NLR Air Transport Safety Institute
Research & Consultancy

Executive summary

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

Problem area
The Netherlands Ministry of Transport has initiated a research effort to develop a causal model for air transport safety (CATS). The purpose of the model is to represent the causes of air transport accidents and the safeguards that are in place to prevent them.
In a previous study, Event Sequence Diagrams (ESDs) have been developed and quantified, which describe various accident scenarios. An ESD consists of an initiating event, pivotal events and end states.
A next step in the process is to identify, qualitatively describe and quantify dependencies between the ESD end states and initiating events of other ESDs.

Description of work
In the ESDs, degraded situations (yellow end states) are indicators of dependencies between different ESDs.
A degraded situation exists when an accident scenario does not result in an accident, but the aircraft's state has changed (like a take-off with ice on the wings). As a consequence, the probability of other scenarios may have changed.
The dependencies are identified by listing all ESD end states in which a degraded situation exists. The nature of the degraded situation and its influence on initiating events of other scenarios is qualitatively described. The dependencies are quantified by calculating the conditional probability using incident data.

Results and conclusions
42 dependencies between end states in which a degraded situation exists and initiating events of other accident scenarios have been identified, qualitatively described and quantified. Future research has to derive the dependencies between end states and pivotal events within other accident scenarios.

Applicability
The numerical estimates provided in this report apply to 'average' world-wide commercial aviation. For particular applications of the model, it may be necessary to derive probability estimates that take into account local effects.

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ABBREVIATIONS

AIDS	Accident/Incident Data System
ASR	Air Safety Report
ASRS	Aviation Safety Reporting System
ATA	Air Transport Association
CATS	Causal model for Air Transport Safety
ESD	Event Sequence Diagram
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FOD	Foreign Object Damage
Ft	Feet
Kts	Knots
MTOW	Maximum Take-off Weight
NTSB	National Transportation Safety Board
SDR	Service Difficulty Report

1 INTRODUCTION

1.1 BACKGROUND

The Netherlands Ministry of Transport, Public Works and Water Management has initiated a research effort to develop a causal model for air transport safety (CATS) [Ale et al 2006, Ale et al 2007]. The purpose of the model is to describe the air traffic system and its safety functions in such a way that it is possible to analyse risk reduction alternatives and to serve as a means of communication between experts and managers within the industry. The model combines Event Sequence Diagrams (ESDs), Fault Trees and Bayesian Belief Nets into a single structure. The ESDs are used to represent accident scenarios like e.g. abrupt manoeuvre, uncontrolled collision with ground, controlled flight into terrain, forced landing, mid-air collision, collision on ground, structure overload, and fire/explosion. A total of 33 generic accident scenarios were developed [Roelen & Wever, 2005]. An ESD consists of an initiating event, pivotal events and end states. Where necessary, the initiating and pivotal events are detailed in a sub model which can be a Fault Tree or a Bayesian Belief Net. In the CATS model, the ESDs are quantified by estimating the probability of occurrence of each event and end state using historical data [Roelen at al, 2006].

Within the CATS model there are three types of scenario end states:
- Accident;
- Degraded state;
- Normal.

In the graphical representation of the model, these three types are colour coded. An accident is red, a degraded state is yellow and a normal state is green. The integrated 'backbone' model combines all scenarios. To successfully complete a flight from departure gate to arrival gate, the aircraft has to circumvent or 'survive' each scenario. Probabilistically, most flights will circumvent all scenarios, i.e. none of the possible initiating event will occur.

If an initiating event occurs, a flight can still recover to a normal (green) state at certain pivotal events. If a flight has recovered to a green state, it is assumed that there are no effects on the rest of the flight, i.e. the fact that the flight has experienced the initiating event and following pivotal events has no effect on the probability of occurrence of any of the other initiating events. If a flight enters a scenario that results in an accident (red end state) it is assumed that the flight has ended, i.e. the probability of occurrence of the other initiating events is no longer relevant. If a flight enters a scenario that results in a degraded (yellow) state, the aircraft has 'survived' the scenario without the occurrence of an accident, but the aircraft's state has changed. As a consequence, the probability of occurrence of the other initiating events may have changed as well. As an example, if an aircraft initiates a take-off while the wing is contaminated with snow or ice, the take-off might still be successful. ESD 6 'aircraft takes off with contaminated wing' is then completed without an accident, but the wing contamination will influence the probability of occurrence of other scenarios. The ice may detach from the wing during climb and be ingested by the engines, causing engine failures[1)]. Yellow states are by definition indicators of dependencies between different accident scenarios.

1.2 Objective

The objective of this report is to identify, describe and quantify dependencies between the event sequence diagrams that are described in [Roelen et al, 2006].

1.3 Research approach

The scope is 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 is used as a primary source of data. Appendix B provides an overview of the types of data collected in this database.

The general approach is to list all 'yellow' end states for each of the event sequence diagrams, describe the nature of the 'degradation' and then describe the influences of these degradations on the initiating events of other scenarios. Some end states will not have an influence on the remainder of the flight, but will have an (indirect) influence on the next flight because unscheduled maintenance will have to be conducted. Although (the effect of) unscheduled maintenance has not yet been incorporated in the model, these influences are described in this document.

[1)] This is what happened to SAS flight 751, a McDonnell-Douglas MD-81 that departed Stockholm's Arlanda airport on 27 December 1991.

The dependencies between yellow end states and initiating events of other scenarios are quantified by calculating the probability of occurrence from incident data.

There will also be dependencies in the more detailed layers of the model, which can be a Fault Tree or a Bayesian Belief Net. However, such detailed interdependencies are not considered in this report.

1.4 Contents of this report

Chapter two of this report provides the qualitative description of dependencies between yellow end states and initiating events of other scenarios. In chapter three all identified dependencies are quantified. Definitions of each dependency are provided and the conditional probabilities are derived.

2 DESCRIPTION OF DEPENDENCIES

This chapter describes all yellow end states of the different accident scenarios and describes their influence on initiating events of other scenarios. Appendix A provides an overview of all ESD dependencies that are identified.

2.1 ESD 1 Aircraft system failure

Yellow end state scenarios:

a) Aircraft system failure → flight crew rejects take-off → V < V1 → maximum braking achieved → *aircraft stops on runway.*
b) Aircraft system failure → flight crew does not reject take-off → *aircraft continues take off.*

Description

In end state (a) the aircraft has successfully aborted the flight because of a system failure. In end state (b) the aircraft has taken-off and continues the remainder of the flight while one of the aircraft's systems has failed. All systems which failure could result in a rejected take-off are considered, with the exception of engine failures or system failures that could result in directional control problems. This includes the following systems:

- Flaps
- Drag control
- Instruments
- Landing gear
- Stall warning
- Pneumatics
- Doors
- Other All systems that are not taken into account in the items listed above, with the exception of engine related failure, directional control related system failures and pitch control related system failures.

Influence on other scenarios

End state (a) influences a next flight because the aircraft system failure will require unscheduled maintenance.

End state (b) influences a series of other scenarios. The presence, during flight, of a failure of one of the aircraft's systems will influence the probability of occurrence of all scenarios in which aircraft systems play a role in the initiating event.

ESD 6 Aircraft takes off with contaminated wing.
The initiating event 'aircraft takes off with contaminated wing' can be influenced by a failure of the wing anti-ice system.

ESD 11 Fire onboard aircraft.
The initiating event 'fire onboard aircraft' can be influenced by a system failure causing an on-board fire.

ESD 12 Flight crew spatially disoriented.
The initiating event 'flight crew member spatially disoriented' can be influenced by a system failure causing incorrect presentation of the aircraft's attitude to the flight crew.

ESD 13 Flight control system failure.
The initiating event 'flight control system failure' can be influenced by a system failure causing a failure of the flight control system during later phases of the flight (e.g. loss of hydraulic pressure).

ESD 14 Flight crew incapacitation.
The initiating event 'flight crew incapacitation' can be influenced by a failure of the aircraft to pressurize, either because of a failure of the pressurisation system or because of a leak in the aircraft's pressure cabin (e.g. malfunctioning door, defective window).

ESD 15 Anti-ice/de-ice system not operating.
The initiating event 'ice accretion on aircraft in flight' can be influenced by a failure of the aircraft's anti-ice or de-ice system (e.g. electrical, pneumatic).

ESD 16 Flight instrument failure.
The initiating event 'flight instrument failure' can be influenced by a system failure causing incorrect presentation of airspeed, altitude or attitude in the aircraft.

ESD 18 Single engine failure in flight.

The initiating event 'single engine failure in flight' can be influenced by a system failure causing the engine to flame out or overheat (e.g. fuel system, oil system).

ESD 28 Single engine failure during landing

The initiating event 'single engine failure during landing' can be influenced by a system failure causing the engine to flame out or overheat (e.g. fuel system, oil system).

ESD 29 Thrust reverser failure.

The initiating event 'thrust reverser failure' can be influenced by a system failure causing the engine to flame out or overheat (e.g. fuel system, oil system), or by failure of the propeller pitch control.

2.2 ESD 2 ATC EVENT

Yellow end state scenario:

a) Air traffic related event → flight crew does not reject take-off → *aircraft continues take-off.*

Description

End state (a) describes a situation where an aircraft has taken off while there is an ATC related occurrence that could have resulted in a decision to reject the take-off. Excluded are runway incursions, as these are covered in ESD 32. Examples of ATC events are possible separation infringements with another departure or with a missed approach on another runway, or an instruction by ATC to abort the take-off because of the presence of birds in the vicinity of the runway.

Influence on other scenarios

ESD 31 Aircraft are positioned on collision course.

The initiating event 'aircraft are positioned on collision course' can be influenced by an ATC event if it involves possible separation infringements with a departure from another runway, a missed approach at another runway or an approach to another runway.

2.3 ESD 3 Aircraft handling by flight crew inappropriate

This ESD has no yellow end states.

2.4 ESD 4 Aircraft directional control system related system failure

Yellow end state scenarios:

a) Aircraft directional control related system failure → flight crew rejects take-off → V < V1 → flight crew maintains control → maximum braking achieved → *aircraft stops on runway.*
b) Aircraft directional control related system failure → flight crew does not reject take-off → flight crew maintains control → *aircraft continues take-off.*

Description

In end state (a) the aircraft has successfully aborted the flight because of a directional control-related system failure. End state (b) describes a situation where an aircraft has taken off while there is a (partial) failure of the directional control system. This may include failures of the aileron and aileron controls, rudder and rudder controls, tyres, and nose wheel steering. The failure itself will also require unscheduled maintenance activities after the flight.

Influence on other scenarios

End state (a) influences a next flight because the aircraft system failure will require unscheduled maintenance.
End state (b) influences the ability of the flight crew to maintain control of the aircraft during flight or during the landing roll. Therefore, end state (b) may influence the following scenarios.

ESD 13 Flight control system failure.
The initiating event ‘flight control system failure’ can be influenced if the directional control problem is related to the flight control system (aileron and rudder).

ESD 27 Aircraft directional control related system failure during landing.
The initiating event ‘aircraft directional control related system failure during landing’ can be influenced if the system failure is not cleared after taking-off.

2.5 ESD 5 Incorrect configuration

Yellow end state scenarios:

a) Incorrect configuration → take-off configuration warning → flight crew does not reject take-off → *aircraft continuous take-off.*
b) Incorrect configuration → no take-off configuration warning → aircraft stalls after rotation → flight crew regains control → *aircraft continues flight.*
c) Incorrect configuration → no take-off configuration warning → aircraft does not stall after rotation → *aircraft continues flight.*

Description

All three end states describe a situation where an aircraft has taken off while the aircraft was not properly configured. An incorrect configuration includes one of 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
- Main landing gear not aligned
- Rudder trim not centred
- Flight control system not properly set (e.g. yaw damper not switched on).

In end state (a) the flight crew has ignored a take-off configuration warning during the take-off roll. In end state (b) the take-off configuration warning did not sound and the aircraft stalls immediately after rotation, but the flight crew is able to maintain control. In end state (c) the take-off configuration warning did not sound, but the aircraft did not stall after rotation. In all these cases the incorrect configuration could be the result of a technical failure of (elements of) the flight control system.

Influence on other scenarios

ESD 11 Fire onboard aircraft.

The initiating event 'fire onboard aircraft' can be influenced by an overheated parking braking that was not released prior to take-off.

ESD 13 Flight control system failure.

The initiating event 'flight control system failure' is influenced if the incorrect configuration is the result of a (technical) failure of the flight control system.

The rejected take-off may require unscheduled maintenance after the aircraft has come to a stop on the runway.

2.6 ESD 6 Aircraft takes-off with contaminated wing

Yellow end state scenarios:

a) Aircraft takes off with contaminated wing → aircraft stalls after rotation → flight crew maintains control → *aircraft continues flight.*

b) Aircraft takes-off with contaminated wing → aircraft does not stall after rotation → *aircraft continues flight.*

Description

Both end states describe a situation where an aircraft commences the take-off while the aircraft wing, horizontal stabiliser, tail and/or flight control surfaces are contaminated with frost, ice, slush or snow. Such contamination can disturb the airflow over the wing and control surfaces, which may lead to an abrupt and drastic reduction of lift. The aircraft is then said to be stalled. In both end-states, the aircraft manages to take-off and start the initial climb. As the airspeed increases during the flight, the contaminant will usually shed off the aircraft surfaces. In case of ice or frost, wing bending can result in the ice breaking loose. Contaminants that detach from the aircraft surfaces may enter the engine (in case of tail mounted engines) or may hit the horizontal or vertical stabiliser, causing flight control difficulties.

Influence on other scenarios

ESD 13 Flight control system failure.

The initiating event 'flight control system failure' is influenced in case the contaminant sheds or breaks loose, hits the vertical or horizontal stabiliser and causes damage.

ESD 18 Single engine failure in flight.

The initiating event 'single engine failure' is influenced in case the contaminant sheds or breaks loose and is ingested by the engine(s). This can happen only at aircraft with engines mounted above or aft of the wing or control surfaces. Multiple engine failure is possible (common cause).

ESD 21 Aircraft mass and balance outside limits during approach.

The initiating event 'aircraft mass and balance outside limits during approach' is influenced when ice accretion on the wings increases the aircraft mass and shifts the centre of gravity beyond limits.

ESD 28 Single engine failure during landing.

The initiating event 'single engine failure during landing' is influenced in case the contaminant sheds or breaks loose and is ingested by the engine(s) during landing. This can happen only at aircraft with engines mounted above or aft of the wing or control surfaces. Multiple engine failure is possible (common cause).

2.7 ESD 7 Aircraft mass and balance outside limits during take-off

Yellow end state scenarios:

a) Aircraft mass and balance outside limits → aircraft stall after rotation → flight crew maintains control → *aircraft continues flight.*
b) Aircraft mass and balance outside limits → aircraft does not stall after rotation → *aircraft continues flight.*

Description

Both end states describe a situation where the aircraft has taken of while the centre of gravity of the aircraft or the aircraft mass differs from the flight crew's expectation to such an extent that they have to take additional action to maintain control of the aircraft, for instance by applying significantly different trim settings or large control pitch control inputs.

Influence on other scenarios

ESD 21 Aircraft mass and balance outside limits during approach.

The initiating event 'aircraft mass and balance outside limits' is influenced when the correct centre of gravity or aircraft mass cannot be restored during the flight.

2.8 ESD 8 Aircraft encounters a performance decreasing windshear after rotation

This ESD has no yellow end states.

2.9 ESD 9 Single engine failure during take-off

Yellow end state scenarios:

a) Single engine failure → flight crew rejects take-off → V < V1 → flight crew maintains control → maximum braking achieved → *aircraft stops on runway.*
b) Single engine failure → flight crew does not reject take-off → flight crew maintains control → *aircraft continues take-off.*

Description

In end state (a) the aircraft has successfully aborted the flight because of an engine failure. In end state (b) the aircraft has taken off with one failed engine. It is highly unlikely that the crew will be able to restore engine power, which means that the remainder of the flight, including approach and landing, must be executed with one engine inoperative. The failure itself will require unscheduled maintenance activities after the flight.

Influence on other scenarios

End state (a) influences a next flight because the engine failure will require unscheduled maintenance.

End state (b) influences the following scenarios:

ESD 18 Single engine failure in flight.
The initiating event 'single engine failure in flight' is influenced by a single engine failure during take-off.

ESD 28 Single engine failure during landing
The initiating event 'single engine failure during landing' is influenced by a single engine failure during take-off.

Next flight.
The failure may require unscheduled maintenance activities after the flight.

2.10 ESD 10 Pitch control problems

Yellow end state scenarios:

a) Pitch control problem → flight crew rejects take-off → V < V1 → flight crew maintains control → maximum braking achieved → *aircraft stops on runway.*
b) Pitch control problem → flight crew does not reject take-off → aircraft rotates and lifts-off → *aircraft continues flight.*

Description

For the purpose of this ESD, pitch control problems are considered as problems due to an issue of the flight control system, or mass and balance problems that result in an (initial) failure to rotate. Mass and balance problems that cause over rotation are not considered here. After take-off the pitch control problem may remain. If the problems are caused by a flight control failure it will require unscheduled maintenance activities after the flight.

Influence on other scenarios

End state (a) influences a next flight because the pitch control problem (if it is a technical problem) will require unscheduled maintenance.

End state (b) influences the following scenarios:

ESD 13 Flight control system failure.
Initiating event 'flight control system failure' is influenced if the pitch control problems are due to problems with the flight control system.

ESD 21 Aircraft mass and balance outside limits during approach.
The initiating event 'aircraft mass and balance outside limits' is influenced by 'pitch control problems' if the pitch control problems are caused by a mass and balance issue.

Next flight.
If the failure has a technical cause, unscheduled maintenance will be required.

2.11 ESD 11 Fire on-board aircraft

Yellow end state scenarios:

a) Fire onboard aircraft → flight crew fails to detect smoke/fire → fire propagates → flight crew maintains control → *aircraft continues flight damaged.*
b) Fire on-board aircraft → flight crew fails to detect smoke/fire → fire does not propagate → *aircraft continues flight damaged.*
c) Fire onboard aircraft → flight crew detects smoke/fire → flight crew fails to extinguish fire → fire propagates → flight crew maintains control → *aircraft continues flight damaged.*
d) Fire onboard aircraft → flight crew detects smoke/fire → flight crew fails to extinguish fire → fire does not propagate → *aircraft continues flight damaged.*
e) Fire on-board aircraft → flight crew detects smoke/fire → flight crew extinguishes fire → *aircraft continues flight damaged.*

Description

A fire on-board an aircraft is a very hazardous situation because the crew has only limited possibilities of extinguishing the fire and because of the destructive character of a fire. A fire can result in system failures, failure of the aircraft structure, and pilot incapacitation (e.g. due to smoke inhalation). Possible indicators of a fire are visible flames, visible smoke, burning smell, or an alert by the 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. 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.

Occurrences in which a fire leads to flight crew incapacitation, structural failure and subsequent loss of control or aircraft system failures that lead directly to loss of control are covered by ESD 11. However, there can also be situations in which the fire results in aircraft system failures that do not lead directly to a loss of control. In these cases the fire influences other scenarios. All detected fires will require unscheduled maintenance activities after the flight.

Influences on other scenarios

ESD 13 Flight control system failure.
The initiating event 'flight control system failure' is influenced if the fire results in a (partial) failure of the flight control system.

ESD 15 Anti-ice / de-ice system not operating.
The initiating event 'ice accretion in flight' is influenced if the fire results in a failure of the aircraft's anti-ice or de-ice system.

ESD 16 Flight instrument failure.
The initiating event 'flight instrument failure' is influenced if the fire results in an instrument failure.

ESD 18 Single engine failure in flight.
The initiating event 'single engine failure' is influenced if the fire results in an engine failure.

ESD 27 Aircraft directional control related system failure during landing.
The initiating event 'aircraft directional control related system failure' is influenced if the fire results in a failure of any of the aircraft's systems that affect directional controllability of the aircraft during the landing roll, such as aileron and aileron controls, rudder and rudder controls, tyres and landing gear.

ESD 28 Single engine failure during landing.
The initiating event 'single engine failure' is influenced if the fire results in an engine failure.

ESD 29 Thrust reverser failure.
The initiating event 'thrust reverser failure' is influenced if the fire results in a failure of the thrust reverser or propeller pitch control system.

Next flight.
The failure may require unscheduled maintenance activities after the flight.

2.12 ESD 12 Flight crew spatially disoriented

This ESD has no yellow end states.

2.13 ESD 13 Flight control system failure

Yellow end state scenario:

a) Flight control system failure → flight crew maintains control → *aircraft continues flight.*

Description

This end state describes a situation where the flight control system or part of it has failed, but this failure does not result in an unrecoverable loss of control during the flight. The failure itself will require unscheduled maintenance activities after the flight.

Influence on other scenarios

ESD 27 Aircraft directional control related system failure during landing. The initiating event 'aircraft directional control related system failure' is influenced if the failure affects the directional controllability of the aircraft.

Next flights

The failure may require unscheduled maintenance activities after the flight.

2.14 ESD 14 Flight crew incapacitation

This ESD has no yellow end states.

2.15 ESD 15 Anti-ice/de-ice system not operating

Yellow end state scenario:

a) Ice accretion on aircraft in flight → flight crew fails to respond appropriately to ice accretion → flight crew maintains control → *aircraft continues flight.*

Description

In end state (a) the aircraft continues the flight while there are still remains of ice on the aircraft, although the ice does not result in a loss of control. The ice could break loose and enter the engine inlets, causing engine problems.

Influence on other scenarios

ESD 18 Single engine failure in flight.

The initiating event 'single engine failure' is influenced when the ice breaks loose and is ingested by the engine(s). Multiple engine failures are possible (common cause). Contrary to the scenario 'aircraft takes-off with contaminated wing' this influence is not only relevant for aircraft with engines mounted above the wings or at the tail of the aircraft. During flight ice may also build-up at the engine intakes.

ESD 21 Aircraft mass and balance outside limits during approach.

The initiating event 'aircraft mass and balance outside limits during approach' is influenced when ice builds up on the wing, fuselage or engine intakes. This increases the aircraft mass and shifts the position of the centre of gravity. Re-configuring the aircraft for approach may affect the controllability of the aircraft.

ESD 28 Single engine failure during landing.

The initiating event 'single engine failure during landing' is influenced when the ice breaks loose and is ingested by the engine(s).

2.16 ESD 16 Flight instrument failure

Yellow end state scenario:

a) Flight instrument failure → flight crew maintains control → *aircraft continues flight.*

Description

The end state describes occurrences of flight instrument failures that do not result in an unrecoverable loss-of-control. For 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. The failure itself will require unscheduled maintenance activities after the flight.

Influence on other scenarios

ESD 19 Unstable approach.

The initiating event 'unstable approach' is influenced, since the flight crew may find it more difficult to fly a stabilised approach if (one of the) instruments do not display correct airspeed, altitude or attitude.

ESD 25 Aircraft handling by flight crew during flare inappropriate
The initiating event 'aircraft handling by flight crew during flare inappropriate' is influenced by 'flight instrument failure', as the flight crew has no instrument input with regard to speed, altitude or attitude.

Next flight.
The failure will require unscheduled maintenance activities after the flight.

2.17 ESD 17 Aircraft encounters adverse weather

This ESD has no yellow end states.

2.18 ESD 18 Single engine failure in flight

Yellow end state scenarios:

a) Single engine failure → dual engine failure → flight crew maintains control → aircraft able to reach an airport → *aircraft continues landing.*
b) Single engine failure → no dual engine failure → flight crew fails to restore engine power → flight crew shut down wrong engine → flight crew maintains control → aircraft able to reach an airport → *aircraft continues landing.*
c) Single engine failure → no dual engine failure → flight crew fails to restore engine power → flight crew does not shut down wrong engine → flight crew maintains control → *aircraft continues landing.*

Description
End states (a) and (b) are identical; they describe a situation in which an aircraft makes a powerless approach to an airport. The ability to perform a stabilised approach when no engine power is available will be compromised. End state (c) describes a situation where the flight continues with one engine inoperative. The engine failure(s) will require unscheduled maintenance after the flight.

Influence on other scenarios

ESD 19 Unstable approach.
The initiating event 'unstable approach' is influenced by end states (a), (b) and (c). The ability to conduct a stabilised approach is compromised if partial (or no) engine power is available.

ESD 28 Single engine failure during landing.
The initiating event 'single engine failure during landing' is influenced by end state (c).

Next flight.
The failure will require unscheduled maintenance activities after the flight.

2.19 ESD 19 Unstable approach

Yellow end state scenario:

a) Unstable approach → flight crew fails to initiate and execute missed approach → flight crew maintains control → aircraft touchdown not fast nor long → aircraft touchdown with excessive sink rate → no structural failure → *aircraft continues landing roll.*

Description
In end state (a) the unstable approach has resulted in a hard landing, but without damage. The aircraft will taxi normally to the gate. The only consequence is that after the flight the crew will have to report the hard landing and a hard landing inspection will have to be carried out by the maintenance crew (unscheduled maintenance).

Influence on other scenarios
Next flight.
The hard landing will require unscheduled maintenance activities after the flight.

2.20 ESD 21 Aircraft mass and balance outside limits during approach

Yellow end state scenario:

a) Aircraft mass and balance outside limits → flight crew maintains control → *aircraft continues flight.*

Description
In this end state the aircraft's mass and balance during the approach phase of the flight are different from the crew's expectations to such an extent that the flight crew have to take additional action to maintain control of the aircraft. There is a possibility that although the aircraft was controllable during the preceding part of the flight, controllability becomes difficult during the approach.

The change in configuration that is required for the approach, particularly the selection of landing flaps, causes a redistribution of the airflow and associated aerodynamic moment. Due to the additional effort required to maintain control of the aircraft, the ability to fly a stabilised approach and to execute a proper flare will be reduced. To avoid double counting, unrecovered loss of control as a direct result of mass and balance problems is considered to be part of ESD 21, even if they occur during an unstable approach.

Influence on other scenarios

ESD 19 Unstable approach.
The initiating event 'unstable approach' is influenced since the ability to conduct a stabilised approach may be compromised if control of the aircraft is more difficult.

ESD 25 Aircraft handling by flight crew during flare inappropriate.
The initiating event 'aircraft handling by flight crew during flare inappropriate' is influenced since the ability to conduct a proper flare is compromised if control of the aircraft is more difficult.

2.21 ESD 23 Aircraft encounters wind shear during approach

Yellow end state scenarios:

a) Aircraft encounters windshear during approach/landing → flight crew fails to detect wind shear → aircraft touchdown with excessive sink rate → no structural failure → *aircraft continues landing roll.*
b) Aircraft encounters windshear during approach/landing → flight crew detects wind shear → flight crew fails to execute windshear escape manoeuvre → aircraft touchdown with excessive sink rate → no structural failure → *aircraft continues landing roll.*

Description

In end states (a) and (b) the windshear encounter has resulted in a hard landing but the aircraft is not damaged. The only consequence is that after the flight the crew will have to report the hard landing and a hard landing inspection will have to be carried out by the maintenance crew (unscheduled maintenance).

Influence on other scenarios

Next flight.
The hard landing will require unscheduled maintenance activities after the flight.

2.22 ESD 25 Aircraft handling by flight crew during flare inappropriate

Yellow end state scenario:

a) Aircraft handling by flight crew during flare inappropriate → aircraft touchdown neither fast nor long → aircraft touchdown with excessive sink rate → no structural failure → flight crew maintains control → *aircraft continues landing roll.*

Description

For the purpose of this ESD, 'aircraft handling by flight 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. In end state (a) the improper flare has resulted in a hard landing but the aircraft is not damaged. The only consequence is that after the flight the crew will have to report the hard landing and a hard landing inspection will have to be carried out by the maintenance crew (unscheduled maintenance).

Influence on other scenarios

Next flight.
The hard landing will require unscheduled maintenance activities after the flight.

2.23 ESD 26 Aircraft handling by flight crew during landing roll inappropriate

This ESD has no yellow end states.

2.24 ESD 27 Aircraft directional control related system failure during landing

Yellow end state scenario:

a) Aircraft directional control related system failure → flight crew maintains control → *aircraft continues landing roll.*

Description

An aircraft directional control related 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. In end state (a) such a failure has occurred, but the flight crew manages to keep the aircraft under control and on the runway. The failure itself will require unscheduled maintenance activities after the flight.

Influence on other scenarios
Next flight.
The failure will require unscheduled maintenance activities after the flight.

2.25 ESD 28 Single engine failure during landing

Yellow end state scenario:

a) Single engine failure → flight crew maintains control → maximum braking achieved → *aircraft continues landing roll.*

Description
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. In end state (a) an engine failure has occurred, but the flight crew manages to keep the aircraft under control and on the runway. The failure itself will require unscheduled maintenance activities after the flight.

Influence on other scenarios
Next flight.
The failure will require unscheduled maintenance activities after the flight.

2.26 ESD 29 Thrust reverser failure

Yellow end state scenario:

a) Thrust reverser failure → flight crew maintains control → maximum braking achieved → *aircraft continues landing roll.*

Description
For the purpose of this ESD a thrust reverser failure is defined as a failure of system ATA 7830 ‘thrust 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. Because of the asymmetric thrust that is a result of the thrust reverser failure, the crew may find it difficult to maintain control, particularly in conditions of crosswind and a slippery runway. In end state (a) a thrust reverser failure has occurred, but the

flight crew manages to keep the aircraft under control and on the runway. The failure itself will require unscheduled maintenance activities after the flight.

Influence on other scenarios
Next flight.
The failure will require unscheduled maintenance activities after the flight.

2.27 ESD 30 Aircraft encounters unexpected wind

This ESD has no yellow end states.

2.28 ESD 31 Aircraft are positioned on collision course

This ESD has no yellow end states.

2.29 ESD 32 Incorrect presence on runway in use

This ESD has no yellow end states.

2.30 ESD 33 Cracks in aircraft pressure cabin

Yellow end state scenario:

a) Cracks in aircraft pressure boundary → no explosive decompression → *aircraft damage.*

Description
End state (a) is the outcome of a crack in the aircraft's pressure boundary which did not result in an explosive decompression. This could mean that there has been a decompression of the pressure cabin but not of an explosive nature or nothing noticeable happened at all. A non-explosive decompression could result in flight crew incapacitation due to hypoxia.

Influence on other scenarios
ESD 14 Flight crew incapacitation.
The initiating event 'flight crew incapacitation' can be influenced by cracks in the aircraft pressure boundary.

2.31 ESD 35 CFIT

This ESD has no yellow end states.

3 QUANTIFICATION OF DEPENDENCIES

3.1 INTRODUCTION

In this section, the dependencies between the ESDs, which have been identified in the previous section, are quantified. This means that conditional probabilities of initial events of one ESD, given a certain end state of a preceding ESD, have to be determined. This conditional probability may range from 0 (no dependency) to 1 (fully dependent).

First, the approach for the quantification is described and second, the conditional probabilities are determined.

3.2 APPROACH

The generic mathematical definition for the conditional probability of an event A given an event B is defined as follows:

$$P(A \mid B) = \frac{P(A \cap B)}{P(B)}, P(B) \neq 0$$

A is the initiating event of an ESD and B the end state of the preceding ESD. If P(B) > 0, the conditional probability is determined as follows:

a) Determine the probability $P(A \cap B)$ which means that both event A and event B are true; and
b) Determine P(B).

The first probability is determined by using the following sources:

- Starting point are the results included in [Roelen et al, 2006]. In this report, initiating and pivotal events are quantified, as well as the various end states. The data samples used in this report are used for quantification of $P(A \cap B)$;
- P(B) is retrieved from [Roelen et al, 2006], in which all events and end states of the ESDs are quantified;
- If the mentioned sources do not provide the required data, other sources may be identified. This is clearly referenced;
- To provide traceability of the results, selection criteria for every search are clearly described and results are stored.

The description of the quantification of the dependencies covers the following items:

– Summary of relevant dependencies for the ESD;
– Definitions of the events and end states;
– Quantification.

3.3 ESD 6 – Aircraft takes off with contaminated wing

The following dependency has been identified for the initiating event of ESD 6 'aircraft takes off with contaminated wing'.

– ESD 1: End state: 'Aircraft continues take-off' - after an aircraft system failure. The initiating event of an aircraft taking off with a contaminated wing can be influenced by a failure of the wing anti-ice system prior to take-off.

3.3.1 Definitions

The initiating event of ESD 6 'aircraft takes off with contaminated wing' describes a situation in which the 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.

Certain aircraft are equipped with a wing anti-ice system, which heats the wing's leading edge with bleed air from the engine(s). As the use of bleed air results in performance penalties, it is only activated during flight when icing conditions are expected. The wing anti-ice system is only activated prior to take-off when the aircraft takes off in actual icing conditions.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurs during take-off and the flight crew has not aborted the take-off. System failures include 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 failures are addressed in ESD 9 and ESD 4 respectively. Pitch control problems are addressed in ESD 10.

3.3.2 Quantification

ESD 1 - ESD 6

$P(A \cap B)$ represents the probability of an aircraft taking off with a contaminated wing in combination with a system failure, after which the take-off is continued.

For quantification of ESD 6 the Air Safety Report database is used in [Roelen et al, 2006] and the following inclusion criteria are applied:

- Incident/accident takes place between 1-1-1998 and 31-12-2004;
- Commercial flights with fixed-wing Western-built aircraft heavier than 5,700 kg MTOW are considered.

The original dataset consists of 9 cases in which the aircraft takes off with contaminated wing. None of these cases involves a system failure. Therefore, the conditional probability that an aircraft takes off with contaminated wings, given a system failure during take-off, is estimated to be 0.

3.4 ESD 11 – Fire onboard aircraft

The following dependencies have been identified for the initiating event of ESD 11 'fire onboard aircraft':

- ESD 1: End state: 'Aircraft continues take-off' - after an aircraft system failure. The initiating event of a fire onboard the aircraft can be influenced when the fire is caused by an aircraft system failure during take-off.
- ESD 5: End state: 'Aircraft continues take-off/flight' - with an incorrect configuration. The initiating event of a fire onboard aircraft can be influenced by an overheated parking brake that is not released prior to take-off.

Note that ESD 5 contains 3 end states that lead to a continuation of the flight

a) Incorrect configuration → take-off configuration warning → flight crew does not reject take-off → *aircraft continuous take-off.*
b) Incorrect configuration → no take-off configuration warning → aircraft stalls after rotation → flight crew regains control → *aircraft continues flight.*
c) Incorrect configuration → no take-off configuration warning → aircraft does not stall after rotation → *aircraft continues flight.*

Not releasing the parking brake before take-off cannot cause the aircraft to stall after take-off and therefore, situation (b) cannot occur in this case. Furthermore, in [Roelen et al, 2006], the probability of situation (c) is assessed to be 0. Therefore, only situation (a) is considered in the dependency between ESD 5 and ESD 11.

3.4.1 DEFINITIONS

The initiating event of ESD 11, 'Fire onboard aircraft', describes a situation in which a combustible substance onboard 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 (e.g. plastics). 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. Events in which meals were overheated causing a burning smell in the cabin were not considered, unless they resulted in a fire.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew has not aborted the take-off. System failures include 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 are addressed in ESD 9, so engine fires are not included in the quantification of the dependency between ESD 1 and ESD 11. Directional control failures and pitch control problems are also not addressed in ESD 1, as these are addressed in ESD 4 and ESD 10 respectively.

The yellow end state of ESD 5 'aircraft continues take-off' describes a situation in which the incorrect aircraft configuration causes a take-off configuration warning, after which the flight crew continue the take-off.

3.4.2 QUANTIFICATION

ESD 1 – ESD 11

$P(A \cap B)$ represents the probability of an on-board fire in combination with a system failure during take-off, after which the take-off is continued. For quantification of ESD 11 the FAA AIDS database is used in [Roelen et al, 2006] and the following inclusion criteria are applied:

– Incident/accident takes place between 1-1-1990 and 31-12-2000;
– Flights are conducted under FAR 121.

The original dataset in [Roelen et al, 2006] consists of 370 cases of genuine fires during all phases of flight.

To derive the number of fires in combination with a system failure during take-off, a new query is created in the FAA AIDS database with the following inclusion criteria:

– Incident/accident takes place between 1-1-1990 and 31-12-2000;
– Flights are conducted under FAR 121;
– The remark contains words like: fire, smoke, spark, smell, burn, flame, fume;
– Flight phase is: Like TKOF and not like ABORTED.

This query results in 100 fire-related events. However, since the dataset also contains the flight phase of initial climb, each record is reviewed to identify genuine fires in combination with system failures during the take-off roll. The review results in 5 cases in which an on-board fire occurs in combination with a system failure during the take-off roll, after which the take-off is continued.

Since the dataset covers 100,860,778 departures, $P(A \cap B)$ is calculated as $5/100{,}860{,}778 = 4.96 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $4.96 \cdot 10^{-8}/1.20 \cdot 10^{-5} = 4.13 \cdot 10^{-3}$. Therefore, the conditional probability that an on-board fire occurs, given a system failure during the take-off roll, after which the take-off is continued, is $4.13 \cdot 10^{-3}$.

ESD 5 – ESD 11

$P(A \cap B)$ represents the probability of an on-board fire in combination with a configuration warning during take-off, after which the take-off is continued. As already stated, the probability of on-board fires that are caused by an overheated parking brake that was not released prior to take-off has to be derived. For quantification of ESD 11 the FAA AIDS database is used in [Roelen et al, 2006] and the following inclusion criteria are applied:

– Incident/accident takes place between 1-1-1990 and 31-12-2000;
– Flights are conducted under FAR 121.

The original dataset consists of 370 cases of genuine fires during all phases of flight.

To derive the number of fires related to brakes, the following inclusion criteria were added:

– The remark contains at least one of the words: fire, smoke, spark, smell, burn, flame or fume;
– Flight phase is: Like TKOF (take-off) and not like ABORTED;
– The remark contains at least one of the words: thrust, brake, flap, spoiler, stab, gear, control, rudder or take.

This query resulted in 90 incidents of in-flight fires, but in none of them was an incorrect configuration involved. Therefore, the conditional probability of an on-board fire, given an incorrect configuration during take-off is estimated to be 0.

3.5 ESD 12 – Flight crew spatially disoriented

The following dependency has been identified for the initiating event of ESD 12 ‘flight crew spatially disoriented’:

- ESD 1: End state: ‘Aircraft continues take-off’ - after an aircraft system failure. The initiating event of ‘flight crew member spatially disoriented’ can be influenced when a system failure causes incorrect presentation of the aircraft’s attitude to the flight crew.

3.5.1 Definitions

The initiating event of ESD 12 ‘flight crew member spatially disoriented’ describes a situation in which 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 aircraft’s pitch, roll or yaw angle or rate of rotation.

The yellow end state of ESD 1 ‘aircraft continues take-off’ describes a situation in which a system failure occurred during take-off and the flight crew has not aborted the take-off. System failures include 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.

3.5.2 Quantification

ESD 1 - ESD 12

$P(A \cap B)$ represents the probability of a flight crew member becoming spatially disoriented in combination with a system failure during take-off, after which the take-off is continued. For quantification of ESD 12 the ASRS database is used in [Roelen et al, 2006] and the following inclusion criteria are applied:

- Incident/accident takes place between 1-1-1990 and 31-12-2004;
- Flights are conducted under FAR 121;
- Aircraft types include jet and turboprop aircraft with a maximum take-off mass of more than 5,700 kg, operated in commercial operations;
- Only Western-built aircraft are considered.

The original dataset consists of 12 cases of spatial disorientation during all phases of flight.

In order the obtain information about system failures during take-off in combination with spatial disorientation, the original query is rebuilt in the ASRS database according the following inclusion criteria:

- Incident/accident takes place between 1-1-1990 and 31-12-2004;
- Flights are conducted under FAR 121;
- Aircraft types include jet and turboprop aircraft with a maximum take-off mass of more than 5,700 kg, operated in commercial operations;
- Only Western-built aircraft are considered;
- Primary problem is flight crew human performance;
- Narrative text contains at least one of the words: disorientation, illusion or vertigo.

Excluded are occurrences in which the take-off was rejected.

Additional word searches in the narratives are performed to find relevant occurrences. A search for words like ‘instruments’, ‘failure’, ‘malfunction’ or ‘error’ results in 2 incidents in which flight crew become disoriented in combination with a system failure. In one case the aircraft took off with inoperative autothrottles, which eventually resulted in an altitude bust. In the second case the captain’s altimeter was set 1000 ft low after maintenance and this was only detected during flight. Both incidents occurred during climb, although both system failures already existed prior to the flight.

Since the dataset covers 143,500,000 flights, $P(A \cap B)$ is calculated as $2/143{,}500{,}000 = 1.39 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $1.39 \cdot 10^{-8}/1.20 \cdot 10^{-5} = 1.16 \cdot 10^{-3}$. Therefore, the conditional probability that flight crew becomes spatially disoriented, given a system failure during the take-off roll, after which the take-off is continued, is $1.16 \cdot 10^{-3}$.

3.6 ESD 13 – Flight control system failure

The following dependencies have been identified for the initiating event of ESD 13 ‘Flight control system failure’:

- ESD 1: End state: ‘Aircraft continues take-off’ – after an aircraft system failure. The initiating event of ‘flight control system failure’ can be influenced when a system failure causes a failure of the flight control system during later phases of the flight.

- ESD 4: End state: 'Aircraft continues take-off' – after an aircraft directional control related system failure. The initiating event of 'flight control system failure' can be influenced when the directional control problem is related to the flight control system (aileron and rudder).
- ESD 5: End states: 'Aircraft continues take-off/flight' – with an incorrect configuration. The initiating event of 'flight control system failure' can be influenced when the incorrect configuration is the result of a (technical) failure of the flight control system.
- ESD 6: End state: 'Aircraft continues flight' – after a take-off with contaminated wings (no stall has occurred). The initiating event of 'flight control system failure' can be influenced when the contaminant sheds or breaks loose, hits the vertical or horizontal stabilizer and causes damage.
- ESD 11: End state: 'Aircraft continues flight damaged' – after an on-board fire. The initiating event of 'flight control system failure' can be influenced if the fire results in a (partial) failure of the flight control system.

3.6.1 Definitions

The initiating event of ESD 13, 'Flight control system failure', describes the 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.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew have not aborted the take-off. System failures include 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.

The yellow end state of ESD 4 'aircraft continues take-off' describes a situation in which a directional control related system failure occurred during take-off and the flight crew have not aborted the take-off and maintains control. Directional control related system failures include all failures of the aileron and aileron controls, rudder and rudder controls, tyres and nose wheel steering. Directional control problems as a result from asymmetric thrust due an engine failure are excluded.

The yellow end state of ESD 5 'aircraft continues take-off' describes a situation in which the incorrect aircraft configuration causes a take-off configuration warning, after which the flight crew continue the take-off. The two other yellow end states of ESD 5 'aircraft continues flight' are quantified in [Roelen et al, 2006] with a probability of 0, so these are not taken into account in calculating the dependency between ESD 5 and ESD 13.

The yellow end state of ESD 6 'aircraft continues flight' describes a situation in which the aircraft takes off with contaminated wings and does not stall after rotation. The other yellow end state of ESD 6 'aircraft continues flight' after the aircraft has stalled after rotation is quantified in [Roelen et al, 2006] with a probability of 0, so this yellow end state is not taken into account in calculating the dependency between ESD 6 and ESD 13.

The yellow end state of ESD 10 'aircraft continues flight' describes a situation in which the aircraft rotates and lifts-off with a pitch control problem. The yellow end states of ESD 11 'aircraft continues flight damaged' describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 13.

3.6.2 Quantification

ESD 1 – ESD 13

$P(A \cap B)$ represents the probability of a flight control system failure in combination with a system failure during take-off, after which the take-off is continued.

For quantification of ESD 13 the SDR database is used in [Roelen et al, 2006] and the following inclusion criteria are applied:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems was considered to be a flight control system failure:
  - o ATA 2710-2719 Aileron system;
  - o ATA 2720-2729 Rudder system;

- o ATA 2730-2739 Elevator system;
- o ATA 2740-2749 Stabilizer system;
- o ATA 2700-2709 & ATA 2750-2797 Other.

Excluded from the dataset are false warnings and aborted take-offs.

The original dataset covered the flight phases of initial climb, en route, approach and landing. To determine the number of flight control system failures during take-off, the initial inclusion criteria for flight phases was replaced to cover flight control system failures during take-off only. This query results in 492 flight control system failures during take-off.

Since the dataset covers 215,800,000 departures, $P(A \cap B)$ is calculated as 492/215,800,000 = $2.28 \cdot 10^{-6}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $2.28 \cdot 10^{-6}$/ $1.20 \cdot 10^{-5}$ = $1.90 \cdot 10^{-1}$. Therefore, the conditional probability that a flight control system failure occurs, given a system failure during the take-off roll, after which the take-off is continued, is $1.90 \cdot 10^{-1}$.

ESD 4 – ESD 13

$P(A \cap B)$ represents the probability of a flight control system failure in combination with a directional control system related system failure during take-off, after which the take-off is continued.

The original dataset is further specified with the following inclusion criteria:

- ATA 2710-2719 Aileron system;
- ATA 2720-2729 Rudder system;
- ATA 2700-2709 & ATA 2750-2797 Other;
- Flight phase is take-off;
- 1st occurrence is FLT CONT AFFECTED;
- Narrative does not contain “flap”.

This query results in 63 occurrences, which are all reviewed to specify the relevant dataset. The review results in 36 occurrences in which flight control system failures occur in combination with a directional control system related failure during take-off, after which the take-off is continued.

Since the dataset covers 215,800,000 departures, $P(A \cap B)$ is calculated as 36/215,800,000 = $1.67 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 4 is quantified as $3.17 \cdot 10^{-5}$. P(A | B) is then calculated as $1.67 \cdot 10^{-7}$/$3.17 \cdot 10^{-5}$ = $5.26 \cdot 10^{-3}$. Therefore, the conditional probability that a flight control system failure occurs, given a directional control system related failure during the take-off roll, is $5.26 \cdot 10^{-3}$.

ESD 5 – ESD 13

$P(A \cap B)$ represents the probability of a flight control system failure in combination with the aircraft taking off with an incorrect configuration.

The original dataset used to quantify ESD 13 covered the flight phases of initial climb, en route, approach and landing. To determine the number of flight control system failures during take-off, the initial inclusion criteria for flight phases was replaced to cover flight control system failures during take-off only. This query results in 492 flight control system failures during take-off. The following inclusion criterion is added to determine cases in which a take-off with incorrect configuration is involved:

- Narrative contains words like “*config*”.

This results in 8 occurrences, but in all of them the take-off was aborted. Therefore, the conditional probability that a flight control system failure occurs, given a configuration warning during take-off, after which the take-off is continued, is estimated to be 0.

ESD 6 – ESD 13

$P(A \cap B)$ represents the probability of a flight control system failure in combination with the aircraft taking off with contaminated wings. It is noted that ESD 6 does not only include contaminated wings, but also contaminated horizontal stabilizers, tail and/or flight control surfaces.

The original dataset is further specified with the following inclusion criteria:

- Flight phase is take-off;
- 1st occurrence is FLT CONT AFFECTED;
- Narrative contains at least one of the words: "*frozen*", "*ice*", "*snow*", "*slush*" or "*contam*".

This query results in 62 occurrences, which are all reviewed to specify the relevant dataset. This review results in 2 occurrences in which flight control system failures occurred in combination with contaminated wings during take-off, after which the take-off is continued.

Since the dataset covers 215,800,000 departures, $P(A \cap B)$ is calculated as 2/215,800,000 = $9.27 \cdot 10^{-9}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 6 is quantified as $9.90 \cdot 10^{-7}$. P(A | B) is then calculated as $9.27 \cdot 10^{-9}/9.90 \cdot 10^{-7} = 9.36 \cdot 10^{-3}$.
Therefore, the conditional probability that a flight control system failure occurs, given that the aircraft takes off with contaminated wings, is $9.36 \cdot 10^{-3}$.

ESD 10 – ESD 13

$P(A \cap B)$ represents the probability of a flight control system failure in combination with pitch control problems during the take-off, after which the take-off is continued. The original dataset is further specified with the following inclusion criteria:

- ATA 2730-2739 Elevator system;
- ATA 2740-2749 Stabilizer system;
- Flight phase is take-off;
- 1st occurrence is FLT CONT AFFECTED.

This query results in 33 occurrences in which flight control system failures occurred in combination with pitch control problems during take-off, after which the take-off is continued.

Since the dataset covers 215,800,000 departures, $P(A \cap B)$ is calculated as 33/215,800,000 = $1.53 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 10 is quantified as $1.94 \cdot 10^{-5}$. P(A | B) is then calculated as $1.53 \cdot 10^{-7}/1.94 \cdot 10^{-5} = 7.88 \cdot 10^{-3}$. Therefore, the conditional probability that a flight control system failure occurs, given a pitch control problem during the take-off roll, after which the take-off is continued, is $7.88 \cdot 10^{-3}$.

ESD 11 – ESD 13

$P(A \cap B)$ represents the probability of a flight control system failure in combination with an on-board fire. The original dataset is further specified with the following inclusion criteria:

- 1st occurrence is FLT CONT AFFECTED
- Narrative contains words at least one of the following words: "*fire*", "*smok*", "*spark*", "*smell*", "*burn*", "*flam*" or "*fume*".

This query results in 16 occurrences, which are all reviewed to specify the relevant dataset. The review results in 12 occurrences in which flight control system failures occurred in combination with an in-flight fire. Of these, 6 related to burnt wires, pins or connectors. 5 related to a burnt flap drive motor and 1 to a shortened and burnt control box. In 2 of the cases the crew was alerted by a smell of smoke and in all of the cases the presence of an actual fire was only discovered after maintenance inspection. In none of the cases there was a need to extinguish the fire, nor had the flight crew any systems at their disposal to detect or extinguish the fire.

Since the dataset covers 215,800,000 departures, $P(A \cap B)$ is calculated as 12/215,800,000 = $5.56 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end states of ESD 11 are quantified as $1.50 \cdot 10^{-6}$ or $2.14 \cdot 10^{-6}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 13. This results in a probability of $1.50 \cdot 10^{-6} + 2.14 \cdot 10^{-6} = 3.64 \cdot 10^{-6}$. P(A | B) is then calculated as $5.56 \cdot 10^{-8}/3.64 \cdot 10^{-6} = 1.53 \cdot 10^{-2}$. Therefore, the conditional probability that a flight control system failure occurs, given an in-flight fire, is $1.53 \cdot 10^{-2}$.

3.7 ESD 14 – Flight crew incapacitation

The following dependencies have been identified for the initiating event of ESD 14 ‘Flight crew incapacitation’:

- ESD 1: End state: ‘Aircraft continues take-off’ - after an aircraft system failure. The initiating event of ‘flight crew incapacitation’ can be influenced when a system failure during take-off causes flight crew incapacitation during later phases of the flight.
- ESD 33: End state: ‘Aircraft damage’ - after an explosive decompression. The initiating event of ‘flight crew incapacitation’ can be influenced when flight crew suffer hypoxia due to cracks in the aircraft pressure boundary.

3.7.1 Definitions

The initiating event of ESD 14, ‘Flight crew incapacitation’, describes a situation in which a flight crew member becomes incapacitated due to a health related factor or hypoxia.

The yellow end state of ESD 1 ‘aircraft continues take-off’ describes a situation in which a system failure occurred during take-off and the flight crew have not aborted the take-off. System failures include 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.

The yellow end state of ESD 33 'aircraft damage' describes a situation in which cracks in the aircraft pressure boundary caused aircraft damage without an explosive decompression.

3.7.2 Quantification

ESD 1 – ESD 14

$P(A \cap B)$ represents the probability of incapacitation of a flight crew member in combination with a system failure during take-off, after which the take-off is continued.

For quantification of ESD 14 the NLR Air Safety Database is used in Roelen et al [2006] and the following inclusion criteria are applied:

- Incident/accident takes place between 1-1-1970 and 31-12-2003;
- Only commercial operations are considered;
- Aircraft types include jet, turbofan and turboprop aircraft with a MTOW of more than 5,700 kg;
- Aircraft manufacturers include Western airframe manufacturers such as Airbus, Boeing, McDonnell Douglas, Lockheed, Fokker, Embraer;
- All operators of these aircraft are included.

Excluded from the dataset are airframe manufacturers from former USSR or Eastern-block countries.

The original dataset contains 118 incidents/accidents of flight crew incapacitation and covers the flight phases of initial climb, en route, approach and landing. All reports in the dataset are reviewed to derive cases in which the flight crew incapacitation occurs in combination with a system failure. This review results in 2 accidents in which flight crew incapacitation occurs in combination with pressurization problems after take-off. In one case the problem originated from a stuck overflow valve. In the other case the aft pressure bulkhead was removed for maintenance and had not been installed. Both accidents are considered as system failures that already existed during take-off.

Since the dataset covers 750,000,000 flights, $P(A \cap B)$ is calculated as 2/750,000,000 = $2.67 \cdot 10^{-9}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $2.67 \cdot 10^{-9} / 1.20 \cdot 10^{-5} = 2.22 \cdot 10^{-4}$. Therefore, the conditional probability that a flight crew member becomes incapacitated, given a system failure during the take-off roll, after which the take-off is continued, is $2.22 \cdot 10^{-4}$.

ESD 33 – ESD 14

$P(A \cap B)$ represents the probability of incapacitation of a flight crew member in combination with an explosive decompression due to cracks in the aircraft pressure boundary.

The original dataset contains 118 incidents/accidents of flight crew incapacitation and covers the flight phases of initial climb, en route, approach and landing. All reports in the dataset are reviewed to derive cases in which the flight crew incapacitation occurs in combination with cracks in the aircraft pressure boundary. This review results in 2 accidents in which flight crew incapacitation occurs in combination with cracks in the aircraft pressure boundary. In one case a fatigue crack in the aft cargo door incapacitated a flight crew member and in the other case a birdstrike penetrated the cockpit windscreen, thereby incapacitating a member of the flight crew.

Since the dataset covers 750,000,000 flights, $P(A \cap B)$ is calculated as 2/750,000,000 = $2.67 \cdot 10^{-9}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 33 is quantified as $1.99 \cdot 10^{-5}$. P(A | B) is then calculated as $2.67 \cdot 10^{-9}/1.99 \cdot 10^{-5} = 1.34 \cdot 10^{-4}$. Therefore, the conditional probability that a flight crew member becomes incapacitated, given that there are cracks in the aircraft pressure boundary, is $1.34 \cdot 10^{-4}$.

3.8 ESD 15 – Anti-ice/de-ice system not operating

The following dependencies have been identified for the initiating event of ESD 15 'Anti-ice/de-ice system not operating':

– ESD 1: End state: 'Aircraft continues take-off' – after an aircraft system failure. The initiating event of 'ice accretion on aircraft in flight' can be influenced by a failure of the aircraft's anti-ice or de-ice system during take-off.
– ESD 11: End state: 'Aircraft continues flight damaged' – after an on-board fire. The initiating event of 'ice accretion on aircraft in flight' can be influenced if the fire results in a failure of the aircraft's anti-ice or de-ice system.

3.8.1 Definitions

The initiating event of ESD 15, 'Ice accretion on aircraft in flight', describes a situation in which ice accretes on the aircraft's outside structure, i.e. fuselage, wing, tail and flight control surfaces.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew have not aborted the take-off. System failures include 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.

The yellow end states of ESD 11 'aircraft continues flight damaged' describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 13.

3.8.2 Quantification

ESD 1 – ESD 15

$P(A \cap B)$ represents the probability of a failure of the anti-ice/de-ice system in combination with a system failure during take-off, after which the take-off is continued. The original dataset in [Roelen et al, 2006] contains 177 occurrences in which 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. In the original dataset, no occurrences are found of a failure of the anti-ice/de-ice system during flight in combination with a system failure during take-off. Therefore, the conditional probability is estimated to be 0.

ESD 11 – ESD 15

$P(A \cap B)$ represents the probability of a failure of the anti-ice/de-ice system in combination with an in-flight fire. In the original dataset, no occurrences are found of a failure of the anti-ice/de-ice system during flight in combination with an in-flight fire. Therefore, the conditional probability is estimated to be 0.

3.9 ESD 16 – Flight instrument failure

The following dependencies have been identified for the initiating event of ESD 16 'Flight instrument failure':

- ESD 1: End state: 'Aircraft continues take-off' – after an aircraft system failure. The initiating event of 'flight instrument failure' can be influenced by a system failure causing incorrect presentation of airspeed, altitude or attitude of the aircraft.
- ESD 11: End state: 'Aircraft continues flight damaged' – after an on-board fire. The initiating event of 'flight instrument failure' is influenced if the fire results in an instrument failure.

3.9.1 Definitions

The initiating event of ESD 16, 'Flight instrument failure', describes a situation in which a flight instrument failure occurs during flight and the flight crew maintains control of the aircraft. 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.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew have not aborted the take-off. System failures include 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.

The yellow end states of ESD 11 'aircraft continues flight damaged' describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 16.

3.9.2 Quantification

ESD 1 – ESD 16

$P(A \cap B)$ represents the probability of a flight instrument failure in combination with a system failure during take-off, after which the take-off is continued.

The original dataset in [Roelen et al, 2006] is built with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems was considered to be a flight control system failure:

- o ATA 3414 Airspeed/Mach indicator;
- o ATA 3416 Altimeter, barometric/encoder;
- o ATA 3417 Air Data Computer;
- o ATA 3420 Attitude and direction data system;
- o ATA 3421 Attitude gyro and indicator system.

Excluded from the dataset are false warnings and aborted take-offs.

To determine the number of flight instrument failures during take-off, an additional criterion (flight phase is take-off) is added to cover flight instrument failures during take-off only. This query results in 88 flight instrument failures during take-off.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 88/216,000,000 = $4.07 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $4.07 \cdot 10^{-7}/1.20 \cdot 10^{-5}$ = $3.40 \cdot 10^{-2}$. Therefore, the conditional probability that a flight instrument failure occurs, given a system failure during take-off, after which the take-off is continued, is $3.40 \cdot 10^{-2}$.

ESD 11 – ESD 16

$P(A \cap B)$ represents the probability of a flight instrument failure in combination with an in-flight fire. The original dataset is further specified with the following inclusion criteria:

– Narrative contains at least one of the following words: "*fire*", "*smok*", "*spark*", "*smell*", "*burn*", "*flam*" or "*fume*".

False warnings and occurrences of flight crew burning off fuel are excluded.

This query results in 56 occurrences in which a flight instrument failure occurred in combination with an in-flight fire. It is noted that the in-flight fires in this dataset have to be interpreted as sparks, (electrical) smoke or a burning smell, as the majority of fires contained in the dataset are of electrical nature (shortcuts/burn-through). None of the cases required extinguishing of the fire.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 56/216,000,000 = $2.59 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end states of ESD 11 are quantified as $1.50 \cdot 10^{-6}$ or $2.14 \cdot 10^{-6}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 16. This results in a probability of $1.50 \cdot 10^{-6} + 2.14 \cdot 10^{-6} = 3.64 \cdot 10^{-6}$. P(A | B) is then calculated as $2.59 \cdot 10^{-7}/3.64 \cdot 10^{-6}$ =

$7.12 \cdot 10^{-2}$. Therefore, the conditional probability that a flight instrument failure occurs, given an in-flight fire, is $7.21 \cdot 10^{-2}$.

3.10 ESD 18 – Single engine failure in flight

The following dependencies have been identified for the initiating event of ESD 18 'Single engine failure in flight':

- ESD 1: End state: 'Aircraft continues take-off' - after an aircraft system failure. The initiating event of 'single engine failure' can be influenced by a system failure causing the engine to flame out or overheat.
- ESD 6: End state 'Aircraft continues flight' - after a take-off with contaminated wings (no stall has occurred). The initiating event of 'single engine failure' can be influenced in case the contaminant sheds or breaks loose and is ingested by the engine(s).
- ESD 9: End state 'Aircraft continues take-off '- with a single engine failure during take-off. The initiating event of 'single engine failure' (in flight) can be influenced by a single engine failure during take-off.
- ESD 11: End state: 'Aircraft continues flight damaged' - after an on-board fire. The initiating event of 'single engine failure' is influenced if the fire results in an engine failure.
- ESD 15: End state 'Aircraft continues flight' - after ice accretion on aircraft in flight to which the crew fails to respond appropriately. The initiating event of 'single engine failure' is influenced if ice breaks loose and is ingested by the engine(s).

3.10.1 Definitions

The initiating event of ESD 18, '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 in which the engine detaches from the aircraft. Engine fires are not included, as these are covered in ESD 11. Engine failures during take-off and landing are addressed in ESD 9 and 28 respectively.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew have not aborted the take-off. System failures include 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.

The yellow end state of ESD 6 'aircraft continues flight' describes a situation in which the aircraft takes off with contaminated wings and does not stall after rotation. The other yellow end state of ESD 6 'aircraft continues flight' after the aircraft has stalled after rotation is quantified in [Roelen et al, 2006] with a probability of 0, so this yellow end state is not taken into account in calculating the dependency between ESD 6 and ESD 18.

The yellow end state of ESD 9 'aircraft continues flight' describes a situation in which the aircraft continues the take-off with a single engine failure and the flight crew maintains control. It is assumed that when the take-off is continued with an engine failure, the engine failure condition remains at least during the initial climb.

The yellow end states of ESD 11 'aircraft continues flight damaged' describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 18.

The yellow end states of ESD 15 'aircraft continues flight' describe a situation in which ice accretes on the aircraft in flight and the flight crew maintains control, operate anti/de-icing systems or exit the icing conditions. For the purpose of this assignment both yellow and states summed for quantification of the dependency between ESD 15 and ESD 18.

3.10.2 Quantification

ESD 1 – ESD 18

$P(A \cap B)$ represents the probability of a single engine failure in flight in combination with a system failure during take-off, after which the take-off is continued. The original dataset in [Roelen et al, 2006] consists of 79 occurrences of engine failures during initial climb, en route and approach.

The original query is rebuilt with the following inclusion criteria:

- Phase of flight is not one of the following: "taxi*", "push-back", "parked", "take-off", "landing";
- Major CAT 1 is not like "environmental";
- Event 1, 2 or 3 = ENGINE.

This query results in 79 engine-failure related occurrences. In 36 of the cases, events or keywords in the dataset indicate a relation with other system failures (e.g. fuel, oil, computer, etc.). In none of the cases it can be derived whether the system failure was already present during take-off. Therefore, based on the original dataset, no assumptions can be made in quantification of the dependency between ESD 1 and ESD 18.

However, the probability that a failed engine is restarted during flight is in [Roelen et al, 2006] derived to be 0. Therefore, it is assumed that any combination of an engine and system failure during take-off, after which the take-off is continued, results in an engine failure during flight.

The SDR database is used to identify relevant occurrences and a query is built with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be an engine failure:
  - ATA 6100-6197 Propeller/rotor;
  - ATA 7100-8097 Powerplant and accessories;
- Flight phase is take-off;
- Keyword contains AFFECT SYSTEMS or OTHER AFFECT SYSTEMS.

Aborted take-offs are excluded from the dataset.

This query results in 20 occurrences in which an engine failure occurs in combination with a system failure during take-off, after which the take-off is continued.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 20/216,000,000 = $9.26 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $9.26 \cdot 10^{-8} / 1.20 \cdot 10^{-5} = 7.72 \cdot 10^{-3}$. Therefore, the conditional probability that an engine failure in flight occurs, given a system failure during take-off, after which the take-off is continued, is $7.72 \cdot 10^{-3}$.

ESD 6 – ESD 18

$P(A \cap B)$ represents the probability of a single engine failure in flight in combination with the aircraft taking off with contaminated wings. The 79 occurrences are reviewed but none can be identified in which the engine failed in combination with a take-off with contaminated wings. Therefore, the conditional probability is assumed to be 0.

ESD 9 – ESD 18

$P(A \cap B)$ represents the probability of a single engine failure in flight in combination with a single engine failure during take-off, after which the take-off is continued. In this yellow end state, the aircraft takes off with an engine failure, so it is assumed that the engine failure condition remains at least during the initial climb. Therefore, the conditional probability that a single engine failure in flight occurs in combination with a single engine failure during take-off is estimated to be 1.

ESD 11 – ESD 18

$P(A \cap B)$ represents the probability of a single engine failure in flight in combination with an in-flight fire. In [Roelen et al, 2006], the quantification of the initiating event of ESD 11 also provides a further specification of fires on-board the aircraft. The number of occurrences of engine fires is given (184) and the frequency per flight is calculated as $1.82 \cdot 10^{-6}$ per flight. It is assumed that all engine fires result in an engine failure.

In [Roelen et al, 2006], the yellow end states of ESD 11 are quantified as $1.50 \cdot 10^{-6}$ or $2.14 \cdot 10^{-6}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 18. This results in a probability of $1.50 \cdot 10^{-6} + 2.14 \cdot 10^{-6} = 3.64 \cdot 10^{-6}$. P(A | B) is then calculated as $1.82 \cdot 10^{-6}/3.64 \cdot 10^{-6} = 5.0 \cdot 10^{-1}$. Therefore, the conditional probability that a single engine failure occurs, given an in-flight fire, is $5.0 \cdot 10^{-1}$.

ESD 15 – ESD 18

$P(A \cap B)$ represents the probability of a single engine failure in flight in combination with ice accretion on the aircraft in flight. The 79 occurrences are reviewed but none could be identified in which the engine failed in combination with ice accretion on the aircraft in flight. Therefore, the conditional probability is estimated to be 0.

3.11 ESD 19 – Unstable approach

The following dependencies have been identified for the initiating event of ESD 19 'Unstable approach':

– ESD 16: End state: 'aircraft continues flight' – with a flight instrument failure. The initiating event of 'unstable approach' can be influenced when (one of the) instruments do not display correct airspeed, altitude or attitude.

- ESD 18: End state: 'aircraft continues flight/landing' – with a single or dual engine failure. The initiating event of 'unstable approach' can be influenced when partial (or no) engine power is available.
- ESD 21: End state: 'aircraft continues flight' – with the aircraft mass and balance outside limits. The initiating event of 'unstable approach' can be influenced when control of the aircraft is more difficult due to mass and balance limit exceedences.

3.11.1 Definitions

The initiating event of ESD 19, 'Unstable approach', is defined as an approach in which any of the following criteria is not met:

- Correct glide path;
- Only small changes in heading/pitch;
- Speed between Vref and Vref +20 kts;
- Correct landing configuration;
- Sink rate is not 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.

The yellow end state of ESD 16 'aircraft continues flight' describes a situation in which a flight instrument failure occurs and the flight crew maintain control.

The yellow end states of ESD 18 'aircraft continues landing' describes a situation in which a single or double engine failure occurs, the flight crew maintains control and continues the landing. A third yellow end state of ESD 18 'aircraft continues flight' after a single engine failure with the flight crew maintaining control of the aircraft is quantified in [Roelen et al, 2006] with a probability of 0. Therefore, this third yellow end state is not considered. For the purpose of this assignment the first and second yellow end states are summed for quantification of the dependency between ESD 18 and ESD 19.

The yellow end state of ESD 21 'aircraft continues flight' describes a situation in which the aircraft mass and balance is outside limits during approach, but the approach is continued.

3.11.2 QUANTIFICATION

ESD 16 – ESD 19

$P(A \cap B)$ represents the probability of an unstable approach in combination with a flight instrument failure. In [Roelen et al, 2006] data from a large European airline that operates globally has been used for quantification of the initiating event of ESD 19. This dataset covers a time interval of 1998 to 2001 and contains 1642 unstable approaches out of a total of 312,044 flights. Since the original dataset does not contain the necessary information for quantification of dependencies between ESD 19 and other ESD's, another dataset is compiled. A new query is created in the NLR Air Safety Report database with the following inclusion criteria:

- Flight phase is approach;
- Event title contains the word "*stab*", or
- Summary contains the words "*unstab*";
- Summary does not contain the word "*stabilizer*".

This query results in 1566 occurrences, of which BASIS References 1, 2 and 3 are reviewed to identify occurrences in which the unstable approach occurs in combination with a flight instrument failure. As approaches may be flown with assistance of the autoflight and/or autothrottle system, failures of these systems are also considered in quantification of the dependency between ESD 16 and ESD 19. Occurrences for which the following BASIS References are given are reviewed:

- AUTOFLIGHT;
- ICE/RAIN PROTECTION;
- NAV EQUIPMENT;
- COMPUTER;
- FMS.

This review results in 9 occurrences in which an unstable approach is flown with a failure of flight instruments, autopilot, autothrottle or Automatic Flight Control System/Flight Management Guidance Computer.

Since the dataset covers 14,000,000 flights, $P(A \cap B)$ is calculated as $9/14{,}000{,}000 = 6.43 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 16 is quantified as $6.55 \cdot 10^{-6}$. $P(A \mid B)$ is then calculated as $6.43 \cdot 10^{-7}/6.55 \cdot 10^{-6} = 9.81 \cdot 10^{-2}$. Therefore, the conditional probability that an unstable approach occurs, given a flight instrument failure, is $9.81 \cdot 10^{-2}$.

ESD 18 – ESD 19

$P(A \cap B)$ represents the probability of an unstable approach in combination with a single engine failure in flight. The original query is enhanced with the following inclusion criterion:

– BASIS Reference 1, 2 or 3 is ENGINE.

This review results in 3 occurrences of which one is considered relevant. In this occurrence the #2 engine reverser light illuminated, after which the approach became unstable.

Since the dataset covers 14,000,000 flights, $P(A \cap B)$ is calculated as 1/14,000,000 = $7.14 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end states of ESD 18 are quantified as $1.00 \cdot 10^{-7}$ or $2.75 \cdot 10^{-4}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 18 and ESD 19. This results in a probability of $1.00 \cdot 10^{-7} + 2.75 \cdot 10^{-4} = 2.75 \cdot 10^{-4}$. P(A | B) is then calculated as $7.14 \cdot 10^{-8}/2.75 \cdot 10^{-4} = 2.60 \cdot 10^{-4}$. Therefore, the conditional probability that an unstable approach occurs, given a single engine failure in flight, is $2.60 \cdot 10^{-4}$.

ESD 21 – ESD 19

$P(A \cap B)$ represents the probability of an unstable approach in combination with the aircraft mass and balance outside limits during approach. The original query is enhanced with the following inclusion criterion:

– Summary contains at least one of the words: "*load*", "*weight*", *gravity*", or "*balance*".

This query results in 36 occurrences, but none of them are considered relevant for quantification of the dependency between ESD 21 and ESD 19, as most of them are related with workload or high/low aircraft mass affecting the deceleration of the aircraft. Therefore, the conditional probability that an unstable approach occurs, given that the aircraft mass and balance is outside limits during approach, is estimated to be 0.

3.12 ESD 21 – Aircraft mass and balance outside limits during approach

The following dependencies have been identified for the initiating event of ESD 21 'Aircraft mass and balance outside limits during approach':

– ESD 6: End state: 'Aircraft continues flight' – after a take-off with contaminated wings (no stall has occurred). The initiating event of 'aircraft mass and balance outside limits' can be influenced when ice accretion on the wings increases the aircraft mass and shifts the centre of gravity beyond limits.

- ESD 7: End state: 'Aircraft continues flight' – after a take-off with aircraft mass and balance outside limits (no stall has occurred). The initiating event of 'aircraft mass and balance outside limits' (during approach) can be influenced when the correct centre of gravity or mass cannot be restored during the flight.
- ESD 10: End state 'Aircraft continues flight' – after pitch control problems during take-off. The initiating event of 'aircraft mass and balance outside limits' is influenced when the pitch control problem are caused by a mass and balance issue.
- ESD 15: End state 'Aircraft continues flight' – after ice accretion on aircraft in flight to which the crew fails to respond appropriately. The initiating event of 'aircraft mass and balance outside limits' is influenced when ice builds up on the wing, fuselage or engine intakes.

3.12.1 Definitions

The initiating event of ESD 21, 'Aircraft mass and balance outside limits', describes a situation in which the aircraft mass and balance is outside limits. This includes the following situations: centre of gravity incorrect/outside limits, cargo loose or shifted, incorrect number of passengers, incorrect loadsheet or mass limits incorrect/exceeded. This means that also situations are accounted for where the mass and balance is not strictly outside limits, but is different than the flight crew expects. Not considered are overweight landings, problems with lateral fuel balance and jettison of fuel during descent.

The yellow end state of ESD 6 'aircraft continues flight' describes a situation in which the aircraft takes off with contaminated wings and does not stall after rotation. The other yellow end state of ESD 6 'aircraft continues flight' after the aircraft has stalled after rotation is quantified in [Roelen et al, 2006] with a probability of 0, so this yellow end state is not taken into account in calculating the dependency between ESD 6 and ESD 21.

The yellow end state of ESD 7 'aircraft continues flight' describes a situation in which the aircraft takes off with its mass and balance outside limits and does not stall after rotation. The other yellow end state of ESD 7 'aircraft continues flight' after the aircraft has stalled and the flight crew maintains control is quantified in

[Roelen et al, 2006] with a probability of 0, so this yellow end state is not taken into account in calculating the dependency between ESD 7 and ESD 21.

The yellow end state of ESD 10 ‘aircraft continues flight’ describes a situation in which the aircraft rotates and lifts-off with a pitch control problem.

The yellow end states of ESD 15 ‘aircraft continues flight’ describe a situation in which ice accretes on the aircraft in flight and the flight crew maintains control, operate anti/de-icing systems or exit the icing conditions. For the purpose of this assignment both yellow end states are summed for quantification of the dependency between ESD 15 and ESD 21.

3.12.2 Quantification

ESD 6 – ESD 21

$P(A \cap B)$ represents the probability of the aircraft’s mass and balance outside limits during approach in combination with the aircraft taking off with contaminated wings (no stall has occurred).

The original dataset in [Roelen et al, 2006] contains 18 occurrences related to mass and balance problems during approach. This dataset is derived from the NLR Air Safety Report database. To identify occurrences in which the aircraft has taken off with contaminated wings, causing mass and balance problems during approach, the query is rebuilt according to the following inclusion criteria:

- Occurrence takes place between 1-1-1997 and 31-12-2004;
- Flight phase is approach;
- Summary contains at least one of the following words: “*load*”, “*weight*”, “*gravity*” or “*balance*” AND;
- Summary contains at least one of the following words: “*frozen*”, “*ice*”, “*snow*”, “*slush*” or “*contam*”.

The 81 occurrences of this dataset are reviewed for their applicability, but no relevant occurrences are found. Therefore, the conditional probability of the aircraft’s mass and balance outside limits during approach in combination with the aircraft taking off with contaminated wings is estimated to be 0.

ESD 7 – ESD 21

$P(A \cap B)$ represents the probability of the aircraft’s mass and balance outside limits during approach in combination with the aircraft taking off with mass and balance outside limits (no stall has occurred).

The original dataset in [Roelen et al, 2006] contains 18 occurrences related to mass and balance problems during approach. This dataset is derived from the NLR Air Safety Report database. To identify occurrences in which the mass and balance problem is already present during take-off, but not noticed, the query is rebuilt according to the following inclusion criteria:

- Occurrence takes place between 1-1-1997 and 31-12-2004;
- Flight phase is approach;
- Keywords contain the word LOAD*.

This query results in 33 occurrences in which the aircraft's mass and balance was outside limits during approach. Non-relevant occurrences are excluded from this dataset, as well as cargo shifts during flight, as these do not play a role in the combination of ESD 7 and ESD 21. When these occurrences are excluded, the final dataset results in 13 occurrences in which either corrected load information was received during flight (4), causing mass and balance considerations for landing, or loading errors were suspected during approach and were discovered after landing (9).

Since the dataset covers 9,500,000 flights, $P(A \cap B)$ is calculated as 13/9,500,000 = $1.37 \cdot 10^{-6}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 7 is quantified as $1.09 \cdot 10^{-5}$. P(A | B) is then calculated as $1.37 \cdot 10^{-6} / 1.09 \cdot 10^{-5} = 1.26 \cdot 10^{-1}$. Therefore, the conditional probability that the aircraft's mass and balance is outside limits during the approach occurs, given the aircraft's mass and balance is outside limitations during take-off (no stall has occurred), is $1.26 \cdot 10^{-1}$.

ESD 10 – ESD 21

$P(A \cap B)$ represents the probability of the aircraft's mass and balance out of limits during approach in combination with pitch control problems during take-off. To identify relevant occurrences, the query is rebuilt according to the following inclusion criteria:

- Occurrence takes place between 1-1-1997 and 31-12-2004;
- Flight phase is approach;
- Keywords contain the word "LOAD*".

This query results in 33 occurrences in which the aircraft's mass and balance was outside limits during approach. In this dataset there is only one occurrence found in which mass and balance difficulties are noticed just prior to take-off and are corrected on-board, but still result in mass and balance problems during the approach. In this case, passengers had to move aft to keep the aircraft within mass and balance limits. For take-off a stabilizer setting of 8.6 units nose-up had to be used, but this stabilizer setting resulted in an overshoot of the approach altitude.

Since the dataset covers 9,500,000 flights, $P(A \cap B)$ is calculated as 1/9,500,000 = $1.05 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 10 is quantified as $1.94 \cdot 10^{-5}$. P(A | B) is then calculated as $1.05 \cdot 10^{-7}/1.94 \cdot 10^{-5}$ = $5.43 \cdot 10^{-3}$. Therefore, the conditional probability that the aircraft's mass and balance is outside limits during the approach, given pitch control problems during take-off, is $5.43 \cdot 10^{-3}$.

ESD 15 – ESD 21

$P(A \cap B)$ represents the probability of the aircraft's mass and balance out of limits during approach in combination with ice accretion on the aircraft in flight. The 81 occurrences of the dataset used for quantifying the probability of the combination of ESD 6 and ESD 21 are reviewed for their applicability, but no relevant occurrences are found. Therefore the conditional probability that the aircraft's mass and balance is out of limits during approach, given ice accretion on the aircraft in flight, is estimated to be 0.

3.13 ESD 23 – Aircraft encounters wind shear during approach

No dependencies have been identified for the initiating event of ESD 23 'Aircraft encounters windshear during approach/landing'.

3.14 ESD 25 – Aircraft handling by flight crew during flare inappropriate

The following dependencies have been identified for the initiating event of ESD 25 'Aircraft handling by crew during flare inappropriate':

- ESD 16: End state: 'aircraft continues flight' – with a flight instrument failure. The initiating event of 'aircraft handling by crew during flare inappropriate' can be influenced when (one of the) instruments do not display correct airspeed, altitude or attitude.
- ESD 21: End state: 'aircraft continues flight' – with the aircraft mass and balance outside limits. The initiating event of 'aircraft handling by crew

during flare inappropriate' can be influenced when control of the aircraft is more difficult due to mass and balance limit exceedences.

3.14.1 Definitions

The initiating event of ESD 25, 'Aircraft handling by crew during flare inappropriate', describes a situation in which the flare starts from a stabilized condition at the runway threshold, but the manoeuvre itself is conducted inappropriately. A stabilized 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. Inappropriate aircraft handling by the crew during flare is assumed to be either a hard or long landing.

The yellow end state of ESD 16 'aircraft continues flight' describes a situation in which a flight instrument failure occurs and the flight crew maintain control.
The yellow end state of ESD 21 'aircraft continues flight' describes a situation in which the approach is flown with the aircraft's mass and balance outside limits.

3.14.2 Quantification

ESD 16 – ESD 25

$P(A \cap B)$ represents the probability of inappropriate aircraft handling by the flight crew during the flare in combination with a flight instrument failure. To determine the frequency of inappropriate aircraft handling during the flare, [Roelen et al, 2006] uses a study of landing performances during ILS approaches conducted by NLR [Van Es & van der Geest, 2006]. However, this study uses flight data that has been obtained from the flight data monitoring program, which only provides absolute numbers and no further information with regard to causes, contributing factors, etc. In order to obtain a dataset in which this information is available for further analysis, a query is built in the NLR Air Safety Report database with the following inclusion criteria:

- Occurrence takes place between 1-1-1992 and 31-12-2005;
- Flight phase is landing;
- Basis reference 1,2 or 3 contains "PILOT HNDLG/AIRMNSHP";
- Summary contains at least one of the following words: "*hard*", "*firm*", "*excessive*", "*long*" or "*deep*".

Overweight landings are excluded from the dataset.

This query results in 986 occurrences in which a hard or long landing is made. In 2 of the occurrences a failure of the radio altimeter is identified as a contributing factor in the keywords.

Since the dataset covers 14,000,000 flights, $P(A \cap B)$ is calculated as 2/14,000,000 = $1.43 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 16 is quantified as $6.55 \cdot 10^{-6}$. P(A | B) is then calculated as $1.43 \cdot 10^{-7}/6.55 \cdot 10^{-6}$ = $2.18 \cdot 10^{-2}$. Therefore, the conditional probability that the aircraft handling by the flight crew is inappropriate during the flare, given a flight instrument failure, is $2.18 \cdot 10^{-2}$.

ESD 21 – ESD 25

$P(A \cap B)$ represents the probability of inappropriate aircraft handling by the flight crew during the flare in combination with the aircraft's mass and balance outside limits during approach. In order to obtain a dataset in which information is available for further analysis, the following criterion is added to the query:

– Summary contains at least one of the following words: "*weight*", "*mass*" or "*balance*".

This query results in 17 occurrences which are further analyzed to identify relevant occurrences. Three relevant occurrences of hard, firm or long landings were found in the dataset. In one case the aircraft had a low mass during landing, causing a tailstrike. In the second case there was a sudden wind change during landing, making the aircraft overweight for landing. The landing was continued on a wet runway and the aircraft skidded to a stop in the runway overrun area. In the third case a hard landing was made due to the aircraft overweight.

Since the dataset covers 14,000,000 flights, $P(A \cap B)$ is calculated as 3/14,000,000 = $2.14 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 21 is quantified as $1.88 \cdot 10^{-6}$. P(A | B) is then calculated as $2.14 \cdot 10^{-7}/1.88 \cdot 10^{-6}$ = $1.14 \cdot 10^{-1}$. Therefore, the conditional probability that the aircraft handling by the flight crew is inappropriate during the flare, given that the aircraft's mass and balance is outside limits during approach, is $1.14 \cdot 10^{-1}$.

3.15 ESD 26 – Aircraft handling by flight crew during landing roll inappropriate

No dependencies have been identified for the initiating event of ESD 26 'Aircraft handling by flight crew during landing roll inappropriate'.

3.16 ESD 27 – Aircraft directional control related system failure during landing

The following dependencies have been identified for the initiating event for ESD 27 'Aircraft directional control related system failure':

- ESD 4: End state: 'Aircraft continues take-off' - after an aircraft directional control related system failure. The initiating event of 'aircraft directional control related system failure (during landing)' can be influenced by an aircraft directional control related system failure during take-off.
- ESD 11: End state: 'Aircraft continues flight damaged' - after an on-board fire. The initiating event of 'aircraft directional control related system failure' is influenced if the fire results in a failure of any of the aircraft's systems that affect directional controllability of the aircraft during the landing roll, such as aileron and aileron controls, rudders and rudder controls, tyres and landing gear.
- ESD 13: End state: 'Aircraft continues flight' - after a flight control system failure. The initiating event of 'aircraft directional control related system failure' is influenced if the failure affects the directional controllability of the aircraft.

3.16.1 Definitions

The initiating event of ESD 27, 'Aircraft directional control related system failure', describes a situation in which a landing is made with 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.

The yellow end state of ESD 4 'aircraft continues take-off' describes a situation in which a directional control related system failure occurred during take-off and the flight crew have not aborted the take-off and maintains control. Directional control related system failures include all failures of the aileron and aileron controls, rudder and rudder controls, tyres and nose wheel steering. Directional control problems as a result from asymmetric thrust due an engine failure are excluded.

The yellow end states of ESD 11 ‘aircraft continues flight damaged’ describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 27.

The yellow end state of ESD 13 ‘aircraft continues flight’ describes a situation in which a flight control system failure occurs, but the flight crew maintain control of the aircraft.

3.16.2 Quantification

ESD 4 – ESD 27

$P(A \cap B)$ represents the probability of a directional control related system failure during landing in combination with a directional control related system failure during take-off. The original dataset in [Roelen et al, 2006] is compiled from data from the SDR database. For the quantification of the dependency between ESD 4 and ESD 27 it is assumed that the directional control problems encountered during take-off, which require an unscheduled landing, still exist during landing. Therefore, the original dataset is reproduced with the following (additional) inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be a flight control system failure:
  - ATA 2710 Aileron control system;
  - ATA 2711 Aileron tab control system;
  - ATA 2720 Rudder control system;
  - ATA 2722 Rudder actuator;
  - ATA 32* Landing gear;
- Flight phase is take-off;
- The directional control problems results in an unscheduled landing.

False warnings and aborted take-offs are excluded from the dataset.

This query results in 1626 occurrences in which a directional control problem occurs during take-off after which an unscheduled landing is made.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 1626/216,000,000 = $7.53 \cdot 10^{-6}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 4 is quantified as $3.17 \cdot 10^{-5}$. P(A | B) is then calculated as $7.53 \cdot 10^{-6}/3.17 \cdot 10^{-5} = 2.37 \cdot 10^{-1}$. Therefore, the conditional probability that a directional control problem during take-off still exists during landing is $2.37 \cdot 10^{-1}$.

ESD 11 – ESD 27

$P(A \cap B)$ represents the probability of a an aircraft directional control related failure during landing in combination with an in-flight fire. The original dataset [Roelen et al, 2006] is compiled from data from the SDR database. The original dataset is reproduced with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be a flight control system failure:
  - ATA 2710 Aileron control system;
  - ATA 2711 Aileron tab control system;
  - ATA 2720 Rudder control system;
  - ATA 2722 Rudder actuator;
  - ATA 32* Landing gear;
- Flight phase is landing;
- Narrative contains at least one of the following words: "*fire*", "*smok*", "*spark*", "*smell*", "*burn*", "*flam*" or "*fume*".

False warnings and occurrences of flight crew burning off fuel are excluded.

This query results in 71 occurrences in which a directional control problem occurred in combination with a fire. It is noted that the majority of the fires (63) contained in this dataset are brake fires during or after the landing roll. The remaining 8 cases are of electrical nature (shortcuts, burn-through). As the brake fires during or after the landing roll are a direct result of directional control problems, these are excluded from the dataset.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 8/216,000,000 = $3.70 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end states of ESD 11 are quantified as $1.50 \cdot 10^{-6}$ or $2.14 \cdot 10^{-6}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 27. This results in a probability of $1.50 \cdot 10^{-6}$

+ $2.14 \cdot 10^{-6} = 3.64 \cdot 10^{-6}$. P(A | B) is then calculated as $3.70 \cdot 10^{-8} / 3.64 \cdot 10^{-6} = 1.02 \cdot 10^{-2}$. Therefore, the conditional probability that a directional control problem occurs, given an in-flight fire, is $1.02 \cdot 10^{-2}$.

ESD 13 – ESD 27

$P(A \cap B)$ represents the probability of a directional control problem during landing in combination with a flight control system failure during flight. To derive the number of relevant occurrences, the original dataset is rebuilt, but excludes directional control problems related to the landing gear. The query is built with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems was considered to be a flight control system failure:
  - ATA 2710 Aileron control system;
  - ATA 2711 Aileron tab control system;
  - ATA 2720 Rudder control system;
  - ATA 2722 Rudder actuator;
- Flight phase is landing;

False warnings are excluded from the dataset.

This query results in 31 occurrences in which a directional control problem occurred in combination with a flight control related system failure (aileron and rudder).

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 31/216,000,000 = $1.44 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 13 is quantified as $3.61 \cdot 10^{-5}$. P(A | B) is then calculated as $1.44 \cdot 10^{-7} / 3.61 \cdot 10^{-5} = 3.98 \cdot 10^{-3}$. Therefore, the conditional probability that a directional control problem during landing occurs, given a flight control system failure, is $3.98 \cdot 10^{-3}$.

3.17 ESD 28 – Single engine failure during landing

The following dependencies have been identified for the initiating event for ESD 28 'Single engine failure during landing':

- ESD 1: End state: 'Aircraft continues take-off' – after an aircraft system failure. The initiating event of 'single engine failure' can be influenced by a system failure causing the engine to flame out or overheat.

- ESD 6: End state: 'Aircraft continues flight' – after a take-off with contaminated wings (no stall has occurred). The initiating event of 'single engine failure' can be influenced when the contaminant sheds or breaks loose and is ingested by the engine(s).
- ESD 9: End state 'Aircraft continues take-off '– with a single engine failure during take-off. The initiating event of 'single engine failure' (during landing) can be influenced by a single engine failure during take-off.
- ESD 11: End state: 'Aircraft continues flight damaged' – after an on-board fire. The initiating event of 'single engine failure' is influenced if the fire results in an engine failure.
- ESD 15: End state 'Aircraft continues flight' – after ice accretion on aircraft in flight to which the crew fails to respond appropriately. The initiating event of 'single engine failure' is influenced when ice breaks loose and is ingested by the engine(s).
- ESD 18: End state: 'aircraft continues landing' – with a single engine failure. The initiating event of 'single engine failure (during landing)' can be influenced when partial engine power is available.

3.17.1 Definitions

The initiating event of ESD 28, 'Single engine failure', is defined as a failure of one of the systems that correspond with the ATA codes between 6100 and 6197 or between 7100 and 8097.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew has not aborted the take-off. System failures include 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.

The yellow end state of ESD 6 'aircraft continues flight' describes a situation in which the aircraft takes off with contaminated wings and does not stall after rotation. The other yellow end state of ESD 6 'aircraft continues flight' after the aircraft has stalled after rotation is quantified in [Roelen et al, 2006] with a probability of 0, so this yellow end state is not taken into account in calculating the dependency between ESD 6 and ESD 28.

The yellow end state of ESD 9 'aircraft continues flight' describes a situation in which the aircraft continues the take-off with a single engine failure and the flight crew maintains control. It is assumed that when the take-off is continued with an engine failure, the engine failure condition remains at least during the initial climb.

The yellow end states of ESD 11 ‘aircraft continues flight damaged’ describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 28.

The yellow end states of ESD 15 ‘aircraft continues flight’ describe a situation in which ice accretes on the aircraft in flight and the flight crew maintains control, operate anti/de-icing systems or exit the icing conditions. For the purpose of this assignment both yellow end states summed for quantification of the dependency between ESD 15 and ESD 28.

The yellow end states of ESD 18 ‘aircraft continues landing’ describes a situation in which a single or double engine failure occurs, the flight crew maintains control and continues the landing. A third yellow end state of ESD 18 ‘aircraft continues flight’ after a single engine failure with the flight crew maintaining control of the aircraft is quantified in [Roelen et al, 2006] with a probability of 0. Therefore, this third yellow end state is not considered. For the purpose of this assignment the first and second yellow end states are summed for quantification of the dependency between ESD 18 and ESD 28.

3.17.2 Quantification

ESD 1 – ESD 28

$P(A \cap B)$ represents the probability of a single engine failure during landing in combination with a system failure during take-off, after which the take-off is continued. The probability that a failed engine is restarted during flight is in [Roelen et al, 2006] derived to be 0. Therefore, it is assumed that any combination of an engine and system failure during take-off, which requires an unscheduled landing, still exists during landing. The SDR database is used to identify relevant occurrences and the original query is rebuilt with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be an engine failure:
    - ATA 6100-6197 Propeller/rotor;
    - ATA 7100-8097 Powerplant and accessories;

- Flight phase is take-off;
- Keyword contains AFFECT SYSTEMS or OTHER AFFECT SYSTEMS.

Aborted take-offs are excluded from the dataset.

This query results in 20 occurrences in which an engine failure occurred in combination with a system failure during take-off, after which the take-off is continued. Of these, 19 resulted in an unscheduled landing with an engine failure.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 19/216,000,000 = $8.80 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $8.80 \cdot 10^{-8}/1.20 \cdot 10^{-5} = 7.33 \cdot 10^{-3}$. Therefore, the conditional probability that an engine failure during landing occurs, given a system failure during take-off, after which the take-off is continued is $7.33 \cdot 10^{-3}$.

ESD 6 – ESD 28

$P(A \cap B)$ represents the probability of a single engine failure during landing in combination with the aircraft taking off with contaminated wings. The original dataset is rebuilt with the additional inclusion criteria:

- Narrative contains the word: "*wing*"

This query results in 42 occurrences, but none of them are considered relevant for quantification of this dependency. However, In [Roelen et al, 2006] an analysis has been made with regard to consequences of taking off with contaminated wings. The results indicate that the NLR Air Safety Database contains 1 case in which a take-off with contaminated wings results in a double engine failure and subsequent forced landing. This dataset covers the years 1990-2003 and 387,000,000 flights.

Since this dataset covers 387,000,000 flights, $P(A \cap B)$ is calculated as 1/387,000,000 = $2.58 \cdot 10^{-9}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 6 is quantified as $9.90 \cdot 10^{-7}$. P(A | B) is then calculated as $2.58 \cdot 10^{-9}/9.90 \cdot 10^{-7} = 2.61 \cdot 10^{-3}$. Therefore, the conditional probability that an engine failure during landing occurs, given a take-off with contaminated wings, is $2.61 \cdot 10^{-3}$.

ESD 9 – ESD 28

$P(A \cap B)$ represents the probability of a single engine failure during landing in combination with a single engine failure during take-off, after which the take-off is continued.

The probability that a failed engine is restarted during flight is in [Roelen et al, 2006] assumed to be 0. Therefore, the conditional probability that a single engine failure during landing occurs, given a single engine failure during take-off, after which the take-off is continued, is estimated to be 1.

ESD 11 – ESD 28

$P(A \cap B)$ represents the probability of a single engine failure during landing in combination with an in-flight fire.

To identify relevant occurrences the original query was rebuilt to cover all flight phases and the following additional inclusion criterion is added:

- Keywords contain at least one of the words: “FLAME” Or “SMOKE” Or “FLAME/FIRE”.

Aborted take-offs are excluded from the dataset.

This query results in 46 engine failures during landing in combination with an in-flight fire.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 46/216,000,000 = $2.13 \cdot 10^{-7}$/flight. In [Roelen et al, 2006], the yellow end states of ESD 11 are quantified as $1.50 \cdot 10^{-6}$ or $2.14 \cdot 10^{-6}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 28. This results in a probability of $1.50 \cdot 10^{-6} + 2.14 \cdot 10^{-6} = 3.64 \cdot 10^{-6}$. P(A | B) is then calculated as $2.13 \cdot 10^{-7}/3.64 \cdot 10^{-6} = 5.85 \cdot 10^{-2}$. Therefore, the conditional probability that an engine failure during landing occurs, given an in-flight fire is $5.85 \cdot 10^{-2}$.

ESD 15 – ESD 28

$P(A \cap B)$ represents the probability of a single engine failure during landing in combination with ice accretion on the aircraft in flight. The original query is rebuilt with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be an engine failure:
    - ATA 6100-6197 Propeller/rotor;
    - ATA 7100-8097 Powerplant and accessories;
- Flight phase is take-off, climb, cruise, descent, approach and landing;
- Keywords contain F.O.D.;
- Narrative contains the word “*ice*”.

Aborted take-offs are excluded from the dataset.

This query results in 210 occurrences in which an engine failure occurred in combination with F.O.D. from birds, ice or other sources. This dataset is further analysed to identify the occurrences in which ice is ingested in the engines. This analysis results in 20 occurrences in which an engine failure during flight is related to ice ingestion or ice hitting the engine/propeller.

Since the dataset covers 216,000,000 flights, $P(A \cap B)$ is calculated as 20/216,000,000 = $9.26{\cdot}10^{-8}$/flight. In [Roelen et al, 2006], the yellow end states of ESD 15 are quantified as $4.39{\cdot}10^{-8}$ or $1.96{\cdot}10^{-5}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 15 and ESD 28. This results in a probability of $4.39{\cdot}10^{-8} + 1.96{\cdot}10^{-5} = 1.96{\cdot}10^{-5}$. P(A | B) is then calculated as $9.26{\cdot}10^{-8}/1.96{\cdot}10^{-5} = 4.72{\cdot}10^{-3}$. Therefore, the conditional probability that an engine failure during landing occurs, given ice accretion on the aircraft during flight, is $4.72{\cdot}10^{-3}$.

ESD 18 – ESD 28

$P(A \cap B)$ represents the probability of a single engine failure during landing in combination with a single engine failure in flight. The probability that a failed engine is restarted during flight is in [Roelen et al, 2006] derived to be 0. Therefore, the conditional probability that a single engine failure during landing occurs, given a single engine failure during flight, is estimated to be 1.

3.18 ESD 29 – Thrust reverser failure

The following dependencies have been identified for the initiating event for ESD 29 'Thrust reverser failure':

- ESD 1: End state: 'Aircraft continues take-off' – after an aircraft system failure. The initiating event of 'thrust reverser failure' can be influenced by a system failure causing the engine to flame out or overheat, or by failure of the propeller pitch control.
- ESD 11: End state: 'Aircraft continues flight damaged' – after an on-board fire. The initiating event of 'thrust reverser failure' is influenced if the fire results in a failure of the thrust reverser or propeller pitch control system.

3.18.1 Definitions

The initiating event of ESD 29, 'Thrust reverser failure', is defined as a failure of systems corresponding with ATA code 7830 for aircraft with jet propulsion and ATA code 6120 for aircraft with propeller propulsion.

The yellow end state of ESD 1 'aircraft continues take-off' describes a situation in which a system failure occurred during take-off and the flight crew has not aborted the take-off. System failures include 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.

The yellow end states of ESD 11 'aircraft continues flight damaged' describe a situation in which an on-board fire occurs during flight and the fire is either extinguished or does not propagate. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 29.

3.18.2 Quantification

ESD 1 – ESD 29

$P(A \cap B)$ represents the probability of a thrust reverser failure during landing in combination with a system failure during take-off, after which the take-off is continued. The original dataset in [Roelen et al, 2006] considers thrust reverser failures during approach and landing only. It is assumed that any combination of a thrust reverser and system failure during take-off, which requires an unscheduled landing, still exists during landing.

The SDR database is used to identify relevant occurrences and the original query is rebuilt with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be an engine failure:
  - o ATA 7830 Thrust reverser system;
  - o ATA 6120 Propeller control system;
- Flight phase is take-off;
- Keyword contains AFFECT SYSTEMS or OTHER AFFECT SYSTEMS.

Aborted take-offs are excluded from the dataset.

This query results in 11 occurrences in which a thrust reverser failure occurred in combination with a system failure during take-off, after which the take-off is continued. Of these, 10 resulted in an unscheduled landing with a thrust reverser failure.

Since the dataset covers 260,200,000 flights for jet (equipped with reversers) and propeller aircraft, $P(A \cap B)$ is calculated as 10/260,200,000 = $3.84 \cdot 10^{-8}$

/flight. In [Roelen et al, 2006], the yellow end state of ESD 1 is quantified as $1.20 \cdot 10^{-5}$. P(A | B) is then calculated as $3.84 \cdot 10^{-8}/1.20 \cdot 10^{-5} = 3.20 \cdot 10^{-3}$. Therefore, the conditional probability that a thrust reverser failure during landing occurs, given a system failure during take-off, after which the take-off is continued, is $3.20 \cdot 10^{-3}$.

ESD 11 – ESD 29

$P(A \cap B)$ represents the probability of a thrust reverser failure during landing in combination with an in-flight fire. The flight phase of landing is also considered as in-flight. To quantify this probability the original dataset is rebuilt with the following inclusion criteria:

- Incident/accident takes place between 1-1-1985 and 31-12-2003;
- Only air carrier operations are considered;
- Failure of any of the following systems is considered to be an engine failure:
  - ATA 7830 Thrust reverser system;
  - ATA 6120 Propeller control system;
- Flight phase is approach or landing.

False warnings are excluded from the dataset.

The query results in 4 occurrences in which a propeller control system or thrust reverser failure occurs in combination with a fire. In none of the 4 cases flight crew tried to extinguish the fire.

Since the dataset covers 260,200,000 flights for jet (equipped with reversers) and propeller aircraft, $P(A \cap B)$ is calculated as 4/260,200,000 = $1.54 \cdot 10^{-8}$ /flight. In [Roelen et al, 2006], the yellow end states of ESD 11 are quantified as $1.50 \cdot 10^{-6}$ or $2.14 \cdot 10^{-6}$. Since both yellow end states lead to the same situation, both probabilities are summed for quantification of the dependency between ESD 11 and ESD 28. This results in a probability of $1.50 \cdot 10^{-6} + 2.14 \cdot 10^{-6} = 3.64 \cdot 10^{-6}$. P(A | B) is then calculated as $1.54 \cdot 10^{-8}/3.64 \cdot 10^{-6} = 4.22 \cdot 10^{-3}$. Therefore, the conditional probability that thrust reverser failure during landing occurs, given an in-flight fire, is $4.22 \cdot 10^{-3}$.

3.19 ESD 30 – Aircraft encounters unexpected wind

No dependencies have been identified for the initiating event of ESD 30 ‘Aircraft encounters unexpected wind’.

3.20 ESD 31 – Aircraft are positioned on collision course

The following dependency has been identified for the initiating event for ESD 31 'Aircraft are positioned on collision course':

- ESD 2: End state: 'Aircraft continues take-off' - after an air traffic related event. The initiating event of 'aircraft are positioned on collision course' can be influenced by an ATC event if it involves possible separation infringements with a departure from another runway, a missed approach or an approach to another runway.

3.20.1 Definitions

The initiating event of ESD 31, '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]. Airproxes are classified into four different categories (A-D) with classes A and B being "risk bearing" proximities.

The yellow end state of ESD 2 'aircraft continues take-off' describes a situation in which ATC instructs the flight crew to reject the take-off but the flight crew do not comply, or an ATC event occurs during the take-off roll but neither ATC nor the flight crew detects it or reacts to it.

3.20.2 Quantification

ESD 2 - ESD 31

$P(A \cap B)$ represents the probability of an airprox in combination with an air traffic related event during take-off, after which the take-off is continued.

The frequency of airproxes in four European states has been used in [Roelen et al, 2006] for the quantification of the initiating event of ESD 31. These frequencies, however, do not provide further details with regard to the nature of the airprox. Therefore, the NLR Air Safety Report database is queried for quantification of the dependency between ESD 2 and ESD 31. The following inclusion criteria are applied:

- Incident/accident takes place between 1-1-1992 and 31-12-2005;
- BASIS REFERENCE 1/2/3 contains AIRPROX;
- Flight phase is take-off.

Occurrences in which the take-off is aborted are excluded from the dataset.

This query results in 62 airproxes during take-off. This dataset is further analysed to identify occurrences in which the airprox occurs during take-off in combination with an air traffic related event. This analysis results in 1 occurrence in which an airprox occurs during take-off in combination with conflicting (helicopter) traffic.

Since the dataset covers 14,000,000 flights, $P(A \cap B)$ is calculated as 1/14,000,000 = $7.14 \cdot 10^{-8}$/flight. In [Roelen et al, 2006], the yellow end state of ESD 2 is quantified as $9.52 \cdot 10^{-8}$. P(A | B) is then calculated as $7.14 \cdot 10^{-8}/9.52 \cdot 10^{-8} = 7.50 \cdot 10^{-1}$. Therefore, the conditional probability that an airprox occurs, given an air traffic related event during take-off, after which the take-off is continued, is $7.50 \cdot 10^{-1}$.

4 Final remarks

In this report, 42 dependencies between yellow end states and initiating events of other accident scenarios are identified, qualitatively described and quantified with conditional probabilities. In 10 cases it is estimated that there is no dependency between the ESDs, since conditional probabilities cannot not be obtained from the data available. In 3 cases the conditional probabilities are calculated as being 1, so these ESDs are fully dependent. In the remaining 29 cases the conditional probabilities are calculated between 0 and 1, so these ESDs are partially dependent.
For future research it is recommended to assess the significance of the difference between the probability of the initiating event occurring and the conditional probability of the initiating event occurring, given a certain yellow end state.

When the dependencies are described, it is assumed that both accident scenarios may occur sequentially, i.e. one scenario has to be finished (yellow end state) before another can start (initiating event). However, yellow end states may also affect certain pivotal events in another accident scenario. This implies that the development of one accident scenario may be influenced by one or more other scenarios, thereby affecting the outcome. Further research has to derive the dependencies between yellow end states and pivotal events.

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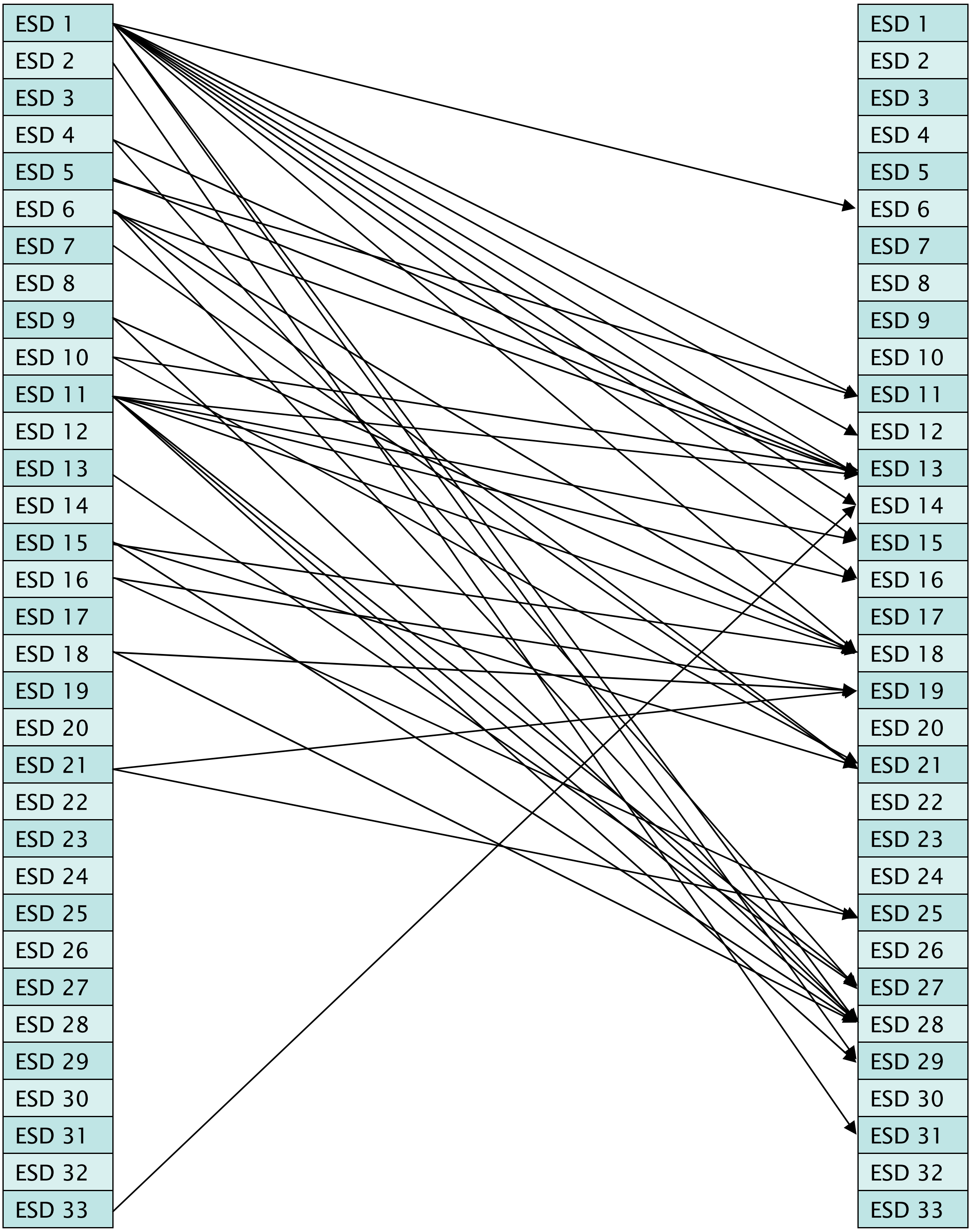
Appendix A ESD DEPENDENCIES



Appendix B 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 characterize 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 the year 1960 and 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.4. Next to 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.

B.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. The FAA SDR program has been criticized 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.

B.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 covers 14 million flights between 1992 and 2005.

B.3 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.

B.4 AVIATION SAFETY REPORTING SYSTEM

The Aviation Safety Reporting System (ASRS) is a confidential incident reporting system in the Unites 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.