<td>97</td>
<td>43</td>
<td>140</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>181</strong></td>
<td><strong>91</strong></td>
<td><strong>272</strong></td>
</tr>
</tbody>
</table>
By distinguishing between the different flight phases, using the ratios as given in Table 39, the following probabilities are derived.

Table 40: Summary of runway incursion probabilities per flight phase

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>Number of occurrences</th>
<th>Probability of runway incursion</th>
<th>Probability of collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>35</td>
<td>$3.30 \times 10^{-6}$</td>
<td>$7.41 \times 10^{-8}$</td>
</tr>
<tr>
<td>Take-off</td>
<td>97</td>
<td>$9.14 \times 10^{-6}$</td>
<td>$2.05 \times 10^{-7}$</td>
</tr>
<tr>
<td>Landing</td>
<td>140</td>
<td>$1.32 \times 10^{-5}$</td>
<td>$2.96 \times 10^{-7}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>272</strong></td>
<td><strong>$2.56 \times 10^{-5}$</strong></td>
<td><strong>$5.76 \times 10^{-7}$</strong></td>
</tr>
</tbody>
</table>

It was computed before that 97.78% of all incidents are resolved by ATC or the flight crew. From the ratio between the number of conflicts resolved by ATC and by the flight crew as given in Table 39, the conditional probabilities are derived. For an aircraft in landing, $97/140 = 69.3\%$ of all conflicts are resolved by ATC. So, the probability that ATC resolves the conflict is $97.78\% \times 69.3\% = 0.677$. The corresponding probability that ATC fails to resolve the conflict is $3.23 \times 10^{-1}$. The probability that the flight crew or the vehicle driver fails to resolve the conflict given that ATC does not resolve the conflict becomes $0.0223 / (1-0.677) = 6.92 \times 10^{-2}$. The other flight phases are calculated in a similar way. The results are given in the table below.

Table 41: Summary of conditional probabilities of the pivotal events per flight phase

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>Probability that ATC fails to resolve conflict</th>
<th>Probability that flight crew fails to resolve conflict</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>$3.02 \times 10^{-1}$</td>
<td>$7.39 \times 10^{-2}$</td>
</tr>
<tr>
<td>Take-off</td>
<td>$4.05 \times 10^{-1}$</td>
<td>$5.50 \times 10^{-2}$</td>
</tr>
<tr>
<td>Landing</td>
<td>$3.23 \times 10^{-1}$</td>
<td>$6.91 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Accident type: collision on ground.
Flight phases: taxi
Initiating event: incorrect presence of aircraft/vehicle on runway in use
Accident type: collision on ground.
Flight phases: take-off
Initiating event: incorrect presence of aircraft/vehicle on runway in use

Accident type: collision on ground.
Flight phases: landing
Initiating event: incorrect presence of aircraft/vehicle on runway in use
32 ESD 33 – Cracks in aircraft pressure cabin

Accident type: structure overload.
Phases: take-off, initial climb, en route, approach and landing.
Initiating event: cracks in aircraft pressure boundary

32.1 Definitions
The various events (initiating and pivotal) and end states are defined as follows:

Cracks in aircraft pressure boundary (initiating event)
This event covers a crack in an aircraft pressure boundary. This crack can vary in location and size and it develops over time [Salamanca & Quiroz, 2005]. For this ESD, the focus is on those cracks that are, or should have been, detected during maintenance or line checks.

Explosive decompression (pivotal event)
In the event of an explosive decompression, the aircraft cabin quickly decompresses, resulting in major structural failure to the aircraft fuselage. Although there have been cases where aircraft landed ‘safely’ following an explosive decompression, most notably Aloha Airlines flight 243 on 28 April 1988, it is assumed here that a explosive decompression results in the end-state ‘in flight break-up’.

In-flight break-up (end state)
Severe damage to the aircraft caused by an explosive decompression. This could be a crash of the aircraft but also damage without crashing, but which fits the ICAO Annex 13 definition of an accident.

Aircraft damage / aircraft continues flight
This is the outcome of a crack in the aircraft pressure boundary which did not cause an explosive decompression. This could mean that there has been decompression of the pressure cabin but not of an explosive nature and it did not result in an accident, or nothing happened at all such that the aircraft safely continued the flight.
32.2 Quantification
In [van Es & Post 2006] ‘outcome ratios’ have been calculated for a number of unsafe conditions. These outcome ratios express the conditional probability that given the occurrence being assessed, a particular aircraft level unsafe outcome will result. Among the unsafe conditions studied, the following two are useful for the quantification of ESD 33:
- Cracks in the pressure boundary;
- Cabin decompression or failure to pressurize.

The frequency of occurrence of these two unsafe conditions and the unsafe outcomes of these conditions have been assessed by means of a combination of statistical data from the NLR Air Safety Database and background technical knowledge. The selection criteria for data analysis that were used by [van Es & Post, 2006] are the following:
- Fixed wing aircraft with a take-off mass of 5,700 kg or higher;
- Western-built aircraft;
- No business jet aircraft;
- No occurrences due to unlawful actions; and

Cracks in aircraft pressure boundary
An estimate of the frequency of occurrence of the initiating event “cracks in the pressure boundary” is based on service difficulty reports (see Appendix A). The dataset of service difficulty reports contains descriptions of all occurrences where ‘reportable’ cracks have been detected during maintenance or line checks.

The dataset contains at total of 3050 occurrences of “cracks in aircraft pressure boundary” and covers a total of 153.5 million flights. The associated frequency is $1.99 \cdot 10^{-5}$ per flight.

In-flight break-up
According to the NLR Air Safety database, there have been 4 accidents that where initiated by ‘cracks in the aircraft pressure cabin’ and meeting the data inclusion criteria listed in the previous section. The corresponding number of flights is 438.2 million, which results in a frequency of $9.12 \cdot 10^{-9}$.

Explosive decompression
The conditional probability of an explosive decompression if there are cracks in the aircraft pressure boundary is $9.12 \cdot 10^{-9} / 1.99 \cdot 10^{-5} = 4.58 \cdot 10^{-4}$. 
Table 42: Summary of the probabilities for each end state

<table>
<thead>
<tr>
<th></th>
<th>Estimated probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracks in the pressure boundary</td>
<td>$1.99 \times 10^{-5}$</td>
</tr>
<tr>
<td>In-flight break-up</td>
<td>$9.12 \times 10^{-9}$</td>
</tr>
<tr>
<td>Aircraft damage</td>
<td>$1.99 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

### 33 ESD35 - Flight crew decision error/operation of equipment error (CFIT)

#### Scenario type: controlled flight into terrain.
Phases: initial climb, en route, and approach.
Initiating event: flight crew decision error/operation of equipment error.

![Event Sequence Diagram](image)

**(1) CRM failure: failure in cross checking, monitoring, challenging
(2) GPWS not installed, early model or system malfunction**

### 33.1 Definitions

This event sequence diagram describes Controlled Flight Into Terrain (CFIT) accidents. CFIT accidents are those in which an aircraft, under the control of the crew, is flown into terrain, obstacles or water, with no prior awareness on the part of the crew of the impending disaster [Khatwa and Roelen 1997].

**Flight crew decision error / operation of equipment error**

This initiating event describes any decision error or operation of equipment error that results in a deviation of the aircraft’s flight path from a previously established safe route.

**Flight crew CRM failure**

A failure by a member of the flight crew in cross checking, monitoring or challenging the other flight crew member(s).

**Flight crew loss of situational awareness**

The flight crew’s mental picture of the position of the aircraft in the horizontal or vertical plane does not correspond with the actual aircraft position.
GPWS failure
This event describes an occurrence where a Ground Proximity Warning System (GPWS) or Terrain Avoidance Warning System (TAWS) is not installed, or the GPWS/TAWS is switched off, or the GPWS/TAWS is not functioning properly.

Flight crew fails to execute GPWS manoeuvre
If a GPWS “terrain, terrain” or “pull up, pull up” warning occurs the flight crew should immediately and simultaneously advance the power levers to the maximum available while disengaging the auto throttle and rotate smoothly to a target pitch attitude of 15 degrees while disconnecting the autopilot. A wing-level pull-up should be made unless terrain being avoided can be seen [Simmons 1998].

Relevant dates on Ground Proximity Warning Systems
- Early 1974 introduction of first GPWS.
- Since May 1994, FAR 135.153 requires GPWS installation for aircraft with more than 10 seats.
- EGWPS introduced in 1996.
- ICAO SARP Annex 6, Part I, Standard 6.15.6 requires for all aircraft a TAWS Class A equivalent from January 2003.
- JAR-OPS 1.665(c)(2) TAWS Class A required from January 2005

33.2 Quantification

Initiating event
The initiating event has been estimated from the fourth CATS interim report [CATS, 2006]. According to that report, analysis of controlled flight towards terrain incidents recorded in the British Airways BASIS system during 1997-2001 shows that the probability of occurrence of ‘flight towards terrain commanded’ is $6.10 \times 10^{-5}$ per flight. The same probability is used here as probability of the initiating event ‘flight crew decision error / operation of equipment error’.

Pivotal event flight crew loss of situational awareness
Operational data from a large western European airline has been used to estimate the probability of the pivotal event ‘flight crew loss of situational awareness’. The data set contains information of 286,753 flights from the year 2001. In this set, 9 ‘EGWPS terrain closure incidents’ have been reported. None of these resulted in a CFIT accident. It is assumed that ‘EGPWS terrain closure incidents’ are by definition similar to ‘flight crew loss of situational awareness’. This probability can then be estimated at $3.14 \times 10^{-5}$ per flight. This frequency is similar to that presented in [Bateman, 2003].
The conditional probability of ‘CRM failure’ in the event of a ‘flight crew decision error / operation of equipment error’ is $3.14 \cdot 10^{-5} / 6.10 \cdot 10^{-5} = 0.515$.

**GPWS failure and failure to execute GWPS manoeuvre**

For quantification of the pivotal events ‘GPWS failure’ and ‘failure to execute GPWS manoeuvre’, the accident data sample was limited to the 10 most recent years for which accurate data was available. This was done because of the significant advances that have been made in GPWS systems over the past decades. These changes are not only technical, but also regulatory. The data sample was restricted to western built large commercial jet aircraft in the period 1993-2002. In this period 40 CFIT accidents have occurred. Information from accident investigation reports (if available) and [Bateman, 2000] and [Bateman, 2003] was combined to determine for each of these accidents whether the aircraft involved was equipped with GPWS and whether the GPWS (if installed) provided a timely warning. Results are summarised in Table 43.

**Table 43: Number of accidents for the different levels of GPWS equipment**

<table>
<thead>
<tr>
<th>Number of accidents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Not GPWS equipped</td>
<td>2</td>
</tr>
<tr>
<td>GPWS equipped</td>
<td>32</td>
</tr>
<tr>
<td>Terrain warning</td>
<td>11</td>
</tr>
<tr>
<td>No terrain warning</td>
<td>12</td>
</tr>
<tr>
<td>Unknown</td>
<td>9</td>
</tr>
<tr>
<td>Unknown</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

From the 11 accidents in which a terrain warning was given, 4 warnings were generated 6 seconds or less before impact. As a typical response time to a GPWS warning is 6 seconds [Bateman 2003], these warnings are regarded as too late because the pilot did not have sufficient time to respond. This corresponds to 36%. In the other 64% of the accidents in which a terrain warning was given more than 6 seconds before the impact and the flight crew responded too late or even did not respond at all.
Table 44: Annual distribution of GPWS and EGPWS equipped aircraft of the western built large commercial jet fleet Source: [Bateman 2003]

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of flights</th>
<th>Not equip</th>
<th>GPWS</th>
<th>EGPWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>17,502,370</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
</tr>
<tr>
<td>1994</td>
<td>18,247,064</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
</tr>
<tr>
<td>1995</td>
<td>18,978,107</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
</tr>
<tr>
<td>1996</td>
<td>19,664,925</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
</tr>
<tr>
<td>1997</td>
<td>20,200,655</td>
<td>3%</td>
<td>90%</td>
<td>7%</td>
</tr>
<tr>
<td>1998</td>
<td>20,696,493</td>
<td>2%</td>
<td>78%</td>
<td>19%</td>
</tr>
<tr>
<td>1999</td>
<td>21,595,794</td>
<td>2%</td>
<td>69%</td>
<td>29%</td>
</tr>
<tr>
<td>2000</td>
<td>22,157,667</td>
<td>2%</td>
<td>67%</td>
<td>31%</td>
</tr>
<tr>
<td>2001</td>
<td>23,015,410</td>
<td>2%</td>
<td>53%</td>
<td>45%</td>
</tr>
<tr>
<td>2002</td>
<td>22,421,310</td>
<td>1%</td>
<td>45%</td>
<td>54%</td>
</tr>
<tr>
<td>2003</td>
<td>23,084,147</td>
<td>1%</td>
<td>26%</td>
<td>73%</td>
</tr>
<tr>
<td>Total</td>
<td>227,563,942</td>
<td>4,945,966</td>
<td>164,865,523</td>
<td>57,752,453</td>
</tr>
</tbody>
</table>

Table 44 and Figure 11 show the number of aircraft with equipped with EGWPS and GPWS [Bateman 2003]. On total there are 227.6 million flights in that period performed by western-built large commercial jet aircraft. It is estimated that 4.9 million flights are performed by non-GPWS equipped aircraft, 164.9 million flights by GPWS equipped aircraft and 57.7 million flights by EGPWS equipped aircraft.
Table 45: Accident probability for non-GPWS, GPWS and EGPWS equipped aircraft

<table>
<thead>
<tr>
<th></th>
<th>Accidents</th>
<th>Flights</th>
<th>Probability per flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-GPWS equipped</td>
<td>2</td>
<td>4.9 million</td>
<td>4.04·10⁻⁷</td>
</tr>
<tr>
<td>GPWS equipped aircraft</td>
<td>32</td>
<td>164.9 million</td>
<td>1.94·10⁻⁷</td>
</tr>
<tr>
<td>EGPWS equipped aircraft</td>
<td>0</td>
<td>57.7 million</td>
<td>&lt;1.70·10⁻⁸</td>
</tr>
</tbody>
</table>

For the purpose of this model, it is assumed that all aircraft are equipped with EGPWS, i.e. the CFIT accident probability is estimated at 1.70·10⁻⁸ per flight.

The probability of a (E)GPWS system malfunction is estimated by using the database of service difficulty reports (SDR), see Appendix A. According to the SDR database, there are 92 reported GPWS failures (ATA 3444) for a total exposure of 2.16·10⁸ flights, a failure frequency of 4.26·10⁻⁷ per flight.

The probability that the flight crew fails to properly execute a GPWS manoeuvre can be calculated from the probabilities for ‘flight crew loss of situational awareness’ (3.14·10⁻⁵), ‘GPWS failure’ (4.26·10⁻⁷) and ‘collision with ground’ (1.70·10⁻⁸). The probability that the flight crew fails to successfully execute the GPWS manoeuvre becomes 5.41·10⁻⁴.

Table 46: Summary of the results for ESD 35

<table>
<thead>
<tr>
<th>Event</th>
<th>Probability (per flight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight crew decision error/operation of equipment error</td>
<td>6.10·10⁻⁷</td>
</tr>
<tr>
<td>Flight crew CRM failure</td>
<td>5.15·10⁻¹</td>
</tr>
<tr>
<td>Flight crew has lost situational awareness = YES</td>
<td>3.14·10⁻⁵</td>
</tr>
<tr>
<td>EGWPS failure</td>
<td>4.26·10⁻⁷</td>
</tr>
<tr>
<td>Flight crew fails to execute GPWS manoeuvre</td>
<td>5.41·10⁻⁴</td>
</tr>
</tbody>
</table>

8 In Bateman 2003 the probability of a CFIT accident by an EGPWS equipped aircraft is estimated at 1.1·10⁻⁸ per flight.
Accident type: controlled flight into terrain.
Flight phases: initial climb, en route, and approach.
Initiating event: flight crew decision error/operation of equipment error.

- Flight crew decision error/operation of equipment
  - yes: Flight crew CRM failure
  - no

- Flight crew loss of situational awareness
  - 4.26 x 10^7

- GPWS failure
  - 1.34 x 10^11

- Collision with ground
  - 1.7 x 10^5

- Aircraft continues flight
  - 3.14 x 10^5

- Flight crew fails to execute GPWS manoeuvre
  - 5.41 x 10^4

- Collision with ground
  - 0

- Aircraft continues flight
  - 2.96 x 10^5

- Aircraft continues flight
References


Appendix A  Description of data sources

For many years NLR maintains a large database with data related to aviation safety, called the NLR Air Safety Database. Air safety data are all data that characterise activities of the air transport system. The NLR Air Safety Database is basically a collection of databases containing different types of data. It contains detailed information on accidents and incidents of fixed wing aircraft from 1960 onward. Currently, it contains information on more than 34,000 accidents and serious incidents that occurred worldwide. The NLR Air Safety Database includes the databases described in sections A.1 through A.7. Besides the data described here, the NLR Air Safety Database also contains a large collection of non-accident related data. These data include: airport databases, flight exposure data (hours and flights at the level of airlines, aircraft type, and airports), weather data, and fleet data.

A.1  FAA Service Difficulty Reports (SDRs)

The objective of FAA's SDR program is to correct conditions adversely affecting aircraft safety. To do this, FAA collects mechanical reliability reports of US airlines; analyzes the reports; and disseminates trends, problems, and safety alert information to the aviation industry and FAA. FAR §§ 121.703 and FAR 135.415 require that holders of certificates issued under part 121 (air carriers) or part 135 (air taxi), respectively, submit reports to the FAA on certain failures, malfunctions, or defects of specific systems and on all other failures, malfunctions, or defects that have endangered or may endanger the safe operation of an aircraft. In addition, FAR §§ 145.63 and 145.79 contain provisions for certificated US and non-US repair stations, respectively, to report to the FAA serious defects in, or other recurring unairworthy conditions of, an aircraft, powerplant, propeller, or component. Under FAR 121.703, an airline must report each aircraft malfunction incident within 72 hours to the FAA Flight Standards District Office responsible for that airline. After an initial review, the district office mails reports to FAA'S National Safety Data Branch in Oklahoma City, Oklahoma, which screens and enters them into a national computerized data base.

The FAA SDR program has been criticised in the past [GAO, 1991]. Some of the criticism is irrelevant for the purpose of this study. However, one of the points of criticism considers underreporting, and this is an important issue. The number of SDRs submitted by airlines operating similar aircraft varies significantly among airlines. Airline officials attribute reporting differences to vague reporting requirements, leading to varying interpretations of what should be reported and to airlines’ concerns over the public’s access to malfunction reports in accordance with the Freedom of Information Act. Concerned about public disclosure of SDR data, some airlines are reluctant to submit malfunction reports to FAA. Differences among
airlines’ reporting practices would diminish the quality of the data because they would not reflect the actual occurrence of mechanical malfunctions.

SDR data is limited to US airlines only. Because the level of safety of US airlines is similar to that of EASA operators [IVW, 2004], it is assumed that SDR data is also representative for European air carriers.

**Research approach**
Aircraft systems were selected on ATA chapter. The main source of information was the database of Service Difficulty Reports (SDRs). The time period 1985-2003 was selected as representative of current aviation. This dataset was large enough to provide a statistically robust sample, even on subsystem level. Information on the failed system and the flight phase during which the failure took place were obtained unaltered from the SRD database.

**Search criteria**
The analysis was limited to air carrier operations, thereby excluding general aviation. Data from 1985 through 2003 was considered. Only events which resulted in precautionary procedures were included in the data sample. Finally, events which were the result of a false warning were excluded. The total data sample included 123,278 reports. The associated number of flights is 224 million.

By limiting the data sample to occurrences that resulted in precautionary procedures, the analysis is restricted to significant occurrences. This has two advantages: a) the reliability of the data is better, and b) only events that really have a potentially adverse effect on safety are considered.

**A.2 Air Safety Reports (ASRs)**
NLR has collected several databases with Air Safety Reports (ASRs) from different European and non-European airlines. ASRs are reports by pilots of unsafe occurrences and hazardous situations that occurred during operations. All data concern commercial operations with ‘western’ aircraft of more than 5700 kg maximum take-off weight and cover 9 million flights between 1998 and 2004.

**A.3 Airclaims database**
The Airclaims database provides brief details of all known major operational accidents to jet and turboprop aircraft worldwide. The subset of the Airclaims database purchased by the NLR contains data and descriptive information about all known airline accidents since 1952. The
accident details have been drawn from many sources both official and unofficial (including press reports). Therefore, they may be incomplete or otherwise incorrect.

A.4 **ICAO ADREP**
The ICAO ADREP database is based on the accident/incident data report supplied to the ICAO organization. ADREP is an acronym for Accident Data REPorting system. The database includes worldwide accident/incident data of aircraft (fixed wing and helicopter) heavier than 5,700 kg since 1970.

A.5 **NTSB aviation accident database**
The NTSB aviation accident database contains information from 1962 and later about civil aviation accidents and selected incidents within the United States, its territories and possessions, and in international waters. Generally, a preliminary report is available online within a few days of an accident. Factual information is added when available, and when the investigation is completed, the preliminary report is replaced with a final description of the accident and its probable cause. Full narrative descriptions may not be available for dates before 1993, cases under revision, or where NTSB did not have primary investigative responsibility.

A.6 **FAA AIDS database**
The FAA Accident/Incident Data System (AIDS) database contains incident data records for all categories of civil aviation in the US. Incidents are events that do not meet the aircraft damage or personal injury thresholds contained in the National Transportation Safety Board (NTSB) definition of an accident. For example, the database contains reports of collisions between aircraft and birds while on approach to or departure from an airport. While such a collision may not have resulted in sufficient aircraft damage to reach the damage threshold of an NTSB accident, the fact that the collision occurred is valuable safety information that may be used in the establishment of aircraft design standards or in programs to deter birds from nesting in areas adjacent to airports. The FAA AIDS database contains incidents that occurred between 1978 and the present. The information contained in AIDS is gathered from several sources including incident reports on FAA Form 8020-5. The data are presented in a report format divided into the following categories: Location Information, Aircraft Information, Operator Information, Narrative, Findings, Weather/Environmental Information, and Pilot Information and other data fields.

A.7 **Aviation Safety Reporting System**
The Aviation Safety Reporting System (ASRS) is a confidential incident reporting system in the United States. Flight crew, air traffic controllers, cabin crew, mechanics, ground personnel and others involved in air traffic operations can submit reports to the ASRS if they are involved in,
or observe, an incident or a situation in which aviation safety was compromised. All submissions are voluntary. The ASRS is operated by NASA. This ensures that the identity of the reporter and parties involved will not be released to the authorities, and consequently increases the willingness to report. To further stimulate the reporting process, the system is non-punitive. ASRS information is not used against reporters in enforcement actions. Unintentional violations of federal aviation regulations that are reported are waived of fines and penalties. The ASRS contains reports from 1975 to present, primarily from US reporters, not restricted to a specific class of operations or aircraft.