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Development of a Rotorcraft Causal Model Prototype

January 2015

Final Report

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16. Abstract

The report describes the development of a proof-of-concept causal risk model for rotorcraft operations. The scope of the current rotorcraft causal model is helicopter emergency medical services and Air Tour operations. The model consists of a set of generic accident scenarios that represent potential accident and accident avoidance scenarios in the form of event sequence diagrams (ESD) with generic fault trees describing the causal factors of the ESD events. The frequency of occurrence of each model element was estimated based on accident, incident, and occurrence data. The quantification is based on a combination of data sources: the National Transportation Safety Board accident/incident data, two voluntary occurrence reporting programs (Aviation Safety Reporting System and the Concern Network), and the Federal Aviation Administration's (FAA's) Service Difficulty Report database. The qualitative ESDs provide a starting point to gain a better understanding of accident scenarios and cause-effect relationships. The model provides a basis for safety assessment and mitigation based on integrated data analysis and knowledge. The model provides a framework to identify in a structured manner where and how changes to the current aviation system impact accident scenarios and influence accident probability. The quantified model supports the prioritization of accident scenarios and determining the relative importance of hazards to the accident probability. It enables the estimation of the change in accident probability as a result of the impact of operational or system changes on model elements. A portion of a Part 135 certificate holder functional model was mapped to the causal model. This effort showed that it is technically feasible to use the causal model as a prioritization tool for Part 135 certificate holder functions. For many detailed events in the current model, data is limited or not available in the datasets used. This report presents five recommendations to improve the quantification. The availability, quality, and level of detail of the data are important enablers for causal model development and quantification. The main reason to report incidents is to be able to use the acquired knowledge to prevent accidents. It is therefore necessary to determine causal relations between incidents and accidents. Hence, the type of information collected in incidents should be similar, as in accidents. It is recommended that the FAA encourage aviation professionals to report on relevant operational circumstances and causal factors. The reporting form should consider the causal model elements as reporting fields to enable populating the model with occurrence data.

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LIST OF ABBREVIATIONS AND ACRONYMS

AND	A gate that indicates that the top event occurs if all of the input events occur
ASRS	Aviation Safety Reporting System
ATA	Air Transport Association of America
ATC	Air Traffic Control
ATCo	Air Traffic Controller
CAST	Commercial Aviation Safety Team
CFIT	Controlled flight into terrain
CFR	Code of Federal Regulations
CG	Center of gravity
CICTT	CAST/ICAO Common Taxonomy Team
EMS	Emergency medical services
ESD	Event sequence diagram
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FT	Fault tree
HEMS	Helicopter emergency medical services
ICAO	International Civil Aviation Organization
IE	Initiating event
IFR	Instrument flight rules
IHST	International Helicopter Safety Team
INIT	A gate that indicates that the top event occurs if the input event occurs in the presence of a condition that must occur before the input can result in the top event
LOC	Loss of control
MOR	Mutually exclusive OR gate that indicates that the top event occurs if one of the input events occurs, but both events cannot occur simultaneously
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NPRM	Notice of Proposed Rulemaking
NTSB	National Transportation Safety Board
OR	Gate that indicates that the top event occurs if at least one of the input events occurs
SA	Situational Awareness
SDR	Service difficulty report
SME	Subject matter expert
SMS	Safety Management System
SPI	Safety performance indicator
TAWS	Terrain awareness and warning system
VFR	Visual flight rules

EXECUTIVE SUMMARY

The project objective was to develop a limited, quantified causal model for rotorcraft operations as a proof of concept. The causal model consists of 19 generic accident and accident-avoidance scenarios in the form of event sequence diagrams (ESDs). The causal factors leading to the events in the ESDs are modeled in the form of fault trees (FTs) that are tied to the ESD events. The scope of the study was helicopter emergency medical services (HEMS) air tour/sightseeing operations. Because of the generic nature of the qualitative causal model, the current set of ESDs is also applicable to other types of helicopter operations. In this study, it was decided to develop FTs to a level of detail for which it was still possible to quantify the events with data and the cause-effect mechanisms could be understood and modeled. There is a need to consider more detailed factors, such as maintenance, operational, and human factors issues, as well as pilot levels of experience and training. Data on such factors in incidents and occurrences were generally not available in the datasets used in this study. The Federal Aviation Administration (FAA) and model developers need to balance the development of a qualitative FT with more details against the availability of data for model quantification.

Quantification of the probabilities of the model elements was performed for HEMS and air tour/sightseeing operations. The quantification effort integrated different datasets, making maximum use of existing data. This approach provides an integrated review of accident, incident, and occurrence data. Most safety analyses consider a data source by itself and do not integrate data from various sources in a structured manner. The model elements were quantified using a combination of accident, incident, and occurrence data for the United States from 2005–2010. Accident and serious incident data from the National Transportation Safety Board were used to quantify the probability of each accident scenario. The quantification of initiating and pivotal events of the ESDs was based on a combination of accident, incident, and occurrence data. Occurrence data were collected from two voluntary reporting systems: the Aviation Safety Reporting System database and the Concern Network, which is a database specific to the Emergency Medical Services (EMS) community. In addition, system failure data was derived from the FAA's Service Difficulty Report database. In a few instances, engineering judgment was applied when data was not available.

A generic functional model of Part 135 certificate holders was developed by the FAA and partners in a previous study. In a separate effort, the FAA reviewed this functional model to identify critical functions applicable to HEMS and tour operations. This review resulted in a subset of 51 functions from the complete functional model. The failure or incorrect performance of functions could impact the safety of the certificate holder's operation. Hence, a relationship can be defined between the functional model and the rotorcraft causal model. The 51 critical functions were mapped to the rotorcraft causal model to prioritize functions based on the relative contribution of the function to the occurrence of an initiating event (IE) and the relative contribution of a function to accident probability. The research team assessed each function to determine if it could impact or had an impact on the IE or pivotal events of each ESD. If so, the function was mapped to the ESD. The current study mapped the functions to the base events of ESD R-14 (loss of power) to determine the feasibility and to compare the outcomes of mapping of a function to the base events and mapping of a function to the ESD initiating and pivotal events.

The function can be weighted and ranked based on three weight factors: (1) the cumulative probability of the ESD IEs which the functions are mapped, which is a measure of the importance of the functions in relation to the occurrence of the IEs; (2) the cumulative probability of the accident end states of the ESDs to which the functions are mapped, which is a measure of the importance of the functions in relation to the accident probability; and (3) the cumulative conditional probability of the IEs leading to accident end states in the ESDs to which the functions are mapped.

This approach helps the analyst to assess the importance of functions in relation to the IE occurrence and accident probability, and to prioritize functions accordingly. The added value of this approach is that the ranking of functions is data-driven because the weight factor for the ranking is based on a structured and integrated analysis of accidents, incidents, and occurrences from various data sources.

The current model can be used in the following areas:

- The model provides a basis for safety assessment and risk mitigation based on integrated data analysis and knowledge. The qualitative ESDs and FT diagrams provide a starting point to gain a better understanding of accident and incident scenarios and cause-effect relationships.

- The model structure supports systematic data analysis. The available accident, incident, and occurrence data were mapped on the accident scenarios and FTs. The quantified model supports the prioritization of accident scenarios and determining the relative importance of hazards to the accident probability.

- The impact of changes to the current aviation system, such as Operational Improvements from NextGen, can be qualitatively evaluated with the model. The model provides a framework that can be used to identify, in a structured manner, where and how changes impact accident scenarios, thus influencing accident probability. The quantitative model enables the calculation of the change in accident probability as a result of a change in the probability of a model element. If the effect of a change on a model element can be quantified, then the effect of this change on accident probability can be assessed.

- The mapping effort in the current study showed that it is technically feasible to use the causal model as a prioritization tool for the Part 135 certificate holder functions. A limitation in the mapping is the current maturity level of the rotorcraft causal model and functional model.

The following recommendations are made:

- It is recommended that the scope of the model be expanded and that ESDs and FTs be further developed to include other types of operations. The FTs may be further decomposed, which would provide more insight in specific causal factors and would also help in integrating the functional model with the causal model elements. The FAA and

model developers need to balance the development of a qualitative FT with more details against the availability and quality of data for model quantification.

- It is recommended to review the current set of FTs in the light of available data to identify areas for improvement. For many FT events in the current rotorcraft causal model, data, if available at all, is limited in the datasets that have been collected. Five recommendations are made in this report to improve the quantification, including the use of expert judgment and expanding the data sample by timeframe and data sources used. The quantification of the FTs may be improved not only by considering other approaches in the quantification process itself, but also by possibly improving definitions of events and the structure in the FT diagrams.

- If the user has a need for a quantified causal model, it is recommended to consider all available data before FT development starts. The available data and the information contained in the data are important enablers in FT development and quantification.

- The main reason to report incidents and occurrences is to be able to use the acquired knowledge to prevent them. Therefore, it is necessary to determine causal relations between incidents and accidents. Hence, the type of information collected for an incident should be similar to that collected for an accident. Data on operational and causal factors in incidents and occurrences were generally not available in the datasets used in this study. The quantified model is useful at identifying the data needed. It has been recommended that the FAA adopt the causal model as a formal analytical tool and then drive the data collection. It is recommended that data collection programs and reporting forms consider the model elements (e.g., FT base events) as reportable events to enable populating the causal model with occurrence data. Because many organizations are collecting data, feedback from the causal model to the source collectors (e.g., regarding the required data and gaps in the current data collection) could result in better data collection and better quality data, while also improving the causal model.

- The functions in the Part 135 certificate holder functional model should be developed in more detail, specifying safety critical tasks or activities, to provide sufficient granularity and to enable the analyst to assess the impact of specific functions or changes to functions on the rotorcraft causal model. The mapping of these functions to the base events of the rotorcraft causal model is recommended because it shows the analyst where or how functions possibly impact accident scenarios.

- It is recommended that the Concern Network encourage EMS professionals to report occurrences in more detail and that it provide a reporting form for relevant operational circumstances and causal factors. On the reporting form, causal model elements should be considered reporting fields to support the further development and quantification of the current rotorcraft causal model.

1. INTRODUCTION.

1.1 PROJECT BACKGROUND.

In 2005, the International Helicopter Safety Team (IHST) was formed to lead a government and industry cooperative effort to address the factors that were affecting the unacceptable accident rate in the helicopter world. The IHST was modeled after the Commercial Aviation Safety Team (CAST), which was established in 1998 to support the reduction in the fatal accident rate by 80% in 10 years in commercial air transport (or Part 121 operations). The IHST established a rotorcraft safety goal to reduce the accident rate by at least 80% by 2016 [1]. For the baseline, an accident rate of 9.1 accidents per 100,000 flight hours (2001–2005 average) has been determined. The target is 1.8 accidents per 100,000 flight hours. The process adopted by IHST is data-driven and "focused on identifying and removing links in the accident causal chain, rather than focusing on 'probable cause' determinations."

The Federal Aviation Administration (FAA) needs to develop a risk model that will provide a solid foundation for conducting risk analyses and identifying safety issues along with its mitigation strategies. The ultimate goal is to reduce the rotorcraft fatal accident rate.

1.2 PROJECT OBJECTIVE.

The project objective is to develop a limited rotorcraft causal model as a proof of concept. The project will develop a set of generic accident scenarios, which will be applicable across all types of helicopter operations. The actual quantified causal model is limited because it focuses on two types of operations: air tour/sightseeing and emergency medical services (EMS).

Scoping of the model development was necessary because of available resources and the need for a proof-of-concept model. The FAA decided to scope the model development based on air tour/sightseeing and EMS helicopter operations. The FAA selected these two operations based on public interest. Accidents and incidents with air tour operators and helicopter emergency medical services (HEMS) operators in recent years have resulted in much public interest and resulted in several safety studies (e.g., reference 10) and safety initiatives. This scope does not imply that other types of helicopter operations should be excluded in a safety analysis. To meet the accident reduction goal of the IHST, all types of operations should be examined for safety issues and potential safety improvements.

The project will develop a set of accident scenarios and fault trees (FTs) that represent air tour/sightseeing and EMS helicopter operations. The model elements will be quantified using the available data, complemented by expert judgment when required, for these two types of operations.

1.3 REPORT STRUCTURE.

The document structure is as follows:

1. Section 2 provides general background on causal modeling and explains the causal modeling methodology, approach, and scope in this study.

2. Section 3 describes the development of accident scenarios and FTs.

3. Section 4 covers the quantification of the model elements.

4. Section 5 contains the diagrams of the accident scenarios, event sequence diagrams (ESDs) and FTs, including definitions of events and quantification results for each model element.

5. Section 6 explains the mapping of functions from the Part 135 certificate holder functional model to the rotorcraft causal model.

6. Section 7 discusses the study and its results.

7. Section 8 provides recommendations.

8. Appendix A contains definitions.

9. Appendix B contains definitions of flight phases.

10. Appendix C describes data sources used in this project.

11. Appendix D contains exposure data used in this project.

12. Appendix E includes the results of the mapping of functions to ESDs.

2. PROPOSED METHODOLOGY AND APPROACH.

2.1 BACKGROUND ON CAUSAL MODELING.

A causal model represents events or conditions; the model's structure captures cause-effect relationships between these elements and, ultimately, their effect on unsafe outcomes. An unsafe outcome is either an accident or serious incident. Such a model is a causal model because it links cause-effect relations contributing to risk. The risk of an event is the combination of the severity level of the event and the likelihood of that severity level. The backbone of a causal model is a set of accident scenarios, which are further detailed into FT submodels. The model elements and causal relationships are established combining thorough analysis of accidents, incidents, and occurrences, as well as engineering knowledge. The (conditional) probability of occurrence of all model elements and their relations are quantified from existing data, complemented with subject matter expert (SME) judgment if data is not available.

The Dutch National Aerospace Laboratory (NLR) has been developing causal models and methods, techniques, data, and tools to develop such models since 1994 [2–8]. The need for such models was identified at that time because legislation was put in place to regulate not only the noise and emissions of Amsterdam Airport Schiphol, but also the third party risk to the population living around the airport. With a cap on the maximum allowable risk, it became important to be able to show the expected impact on safety risk of safety improvement measures. It was necessary to have a model to demonstrate that safety improvements would enable airport

capacity growth within the maximum allowable risk. Two decades of research and development followed, as well as application of models explaining and quantifying the systemwide safety impact of change.

Previous research studies delivered the methodology for developing causal risk models and several projects delivered limited, but detailed, causal models, as well as a full-scale causal model for commercial air transport operations of fixed-wing aircraft. These projects provide much knowledge and expertise in the domain of causal model development.

2.2 MODEL APPLICATIONS.

Causal models are powerful tools that can be used within the Safety Management System (SMS) framework for hazard identification and assessment, safety risk assessment, safety performance indicators (SPIs), and continuous safety monitoring and safety data organization (see appendix A for a definition of hazard and risk). The potential users of causal models are the regulator/authority and industry. Academia are using causal models for ongoing research in risk assessment and risk modeling of various aviation domains.

The capabilities of causal models in relation to the following four application areas are discussed in the following sections: Hazard Identification and Assessment; Safety Risk Assessment; SPIs; and Continuous Safety Monitoring and Organization of Safety Data.

2.2.1 Hazard Identification and Assessment.

The causal model provides a model-based hazard classification system by an organized representation of hazards. It helps to clarify the effect of technical, operational, and managerial factors on the accident risk: the propagation of fault situations or unsafe conditions can be modeled and followed toward an unsafe outcome. In addition, weaknesses in protection against fault propagation can systematically be determined. The model provides an environment for event analysis; data gathering and analysis; and accident precursor analysis. The model is able to provide a ranking of hazards based on their contribution to accident risk. The conditional probabilities of the identified hazards resulting in an accident express the quantitative relative importance of the hazards to an accident.

2.2.2 Safety Risk Assessment.

A quantitative causal risk model is a proper tool for probabilistic risk assessment that can be used to evaluate the safety significance of abnormal conditions, failures, and incidents, and to provide accident and incident risk estimates. With the model, hazards can be ranked based on their quantitative relative importance to accident risk. The model also supports the evaluation of safety measures to determine the potential benefit of measures so that risk reduction efforts are concentrated in areas that will be most effective.

2.2.3 The SPIs.

A third important application of a causal model is to identify and weigh SPIs. In most organizations, the identification and use of SPIs is largely a matter of opportunity and opinion.

Most SPIs are chosen because data on these items is being collected on a regular basis anyway, and that is often because these items can be observed and recorded relatively easily. Most data collection programs are designed with consideration of the relevance of the items to be collected; SMEs are involved in assessing which items would be good indicators of safety performance. However, such efforts suffer from human limitations with regard to understanding complex interactions, systemwide effects, and the interaction of multiple changes.

When mapping SPI schemes on a causal model, it is often clear that some parts of the aviation system are well covered, but other parts (which may have a considerable impact on safety risk) are largely ignored. A good causal model will be very useful in developing an SPI portfolio that provides adequate coverage of all aviation system essential elements.

A common problem worldwide is that, although SPIs are collected, there is very little insight into what a change in an SPI really indicates about safety risk. It is not clear, for example, how a percentage change in SPI frequency of occurrence affects accident probability. Some organizations revert to the weighting of different SPIs by SME to indicate how risk is developing as a whole.

When a causal model is available, it will become clear what a change in a particular SPI says about the development of risk in the aviation system. Through the causal model, SPIs or precursors can be linked to accidents, leading to fatalities or serious injuries. The model provides a mathematical connection of SPIs to the accident rate, or injury and fatality rate. For example, if a model element is selected as SPI and if the frequency of occurrence of this model element changes by x%, the relative change in accident probability as a result of the change in the model element can be determined because of the quantified relation between that model element and the accident probability in the model [9 and 10].

A causal model will also be very useful in designing a set of SPIs in conjunction with changes or safety improvement programs to ensure that the impact of the change is detectable (hence, manageable) well before the impact of the change on safety in the aviation system becomes visible based on, for example, incidents and accidents. In that way, the SPIs are truly predictive.

2.2.4 Continuous Safety Monitoring and Organization of Safety Data.

A fourth important use of causal models lies in the area of organizing the safety performance data as part of the continuous monitoring program. Large volumes of data are currently being collected and kept in various repositories, constituting an important safety resource. Without a causal model, it is difficult to make sense of all the data; evidence of emerging risk may go undetected because there is a limit to how much any organization can do in analyzing the abundance of data.

However, when a causal model is available, the data can be mapped on that model so that possible changes in safety risk can be tracked continuously. The causal model supports analysis of data collected in oversight activities or occurrence-reporting programs to correlate data and findings in different areas and from different sources to improve the aggregate understanding of the system performance.

The causal model effectively provides the bins that the data can be dropped into and also provides insight into how this data relates to safety risk of the air transport system as a whole. Here, too, the causal model may also show that important elements of the air-transport system are not covered by any data collection program and, hence, that emerging risk in these areas will go undetected.

2.3 APPROACH.

It was decided that this project should be consistent with the modeling techniques and approach used in previous projects to allow the exploitation of existing modeling techniques and previously developed causal (sub)models. The modeling techniques applied in previous causal model development projects include ESDs and FTs, which are common tools that have been used for decades in many different domains (e.g., transportation, space, industry, nuclear industry). Until now, the development of aviation causal models was mainly focused on fixed-wing commercial air transport (see section 2.2), but the methodology also applies to a model for rotorcraft operations because the causal modeling technique is independent of the operation, type of aircraft, environment, etc.

Accident scenarios form the backbone of the causal risk model. The accident and accident avoidance scenarios are represented as ESDs. Figure 1 shows a generic ESD. The ESDs consist of several events:

- One initiating event (IE) with an FT
- Several end states, which are the end state of a sequence of events and represent a safe or unsafe (e.g., accident, incident, damage) outcome
- One or more pivotal events, possibly with an FT

The building blocks of the ESDs are intentionally kept broad and generic. Although every incident and accident is different and unique, a limited number of generic scenarios will cover the majority of potential sequences of events and underlying causes on a generic level. During the development of a causal model for fixed-wing commercial air transport, NLR showed that all accidents within the scope of the model could be mapped on a limited set of generic accident scenarios.

The FTs are used to model initiating and pivotal events in ESDs in more detail and to describe the logical relationship between FT events. The initiating and pivotal events in the ESD are the top events in the FTs (see figure 2).

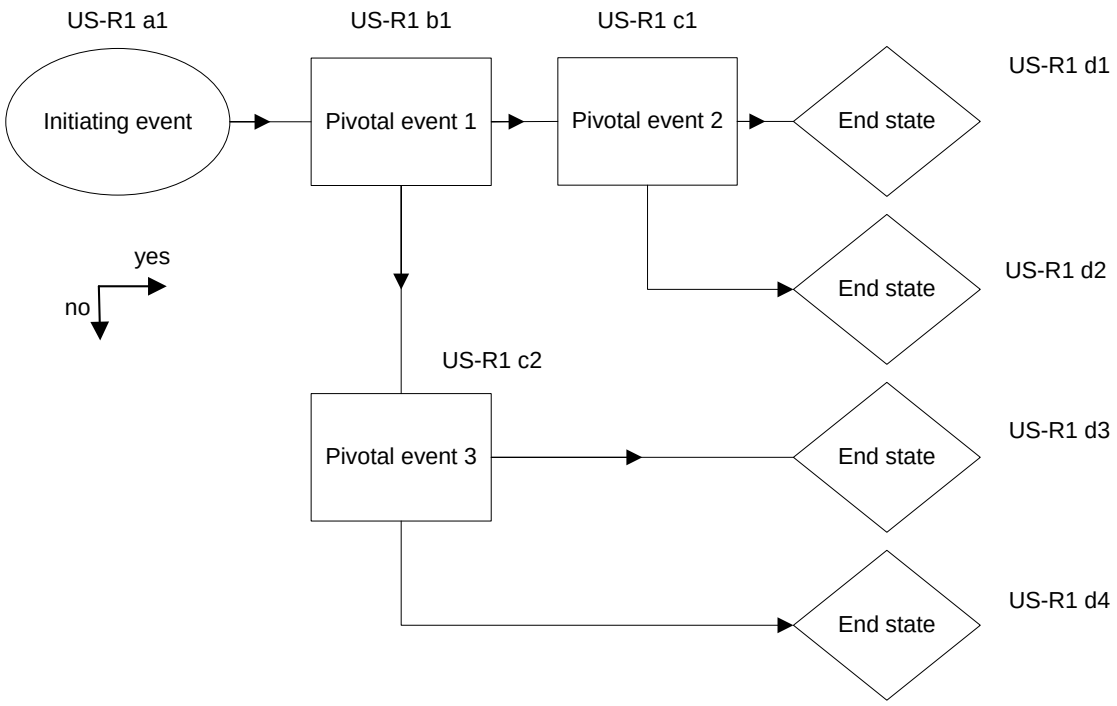


Figure 1. Example of an ESD

Figure 2 shows an FT connected to the IE and two FTs connected to pivotal events. In this example, the pivotal event 2 has no FT, which is sometimes the case in the model and depends on the particular definition of the event. Essentially, when the cause-effect mechanism is not clear, not understood, or cannot be modeled, or when data is not available to support the FT development, the FT is not further developed.

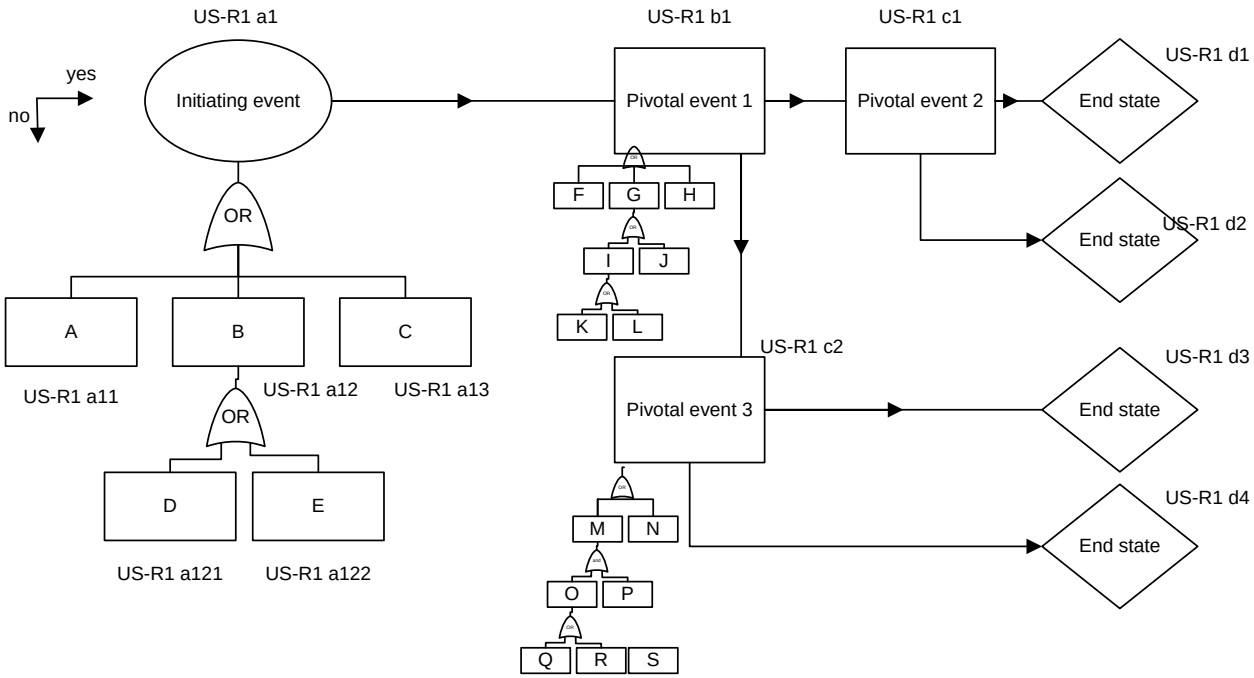


Figure 2. Example of an ESD With FTs

2.4 MODEL SCOPE AND ENVIRONMENT.

2.4.1 Model Scope.

The definition of the scope of the model is important for both the development of the qualitative model and the quantification of model elements. Table 1 shows the different parameters that determine the scope of the model. This scope has been defined in coordination with the FAA.

Table 1. Model Scope for Rotorcraft Causal Model Development and Quantification

	In Scope	Out of Scope
Type of Rotorcraft	Helicopters	Tilt rotor aircraft, gyrocopters, autogyros, gyro glider, unmanned helicopters
Certification Category	Part 27 and Part 29[1]	
Type of Manufacturer	Rotorcraft that have an FAA type certificate, such as Bell, Augusta, Eurocopter, Boeing®, Sikorsky helicopters	Home-built helicopters, and rotorcraft that have no FAA-type certificate
Rotor Types	Single- and two-rotor systems; tail rotor and NOTAR[2] system helicopters	
Engine Type	Turbine and reciprocating engines; Single- and multi-engine	
Weight Class	All	
Type of Operations	Part 135 (operating requirements: commuter and on-demand operations and rules governing persons on board such aircraft); Part 91 (general operating and flight rules); and Part 136	Noncommercial operations, such as test flights, public use (military, federal, state flights, etc.); Part 133 (rotorcraft external load operations); and Part 137 (agricultural aircraft operations)
Schedule	Scheduled and nonscheduled	
Airspace Class	All airspace classes	
IFR/VFR	IFR and VFR	
Landing Sites	All landing sites are considered (e.g., airport, heliport, remote site, hospital rooftop, ship, oil rig)	
Environment	No limitations on terrain conditions (flat, sloping, mountainous, altitude, clear, confined), runway or landing site state/composition (wet, dry, slush, snow, grass, sand, asphalt), and weather conditions (visibility, temp, precipitation, wind, air pressure)	

IFR = instrument flight rules; VFR = visual flight rules

2.4.2 Difference Between Part 91 and Part 135 Operations.

In this study, flight operations conducted under 14 Code of Federal Regulations (CFR) Parts 91 and 135 are considered. Part 91 prescribes rules governing the operation of aircraft within the

[1] Airworthiness standards for normal category rotorcraft (Part 27) and transport category rotorcraft (Part 29).
[2] NOTAR (No Tail Rotor) is the name of an anti-torque system replacing the conventional tail rotor on a helicopter.

United States, including the waters within 3 nautical miles of the U.S. coast. These are generally referred to as general and private aviation operations, whereas Part 135 prescribes rules governing the commuter or on-demand operations ("flying for compensation or hire"). In general, Part 135 regulations are more stringent than Part 91. Part 135 governs, amongst others, visual flight rules/instrument flight rules (VFR/IFR) operating limitations and weather requirements; aircraft and equipment; flight operations; maintenance; and pilot training and experience. Part 135 poses more safety controls on the operation than required by Part 91, including:

- To conduct a Part 135 operation, one is required to hold an Air Carrier certificate or Operating Certificate (as defined in Part 119).
- Part 135 training and maintenance requirements are more stringent than in Part 91.
- Part 135 imposes specific flight crew duty time and rest requirements, whereas Part 91 does not.
- Part 135 operators are required to comply with the drug and alcohol testing requirements as are air carriers operating under Part 121.
- Part 135 regulations contain more strict requirements regarding VFR and IFR operations, minimums, and airport requirements with weather reporting.

2.4.3 Operational Environment for HEMS and Tour Operations.

2.4.3.1 The HEMS Operations.

Air medical transportation has become a key component of health care in many countries throughout the world. Air ambulance operations are aviation operations conducted with helicopters and fixed-wing aircraft to transport patients and donor organs to hospitals/health care facilities. Air medical transport services are particularly important in large countries where traveling time to hospital care may be excessive by surface vehicles or where remote communities might otherwise be deprived of the required level of health care service. In addition to acting as an air ambulance service, aircraft are particularly important in times of national emergency or to provide support to rescue and other emergency services.

The EMS and HEMS are provided in the U.S. by Part 135 air carriers, public entities, hospitals, and EMS providers, and by both profit and not-for-profit organizations. It is estimated by the Association of Air Medical Services that helicopters transport 400,000 patients annually in the U.S. ([11]). A portion of these HEMS operations are conducted in various (often challenging) conditions, such as during poor weather, at night, and at unprepared and unfamiliar landing sites for helicopters (e.g., on a highway, in a field). In addition, there is pressure on the crew to get to the accident site quickly, and then to the hospital.

Air ambulance operations with patients on board or transporting donor organs are carried out under Part 135. However, flights without patients on board may be carried out under Part 91.

The NTSB studied 55 EMS accidents in the period between January 2002 and January 2005, and found that 35 accident flights were conducted with medical crew members (but no patient) on board, under Part 91 [12]. The NTSB study notes that, in particular, the weather/visibility minimums, crew rest requirements, and crew training under Part 135 are stricter than under Part 91. Because these three factors are important in relation to the safety of air ambulance operations, the NTSB concluded that "the FAA should require all EMS operators to comply with Part 135 operations specifications during the conduct of all flights with medical personnel on board" [12]. In October 2010, the FAA issued a Notice of Proposed Rulemaking (NPRM), "Air Ambulance and Commercial Helicopter Operations, Part 91 Helicopter Operations, and Part 135 Aircraft Operations; Safety Initiatives and Miscellaneous Amendments." In this notice, the FAA proposed changes to equipment and operating requirements for commercial helicopter operations, including many specifically for helicopter air ambulance operations. This NPRM requires, for example, "that all helicopter air ambulance operations with medical personnel on board be conducted under the operating rules of Part 135." The impact of this NPRM on the causal model has not been evaluated in the current study.

2.4.3.2 Air Tour Operations.

Air tour operations are conducted in all parts of the U.S. over various types of terrain. This terrain includes, but is not limited to, national parks, fairgrounds, and urban, coastal, and mountainous areas that range from unpopulated to densely populated. The operators conducting these flights as a regular part of their business are commonly known as air tour operators, and their operations are often referred to as commercial air tours. Air tours and sightseeing flights may also take place during charitable, nonprofit, or community events.

Commercial air tours vary in many ways, but certain characteristics apply to nearly all of them:

1. A single pilot typically conducts the flight during daylight hours in a single-engine airplane or helicopter.

2. Flights are typically conducted in visual meteorological conditions, often without radar coverage or traffic advisories from an air traffic control (ATC) facility.

3. Flights may be conducted near popular scenic areas geographically limited in size and in dense air traffic, in which the mix of airplanes and helicopters may have different flight characteristics (e.g., speed and maneuverability).

4. During these sightseeing flights, the pilot is usually talking to passengers about sights or the flight. Because of all of these factors and characteristics, a pilot must use heightened vigilance and greater precision in navigation to conduct a commercial air tour successfully and safely.

In addition, terrain is often a major factor considered in a safely conducted flight. Many popular scenic areas are located in remote, rugged terrain, where the attraction is the natural beauty of the site. To view the natural beauty, commercial air tours are normally conducted at relatively low altitudes, between 500 and 1500 feet above ground level. Flights conducted at these altitudes may be close to obstructions and are often alongside higher terrain. In addition, many air tour

operators conduct flights over water. When the terrain factor is added to those discussed above, you have a unique industry needing equally unique regulations to ensure a safe and pleasurable experience for the passenger [13].

The scope includes both tour operators that conduct flights under Part 135 (or Part 136 commercial air tours) and Part 91 operations. In 14 CFR Part 136, a commercial air tour is defined as "a flight conducted for compensation or hire in an airplane or helicopter where a purpose of the flight is sightseeing. Part 135 regulations allow some air tour operators to fly for hire under Part 91 regulations for general aviation if they operate within a 25-mile radius of their takeoff point and do not make any interim landings" [14]. Currently, the FAA requires air tours operating under Part 91 regulations to obtain an FAA letter of authorization (Section 91.147). If one operates under Part 91, the rule does not require many of the standards in place for Part 135 operators, including pilot-training programs, more stringent maintenance policies, flight time limitations, crew rest restrictions, and an FAA surveillance program [14]. For air tours in national parks (e.g., the Grand Canyon), specific regulations apply (e.g., Part 136, or, for the Grand Canyon, SFAR 50-2, Part 93, subpart U, and Part 119 can also apply).

3. DEVELOPMENT OF ESDs AND FTs.

3.1 DEVELOPMENT OF ESDs.

3.1.1 Accident Definition.

The term "accident" is precisely defined by the International Civil Aviation Organization (ICAO) Annex 13. From this definition, four accident categories are determined, for which eight archetypes of accidents can be defined. Generic accident scenarios are subsequently developed for each accident archetype in the form of ESDs. Accident scenarios describe the combination of events or conditions, including the sequence of occurrence resulting in the transition of a hazard to an accident.

The definition of accident used by the NTSB is generally consistent with the ICAO definition of an accident (see appendix A). The research team has evaluated them and concluded that there are minor differences that do not affect the outcome of this research study.

3.1.2 Accident Categories.

The accident categories should be mutually exclusive, so their results can be added together, and should give complete coverage of all possible accidents. A helicopter can be destroyed or sustain major damage in the following three ways:

1. Collision of the helicopter with the ground
2. Collision of the helicopter with an object (including another aircraft)
3. General disintegration or structural damage of the helicopter

These three cases could result in fatalities and injuries. However, injuries and fatalities also are possible without having helicopter damage; therefore, this category is added as the fourth accident category. Security-related events are considered to be outside the scope of this study

because they involve willful acts of external actors (criminals, terrorists, etc.) to cause damage and injuries/fatalities.

Accordingly, accidents are divided into the following four categories:

1. Collision of the helicopter with the ground
2. Collision of the helicopter with an object
3. General disintegration or structural damage of the helicopter
4. Personal injury/fatality without helicopter damage

3.1.3 Accident Archetypes.

The four accident categories are further subdivided into accident archetypes, the definitions of which are listed in table 2. Definitions of each of the accident archetypes have been developed, taking into account existing definitions, in particular the CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories definitions (ICAO/CAST 2011, version 4.2). The CICTT definitions of occurrence categories could not be used directly, however, because these are designed to permit the association of multiple categories within an accident. In this report, accident archetypes are mutually exclusive. Figure 3 summarizes the breakdown of the ICAO accident definition into accident categories and accident archetypes.

Table 2. Definition of Accident Categories and Accident Archetypes

Accident Category	Accident Archetype	Definition
Personal injury/fatality (with little or no damage to the helicopter)	Abrupt maneuver	Abrupt maneuver of the helicopter due to an action by pilot (intentional or unintentional) or external factors, such as turbulence or system malfunction.
	Cabin environment	Occurrence involving the condition of the cabin environment leading to occupant fatalities or injuries, such as fire, toxic fumes, or lack of oxygen. Helicopters do not have a pressure cabin, but may operate at high altitude (e.g., EMS, heli-skiing).
	External third party injury/ fatality	Occurrence leading to fatalities or injuries of persons not onboard the helicopter without damaging the helicopter (e.g., as result of hoist operations or contact with main or tail rotor), including injury/fatality due to direct contact with any part of the aircraft, as well as parts that have become detached from the aircraft. External load operations are excluded in this study.
Collision of the helicopter with the ground	Uncontrolled collision with ground (LOC)	The LOC of the helicopter while in flight, landing, taking off, taxiing, or standing. This includes engine failure, loss of tail rotor effectiveness, dynamic rollover, vortex ring state, etc. The LOC may be induced by the pilot, by system malfunctions, or by environmental factors (e.g., adverse weather conditions). The LOC may be the result of an in-flight collision with an obstacle.
	Controlled flight into terrain (CFIT)	In-flight collision with terrain, water, or obstacle without indication of (prior) LOC. The CFIT includes collision with trees, power lines, aerial masts, etc. It includes undershoot or overshoot: a touchdown off the runway/ helipad/ helideck surface or unapproved landing sites.
Collision of the helicopter with an object	Midair collision	Collision between aircraft in flight (i.e., helicopter vs. another airborne vehicle). Bird strike is excluded because it is considered a potential causal factor in an LOC or structural overload/failure accident type.
	Collision on ground	A collision of the helicopter at the airport, heliport, remote site, or landing site with a helicopter, an aircraft, person, animal, ground vehicle, building, structure, etc. while taxiing, standing, landing, or taking off. This includes runway incursions: the incorrect presence of a helicopter, aircraft, vehicle, person, or animal (excluding birds) on the runway/ helipad/ taxiway used for landing, takeoff, or taxiing.
General disintegration or structural damage of the helicopter	Structural overload or structural failure	Pre-impact structural overload or structural failure resulting in disintegration of the helicopter, structural overload, or structural failure resulting in helicopter damage. It is not the result of a collision, explosion, or LOC occurrence.
	Fire/explosion	Pre-impact onboard fire or explosion that directly results in major damage to the helicopter, disintegration, or LOC as a result of fire damage to flight controls or flight control surfaces.

LOC = loss of control

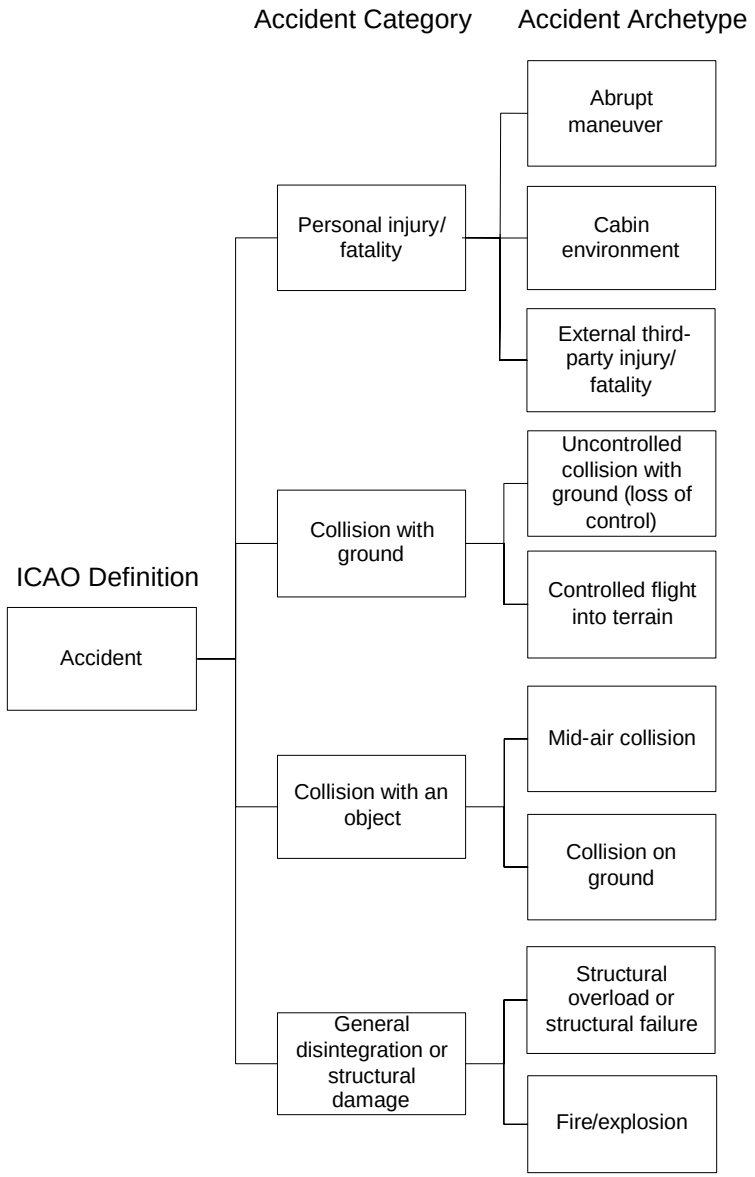


Figure 3. Definition of Accident Into Accident Categories and Accident Archetypes

3.1.4 Development of Generic Accident Scenarios.

A systematic decomposition is required to capture all possible accident scenarios in a causal model. Describing individual accident scenarios in detail in a causal model is not possible because it would be too complex and the model would be unmanageable. Structuring that allows identification of groups of accident scenarios will enable representation of all accidents in a limited set of generic accident scenarios per group. The previous sections explained the structuring applied in this study.

The accident scenarios are determined by using a combination of engineering, operational, and safety knowledge from the research team and SMEs, as well as historical accident and incident data. The development of ESDs is a three-step process:

1. Individual accidents and incidents are analyzed and represented as a sequence of events by the analysts. This step results in accident scenarios specific to the analyzed events.

2. Accident scenarios are generalized per type of accident, initiating event, and flight phase. A review of past accidents will not necessarily result in a complete overview of all possible accidents because some potential accident scenarios may not have been realized.

3. Generalized scenarios are combined into ESDs. Every ESD covers a generic class of accidents. The research team, the FAA, and the involved SMEs have reviewed the ESDs in group sessions.

The definition of the events of the scenario must not allow for the possibility of misinterpretation. A complicating factor is that, to ensure the ESDs are easy to understand, it is preferable not to include complete definitions of events in the ESD. Instead, key sentences are used to label IEs, pivotal events, and end states. The drawback is that, when complex events are condensed into key sentences, information is inevitably lost and misinterpretation may occur.

Because an initiating and pivotal event is the top event of the underlying FT, it is essential that these events are defined as a failure instead of a success. The FTs typically represent failure propagation with a failure as top event. Consequently, following the pivotal events in an ESD to the right represents the continuation of failures toward an unsafe end state (e.g., an incident or accident). An outcome of a pivotal event downwards represents the success or absence of a failure event, which leads to another pivotal event or end state with a safe outcome, as shown in figure 4.

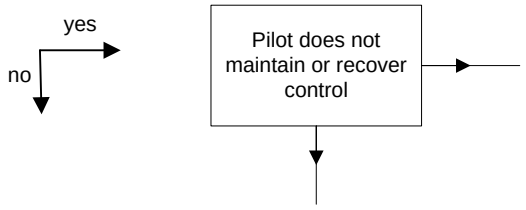


Figure 4. Pivotal Event With Arrows Indicating Failure Propagation to the Right and Success Propagation Downwards

By considering carefully the building blocks of the scenarios, the overall complexity of the causal risk model can be minimized. The required level of detail or abstraction also needs careful consideration. The building blocks of the scenarios are intentionally kept broad and generic to cover many similar situations that have been observed or deemed possible by experts.

The phraseology that is used in the ESDs, in particular the use of the words “does not,” is not used to blame or to indicate failed responsibilities, nor does it exclude the possibility of human error. As an example, “pilot does not maintain control” can indicate a flight crew error, as well as a technical malfunction or insufficient time/altitude available for recovery.

3.2 DEVELOPMENT OF FTs.

3.2.1 The Function of the FT.

The FTs connect to the events in the ESDs. The top event of the FT corresponds to the initiating or pivotal event in the ESD. The FT either shows failure or fault propagation toward the top event, or provides a specification of the top event. The following section explains the approach and guidelines used during the FT development.

3.2.2 Approach to Developing an FT.

3.2.2.1 Criteria for an FT Event.

An FT event should be defined as meeting specific criteria. An FT is:

- A fault or failure condition, not a positive event. For example, a loss of fuel supply or a pilot error is a fault condition.
- Unambiguously and clearly defined.
- Generic (e.g., not based on a specific historic incident or accident).
- Measurable and quantifiable (i.e., a rating scale is available). Quantification with data or expert judgment should be possible with current data and knowledge.

3.2.2.2 Identification of FT Events.

For the identification of FT events, a combination of expert judgment and a data-driven approach was used in this study. Based on the reviewed accident and incident data sample, causal factors in accidents and incidents were identified. That information was combined with a top-down functional and analytical breakdown of faults into deeper-level faults, using a failure-effect and functional reasoning, such as:

- What failure/fault/failure mode can produce this effect?
- What can be the effect of this failure/fault/failure mode?
- Can additional causes be specified for the effect?

The top event can sometimes be regarded as a type of functional failure. By establishing what functions or subfunctions are necessary to fulfill the top-level function, functional failure modes for the lower level (sub)functions may be derived that can be represented in the FT. As an example, the following failure modes can be considered: a loss of function, a degraded function, a function performed out of sequence, a corrupt or incorrectly performed function, a function provided when not needed, etc. The scope of events that were considered in the development of the FTs are provided by the NTSB categorization (see table 3). In addition, the FAA Joint Aircraft System Component Code Table and Definitions (or Air Transport Association of America (ATA) codes) for categorizing aircraft/helicopter system failures was used to identify and structure system failure events in FTs.

The research team, the FAA, and involved SMEs reviewed the FTs in group sessions.

Table 3. The NTSB Categories

Nonperson	Person
Aircraft systems/components	Use of aircraft/equipment
Air traffic facilities	Aircraft operations (handling)
Airport facilities	Airport
Terrain/runway conditions	Air traffic management (including weather services)
Weather conditions	Dispatch
Light conditions	Planning-decision
	Maintenance

3.2.2.3 The Level of Detail in the FT.

The level of detail to which the FT will be developed is an important consideration. In this research report, FTs will be developed to a level of detail at which events can still be quantified with data. Furthermore, the cause-effect mechanisms must be clear and able to be modeled. At the level at which data is not available to support the FT, the exact cause-effect relationship is not clear, or it is not possible to model the next level in the form of an FT, the FT is not further developed. The FT Handbook [15] by the National Aeronautics and Space Administration (NASA), provides the following as a reasonable approach: "The development of a quantitative model is based on the need to get the best possible estimate for the top event probability, considering the data and other information that are available. The FTs are developed to a level of detail where the best failure probability data are available. Further resolution of the system is necessary when decisions about subcomponents or support systems are being made, or when an event cannot be shown to be independent of others in the analysis (e.g., a system that has actuation signals or power in common with other systems). The FT can, and often is, developed to a level of detail that is below the level where data is available to estimate the basic event probabilities or to where the risk discrimination no longer matters. This is often unnecessary."

3.2.2.4 The FT Logic.

The FTs of the rotorcraft causal model show four different types of gates: OR, MOR, AND, and INH. Section 4 explains the definition and shows the mathematical logic associated with each gate.

4. ROTORCRAFT MODEL QUANTIFICATION.

4.1 INTRODUCTION.

The ESDs provide a qualitative description of the accident scenarios. They are quantified by assessing the probability of occurrence of each of the different pathways in the scenarios. An ESD is comparable to a river that starts big and then branches off into smaller bodies of water. The total amount of water that passes through at the beginning is equal to the amount of water

that flows in all the individual branches. There are three different ways to describe how big the river and its individual branches are:

1. The total amount of water can be described in absolute terms for each part of the river. This means that, in the ESD, all probabilities are expressed as absolute probabilities.

2. Each branch of the river can be normalized by the size of the river at the beginning. The quantities of the end states add up to 1.

3. For each individual branch point, the relative distribution of the flow among the different branches can be described. The quantities at each individual pivotal point add up to 1. This means that, in the ESD, all probabilities are expressed as probability of occurrence conditional to the preceding pivotal event.

From an accuracy and completeness viewpoint, the three different descriptions are equal. There are practical reasons as to why it could be more appropriate to use one type instead of another (e.g., depending on communication of the ESD with experts and nonexperts, and on possibilities for retrieving numbers from existing datasets or by means of expert judgment). In practice, when retrieving numbers from datasets, combinations of options 1, 2, and 3 are often used.

The probabilities of the IE and the end states are absolute probabilities. The sum of the probabilities of the end states is equal to the probability of the IE. An absolute probability represents the probability per flight hour in this study.

In this study, all probabilities of the pivotal events are expressed as conditional probabilities. A conditional probability for event B (conditional on event A) represents the probability that event B occurs given event A has occurred. For example, the conditional probability of event B is 0.01, which means that B occurs once in 100 cases of A occurring. The conditional probabilities quantify the strength of the causality in the model. A high conditional probability refers to strong causality; a low conditional probability indicates weak causality.

4.2 QUANTIFICATION STEPS.

The quantification of the ESDs and FTs was done in three steps:

1. The FT base events of the IE are quantified with historical occurrences for that event. The number of applicable events found in the dataset is divided by the corresponding exposure (flight hours). Next, the FT logic is applied to calculate the top event of the FT, the IE, from the base events.

2. The FT base events of the pivotal events are quantified in the same way as the FT events of the IE. The probability of the pivotal event is made conditional on the preceding events in the ESD. This is done by dividing the probability of the pivotal event by the product of the probability of the IE and conditional probabilities of the preceding pivotal events. The IE and pivotal event are quantified bottom-up from its FT base events. In section 5, the number of occurrences found in the databases of these base events is presented for each FT. The corresponding probability of the events is calculated with the

exposure data. For the intermediate events and the top event in the FT, the probability is calculated by the FT logic using the FT base event probabilities.

3. The end states are quantified by the product of the probability of IE and the conditional probabilities of the pivotal events along the pathway toward the end states.

An example of the calculation steps is provided in section 4.4.

4.2.1 Point Estimates.

All quantitative data in this report are provided as point estimates. The research team is keenly aware of the fact that calculations are based on relatively small datasets and some numbers will have large bands of uncertainty. For reasons of consistency, all probabilities in this report are displayed as numbers with two decimal places. This may create an illusion of numerical accuracy that is not always achieved. Levels of uncertainty were not calculated because, in the current state of model development, these uncertainty levels are not yet useful.

4.2.2 Air Safety Data Working Protocol.

Many events in the ESDs and FTs are quantified by means of historical air safety data. This means that accidents, incidents, and occurrences are selected from databases, reviewed by safety analysts, and assigned to the various ESD or FT events. For this process of selecting data sources and qualifying individual occurrences, NLR-ATSI uses a protocol for working with air safety data [16]. This supports transparency and reproducibility of results.

4.3 THE FT LOGIC.

In the FTs of the rotorcraft causal model, four types of gates are used:

1. The OR Gate—An OR gate indicates that the top event occurs if a least one of the input events occurs. The probability of the top event (A) with an OR gate and two base events (B) and (C) is quantified according to the formula:

$$P(A) = P(B) + P(C) - P(B \text{ and } C) \tag{1}$$

where $P(X)$ is the probability of X.

An alternative way of describing this equation is:

$$P(A) = 1 - (1 - P(B)) \times (1 - P(C)) \tag{2}$$

For n base events (X_1, X_2,…X_n), the formula becomes:

$$P(A) = 1 - (1 - P(X_1)) \times (1 - P(X_2)) \times \ldots \times (1 - P(X_n)) \tag{3}$$

2. The MOR Gate—The MOR (mutually exclusive OR) gate indicates that the top event occurs if one of the input events occurs, but both events cannot occur simultaneously.

The probability of a top event (A) with a MOR gate and two base events (B) and (C) is quantified according to the formula:

$$P(A) = P(B) + P(C) \tag{4}$$

where $P(X)$ is the probability of X. As the base events are mutually exclusive, $P(B \text{ and } C) = 0$.

3. The AND Gate—The AND gate indicates that the top event occurs if all of the input events occur. The probability of a top event (A) with an AND gate and two base events (B) and (C) is quantified according to the formula:

$$P(A) = P(B) \times P(C) \tag{5}$$

where $P(X)$ is the probability of X.

4. The Inhibit Gate—The IC (INH) gate indicates that the top event occurs if the input event occurs in the presence of a condition that must occur before the input can result in the top event. The conditional event is connected to the INH gate on the right side of the gate.

4.4 EXAMPLE OF QUANTIFICATION.

Figure 5 shows an ESD with an FT of the IE. The FT has two branches with six base events (A, B, C, E, F, and G) and two intermediate events (D and H). The base events of this FT are quantified according to step 1 in section 4.2. In this example, it is assumed that, for event A, 100 occurrences in one million flight hours are found in historical data. Hence, the probability of event A is estimated as $1.00 \cdot 10^{-4}$ per flight hour. Similarly, the probability of all other base events can be estimated. In this example, event B has a probability of $5.00 \cdot 10^{-4}$ per flight hour and event C has a probability of $8.00 \cdot 10^{-5}$ per flight hour.

The top event of the FT, the IE, is calculated bottom-up from the base event probabilities using the FT logic (i.e., three OR gates in this example). First, the probability of intermediate event D is calculated by applying the OR gate logic to the base event probabilities using the formula in equation 3. The probability of event D becomes $1 - (1 - 1.00 \cdot 10^{-4}) \cdot (1 - 5.00 \cdot 10^{-4}) \cdot (1 - 8.00 \cdot 10^{-5}) = 6.80 \cdot 10^{-4}$ per flight hour. For example, if event H has a probability of $3.00 \cdot 10^{-3}$ per flight hour, then the same OR gate logic application results in a probability for event IE of $3.68 \cdot 10^{-3}$ per flight hour.

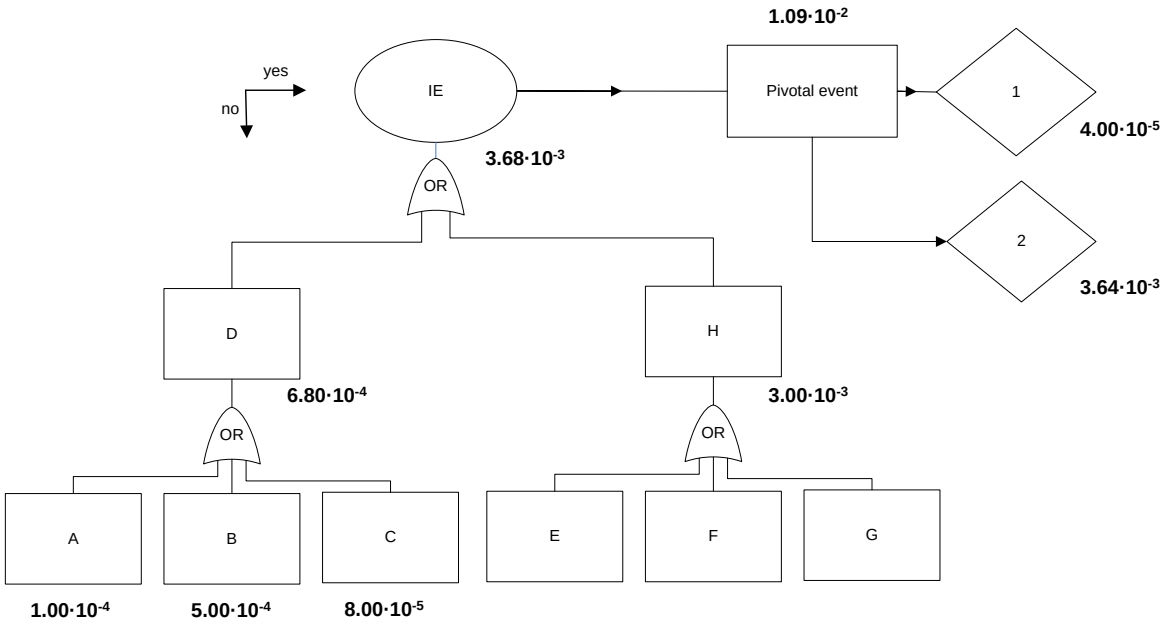


Figure 5. Example of an ESD and FT

This ESD example has one pivotal event. Its absolute probability is determined in the same way as the IE, and is then made conditional on the IE (refer to step 2 in section 4.2). If the absolute probability of the pivotal event is, for example, $4.00 \cdot 10^{-5}$ per flight hour, then the conditional probability becomes $4.00 \cdot 10^{-5} / 3.68 \cdot 10^{-3} = 1.09 \cdot 10^{-2}$ per occurrence of the IE. The probability that the pivotal event does not occur, given the IE, is $1-1.09 \cdot 10^{-2}$.

To calculate the probability of end state 1, according to step 3 in section 4.2, multiplying $3.68 \cdot 10^{-3}$ per flight hour by $1.09 \cdot 10^{-2}$ results in $4.00 \cdot 10^{-5}$ per flight hour. The end state 2 probability is calculated by multiplying $3.68 \cdot 10^{-3}$ and $(1-1.09 \cdot 10^{-2})$, which yields $3.64 \cdot 10^{-3}$ per flight hour. The sum of the probabilities of the end states equals the probability of the IE; hence, as stated previously, the total amount of water that passes through at the beginning is equal to the amount of water that flows in the individual branches.

4.5 DATA SOURCES AND DATA SELECTION.

4.5.1 Data-Selection Criteria.

Different data sources were used in the quantification of the model elements. This section explains the available data sources and the selection criteria applied to build a dataset for the quantification of the ESDs and FTs. An important step in working with air safety data is the definition of the scope for the data selection. The scope for the model quantification is defined by the scope for model development (see table 1) and by a specific set of data-selection criteria (see table 4).

Table 4. Data Selection Criteria for Quantification

Criterion	In Scope
Occurrences	Accidents, incidents, occurrences
Time frame	2005–2010
Region	United States (as location of occurrence)
Type of operation	For quantification of model elements: tour operations and HEMS operations only
Regulatory part	Part 135 and Part 91

The following data sources were used:

- The NTSB accident and incident data
- Concern Network reports
- Aviation Safety Reporting System (ASRS) reports
- Service Difficulty Report (SDR) System data.

These data sources are described in more detail in appendix C.

4.5.2 The NTSB Accident and Incident Data.

For this study, accident and incident data were collected from the NTSB database using the selection criteria defined in tables 1 and 4. The selected data sample from the NTSB contains sufficient records with information to develop the qualitative accident scenarios (see table 5). For the quantification of the accident scenarios for HEMS and tour operations, the NTSB data sample from 2005–2010 is used. Table 6 shows the number of applicable accidents/incidents for HEMS and tour operations.

Table 5. Number of Occurrences by Year in the NTSB Data Sample for This Study
(all rotorcraft operations)

Year	Occurrences
2005	197
2006	170
2007	190
2008	155
2009	154
2010	137
Total	1003

Table 6. Number of Occurrences in the NTSB Data Sample for HEMS and Tour Rotorcraft Operations

Operation	Occurrences	Time frame
HEMS	86	2005–2010
Tour Operation	40	2005–2010

4.5.3 Concern Network Reports.

The Concern Network collects voluntarily submitted occurrence reports that involve accidents, incidents, or minor occurrences in the EMS industry. The Concern Network dataset also contains reports related to modes of transport other than rotorcraft, so each report was analyzed to ensure it fit into the scope of the model. A number of reported occurrences were both recorded in the NTSB and Concern Network dataset. This has been accounted for in the final quantification. Besides, Canadian-registered helicopters were excluded from the analysis. Table 7 shows the number of occurrences from the Concern Network that was used in this study. The applicable reports were used to estimate the probabilities of events in the FTs of the IEs and pivotal events. The allocation of the applicable ESD and FT events to each report was reviewed by the FAA research team and SMEs.

Table 7. Applicable Occurrences in the Concern Network Dataset for HEMS Operations

Year	Applicable reports
2005	16
2006	22
2007	42
2008	43
2009	46
2010	30
Total	199

4.5.4 The ASRS Reports.

Occurrence reports submitted through the NASA ASRS are voluntary reports and, in general, relate to minor occurrences. These reports can be used to estimate the probabilities of events in the FTs of the IEs and pivotal events. The query applied to the ASRS database was based on timeframe (2005–2010) and operation part (Parts 91 and 135). A query filter based on HEMS or tour operations, or by helicopter, could not be made. From the resulting dataset, only U.S. type certificated helicopters were selected. Subsequently, records involving HEMS or tour operations were selected based on the field mission in the data sample. For example, when the field mission corresponded to “ambulance,” “other EMS,” or “other tour,” the record was selected. For other mission types, such as ferry or passenger, the narrative of the record was checked to determine if the record was applicable to the current study. In addition, the narratives were analyzed for keywords and context information indicating that the occurrence involved a HEMS or tour flight.

Table 8 shows the resulting set of ASRS reports covering HEMS and tour operations. The allocation of the applicable ESD and FT events to each record was reviewed by the FAA research team and by SMEs.

Table 8. Applicable Occurrences in the ASRS Dataset for HEMS and Tour Operations Under Parts 91 and 135 From 2005–2010

Operation	Occurrences
HEMS	45
Tour	9

4.5.5 The SDR Database: Systems Failure Data.

The FAA SDR database was used to estimate the probabilities of the system failure events in the FTs of the IEs, and for one pivotal event. Data was retrieved from the FAA SDR database and processed to obtain a representative set for rotorcraft operations. The SDR occurrence data contain an attribute (c604) with wing code. Class G means rotary wing. Attribute c604 also contains some blanks. Selecting only classes G and blanks results in a set of 7365 occurrences. Of these occurrences, 1315 do not contain information about the aircraft manufacturer (column c130), so they were deleted. The resulting set was manually checked for helicopter and aircraft types and fixed-wing aircraft types were removed from the dataset. Occurrences that took place after 2010 were removed. To limit the dataset to Parts 91 and 135 operations only, those occurrences that were reported by the following submitters were considered: Part 91 operators, Part 135 operators, repair stations, mechanics, and pilots. Although the latter three might contain operations other than Parts 91 and 135, this set is assumed to be small. The final dataset contains 2917 records.

The final set was assessed in four steps. In the first step, the ATA code of each occurrence (column c40) was matched to an FT base event. Some ATA codes could not be directly matched to one event. For the occurrences with these codes, the modifying factor (e.g., column c260: broken, malfunctioned, leaked) was analyzed to make a match with an event possible. Thereafter, a query was made to find engine overheats using the modifying factors “overheat” and “over-temperature.” Finally, to determine the number of electrical fire occurrences, the following modifying factors of occurrences of ATA 24 were counted: burned, burned out, chafed, arced, melted, shorted, smoke, and sparks.

4.5.6 Exposure Data.

Helicopter flight hours for HEMS, tour operations, and all rotorcraft operations (under Parts 91 and 135) were obtained through the FAA Rotorcraft Division and the FAA General Aviation and Air Taxi Activity Survey. As Parts 91 and 135 operators are not required to report annual operational data, the flight hours for Parts 91 and 135 are estimated from a voluntary annual general aviation survey: the General Aviation and Air Taxi Activity Survey (see also appendix D).

The FAA provided exposure data for HEMS and tour operations for the years 2005–2010 for Parts 91 and 135, broken down by turbine, piston, and single/multi-engine category. The causal model does not make a distinction by engine type or number of engines. The total number of flight hours was used as exposure (see table 9). The flight hours for HEMS and tour operations are used as exposure for the NTSB, ASRS, and the Concern Network dataset. The flight hours for all rotorcraft are used as exposure for the SDR dataset.

Table 9. Exposure Data for HEMS, Tour, and All Rotorcraft Operations in Flight Hours Under Parts 91 and 135, From 2005–2010, All Engine Types Included

Operation	Flight Hours
HEMS	2,516,798
Tour	1,712,202
All rotorcraft	19,619,437

4.6 ASSUMPTIONS.

The following general assumptions have been made:

- That, for the purpose of the calculations, the databases being used in the analysis are complete (i.e., that there is no overreporting, underreporting, or any other bias in the databases). Although the research team strongly suspects that underreporting is an issue with the occurrence data, this was not further investigated within the current study because of resource limitations.

- That the data samples, which are used for quantification, are representative for the type of operations at which the risk model is aimed.

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

- That each occurrence in the data samples can be uniquely and unambiguously assigned to a particular ESD.

- That, in cases in which no examples of specific accident scenarios are found in the data sample, the probability of occurrence of that scenario is 0.

- That there are no dependencies between the different ESDs.

- That events in the ESDs cannot occur partially (i.e., IEs and pivotal events have only “yes” or “no” output pathways).

- That, because the SDR database has no information on the type of operation, the system failure probabilities derived from the SDR dataset do not depend on the type of operation and helicopter type, and is therefore representative for HEMS and tour operations. The

probability of a system failure event is determined by dividing the number of occurrences by the total number of flight hours generated by all helicopter operations in the U.S. between 2005 and 2010, for Parts 91 and 135. The resulting probability per flight hour was used for HEMS and tour operations.

5. ROTORCRAFT MODEL.

5.1 INTRODUCTION.

The research team has developed 19 rotorcraft accident scenarios represented as ESDs. The ESDs are numbered with the prefix US-R to indicate the scenarios represent the U.S. and rotorcraft. Table 10 shows the resulting set of IEs of the ESDs. Some of the titles of the IEs include the applicable flight phase. For this study, the CICTT flight phase definitions are used. If no flight phase is mentioned, the whole flight is included, starting from the moment any person boards the aircraft with the intention of flight until all persons have disembarked. The jumps in the ESD numbering are a result of the ESD development process, in which the missing numbers refer to ESDs that were deleted or combined with other ESDs during the development process of the ESDs.

Full diagrams of the accident scenarios and FTs and the definitions of the events are provided in the following sections.

Table 10. Resulting Set of Accident Scenarios (ESDs)

ESD	IE
US-R2	Helicopter handling by pilot inappropriate or handling impaired during takeoff
US-R3	Attempted flight with weight/center of gravity outside limits
US-R5	Conflict on taxiway or runway area
US-R6	Loss of tail rotor effectiveness
US-R7	Fire, smoke, or burning odor onboard helicopter
US-R8	Loss of situational awareness in degraded visual environment
US-R9	Loss of visual reference in degraded visual environment
US-R10	Deviation from safe flight path toward obstacle
US-R11	Pilot incapacitation
US-R12	Flight instrument failure
US-R13	Flight control system failure
US-R14	Engine malfunction or loss of power
US-R15	Helicopter enters adverse weather
US-R16	Aircraft are positioned on collision course in flight
US-R17	Pilot judgment, decision, or action error
US-R18	Structural failure in flight
US-R20	Improper approach/flare by pilot
US-R21	Presence of person near helicopter with turning rotors
US-R23	Helicopter enters ground resonance

5.2 GENERAL REMARKS ON ESDs AND FTs.

5.2.1 The ESD and FT Event Coding.

Each event in the ESD and FT has a unique code for the purpose of reference to its definition and event probability. The ESD is coded starting with the IE, from left to right. The sequence of events is numbered alphabetically: a, b, c, and d for the first sequence of events, for example. The numbers are added to indicate that a particular letter is used for the 1st, 2nd, 3rd time, etc.

Each FT event has a unique code. The numbering in the FT has the following logic: A top event code is used as a starting point for the numbering of the next level of events in the FT. The FT events are numbered from left to right, starting with 1.

In the ESD and FT diagrams, the probability of the event is printed next to the event box. The probabilities for HEMS are noted as “H: …” and for air tour operations as “T: …”

5.2.2 Unit of Probability.

The probabilities of the IE and end states are expressed per flight hour. The probabilities of the pivotal events in the ESDs are expressed as conditional probabilities.

The probabilities of the FT events of the IE are, in general, expressed as probabilities per flight hour. The probabilities of the FT events of the pivotal event are expressed as probabilities per flight hour on the level of the base events, whereas the pivotal event itself is a conditional probability. Event probabilities that are based on assumptions are either expressed as per flight hour or as a conditional probability in the FT.

The corresponding description and table with quantification results will provide the unit of probability. For example, a probability per "US-R16a1/b1" means that the probability is conditional on the event US-R16a1 and US-R16b1 occurring. Per "US-R16a1/nb1" indicates that the probability is conditional on the event US-R16a1 occurring and US-R16b1 not (n) occurring.

5.2.3 Scientific Notation.

Most probabilities are expressed in a scientific notation, such as $a \cdot 10^{\mathbf{b}}$, or a times ten raised to the power of b. For example, $1 \cdot 10^{-6}$ per flight hour means 1 in one million flight hours ($10^{-6} = 1 / 10^{6}$, whereas $10^{6} = 1{,}000{,}000$). Likewise, $1 \cdot 10^{-4}$ per flight hour equals 1 in 10,000 flight hours. Hence, $1 \cdot 10^{-4}$ per flight hour is a factor 100 more frequent than $1 \cdot 10^{-6}$ per flight hour.

5.2.4 The Use of Unknown Probability.

The consequence of the lack of data and lack of details is the following: For many events, a small number of occurrences were found and a portion of the events have no corresponding data at all. The frequency of occurrence of the latter events is, therefore, 0 events per flight hour. However, this is the estimated probability from 0 observed events in the databases. It is expected that the actual probability is larger than 0. In the ESD and FT diagrams, an unknown probability is given for events for which the frequency of occurrence was 0 or could not be estimated based on the reviewed data sample. The calculation of the probability of the top event from the base events with one or more unknown probabilities was performed by substituting a probability of 0 for the events with unknown probability, so that the FT logic can be used to calculate the top event.

5.2.5 The Number of Occurrences Per Event.

The FT base events are quantified using the number of occurrences found in the datasets for these events. All other model elements are quantified from the FT base events using FT and ESD logic. The FT top event has a probability based on the associated base event probabilities, even without having any occurrences. The tables in the next sections present only the number of occurrences related to the base events. Event probabilities that have been calculated from the base events have empty, gray cells in the table for the "occurrences" columns because occurrences were not used to estimate the probability.

5.2.6 Pivotal Event: "Pilot Does Not Maintain or Recover Control".

The pivotal event "pilot does not maintain or recover control" represents the situation that the pilot is not able to maintain control or recover control over the helicopter. This pivotal event does not necessarily imply a failure or error by the flight crew. In general, the ability of the flight crew to maintain or recover control of the aircraft is affected by human factors, training, aircraft system failures, weather conditions, available altitude for recovery maneuver, etc. This event includes the pilot's unsuccessful recovery of a (recoverable) loss of control (LOC) situation. When reviewing occurrences, it is often difficult to make a clear distinction between maintaining control and recovery of control. The factors influencing maintaining control and recovery are similar and, for ease of modeling, one pivotal event is preferred to cover the dynamic process of maintaining or recovery of control.

5.2.7 Forced Landing.

A forced landing is defined as a landing necessitated by, for example, failure of engines, systems, or components, which makes continued flight impossible. The forced landing in a helicopter may be a normally flown landing or an autorotation. A forced landing may be successful or may end in helicopter damage, injury, or a fatality. Most IEs could lead to a forced landing. For instance, a flight control system failure, fire on board, pilot incapacitation, etc. could consist of a sequence of events leading to a forced landing. Forced landing was not explicitly defined in the ESDs as an end state or pivotal event. When the pilot initiates a forced landing, it may be regarded as a new phase of flight, for which all relevant ESDs apply.

5.3 US-R02: ESD AND FT DIAGRAMS.

Figures 6 through 8 show the ESD and FT diagrams of US-R02: Helicopter handling by pilot inappropriate or handling impaired during takeoff.

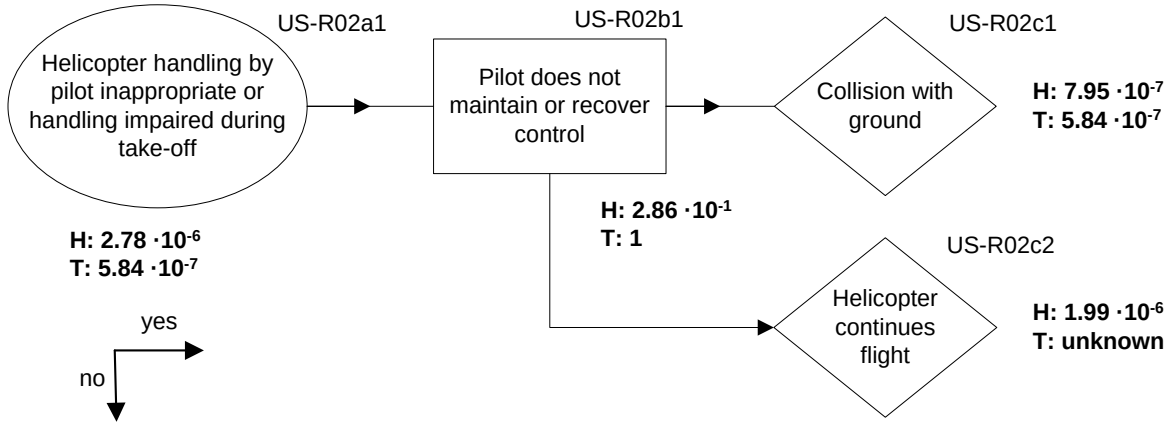


Figure 6. The ESD US-R02—Helicopter Handling by Pilot Inappropriate or Handling Impaired During Takeoff

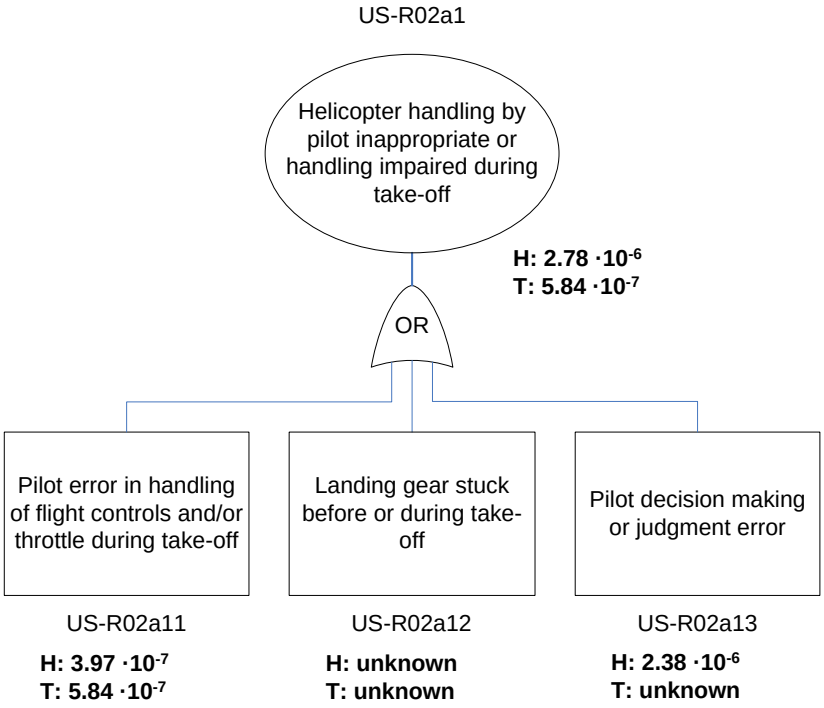


Figure 7. The FT US-R02a1—Helicopter Handling by Pilot Inappropriate or Handling Impaired During Takeoff

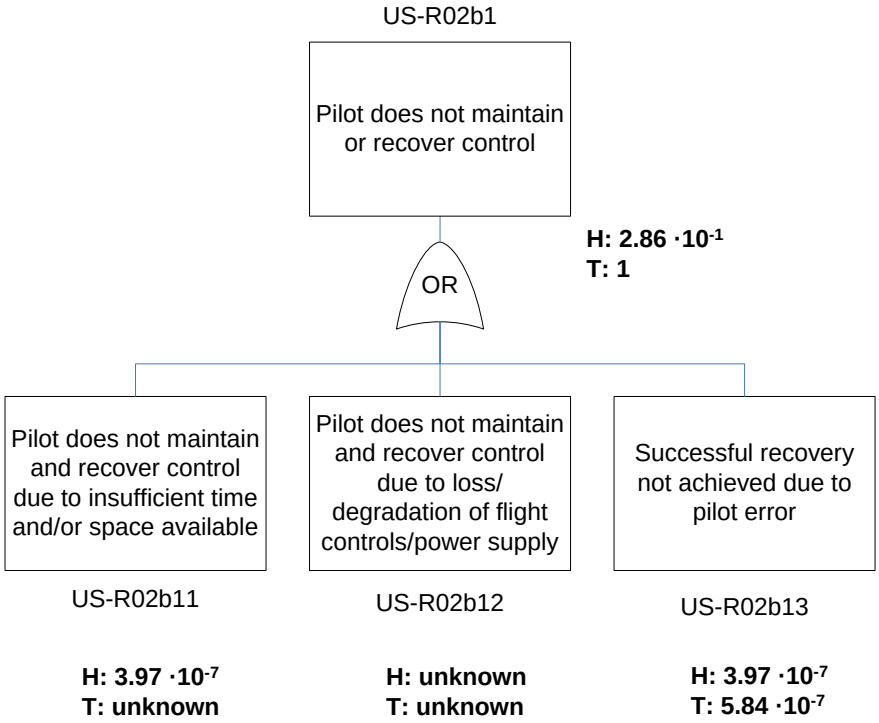


Figure 8. The FT US-R02b1—Pilot Does Not Maintain and Recover Control

5.3.1 Definitions.

The definitions of US-R02 and FT events are shown in table 11.

Table 11. Definitions of ESD US-R02—Helicopter Handling by Pilot Inappropriate or Handling Impaired During Takeoff

Event	Code	Definition
Helicopter handling by pilot inappropriate or handling impaired during takeoff	US-R02a1	The handling by the pilot on the ground or in the air is inappropriate during takeoff because of an inappropriate crew action or unsuitable use of helicopter systems/controls, etc. The handling can also be impaired by a skid or landing gear that is stuck or becomes stuck during takeoff.
Pilot does not maintain or recover control	US-R02b1	The pilot is unable to maintain or recover control during takeoff or after rejecting the takeoff.
Collision with ground	US-R02c1	The helicopter hits the ground after losing control. This includes dynamic rollovers, impact with terrain, and hard landings with damage.
Helicopter continues takeoff	US-R02c2	The pilot is able to continue takeoff with the helicopter. This could result in a safe forced landing.
FT–Initiating Event–US-R02a1		
Pilot error in handling of flight controls/throttle during takeoff	US-R02a11	Pilot does not display appropriate competency or handling skills; handling and operation error of flight controls/throttle during takeoff (ground and airborne part). This can induce a rollover, for example.
Landing gear stuck before or during takeoff	US-R02a12	The landing gear (either wheels or skid) is stuck while on the ground or becomes stuck while hovering over the ground. This includes tie downs not removed.
Pilot decision making or judgment error	US-R02a13	Pilot does not display appropriate judgment and decision making regarding the flight, a maneuver, flight envelope, etc.
FT–Pivotal Event–US-R02b1		
Pilot does not maintain and recover control because of insufficient time/space available	US-R02b11	Pilot does not maintain and recover control because of insufficient time/space available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R02b12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R02b13	Successful recovery not achieved because of pilot error.

5.3.2 Quantification.

5.3.2.1 The IE.

The IE, "helicopter handling by pilot inappropriate or handling impaired during takeoff" (US-R02a1) is quantified using the NTSB, Concern Network, and ASRS databases. For HEMS operations, two occurrences of the IE in the NTSB, one in ASRS, and five in the Concern Network database were found. One occurrence was recorded both in the NTSB and Concern Network databases. For tour operations, one occurrence was found in the NTSB dataset. Table 12 shows the distribution of occurrences over the FT base events for HEMS and tour operations and the corresponding probability per flight hour. The probability of the IE is calculated from the base events.

Table 12. Occurrences and Probabilities of FT Events of US-R02a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R02a1			$2.78 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R02a11	1 (a)	1 (n)	$3.97 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R02a12	0	0	Unknown	Unknown	Flight hour
US-R02a13	6 (c, n)	0	$2.38 \cdot 10^{-6}$	Unknown	Flight hour
(a) = ASRS database; (c) = Concern Network; (n) = NTSB					

5.3.3 Pivotal Event.

The only pivotal event, "pilot does not maintain or recover control," (US-R02b1) can be quantified by using occurrences of collision with the ground after the IE has occurred. In the data sample, two occurrences for HEMS and one for tour operations were found in the NTSB and ASRS datasets. Table 13 shows the distribution of occurrences over the FT base events for HEMS and tour operations and the corresponding probability per flight hour. The conditional probability of the pivotal event is calculated from the base events divided by the IE probability.

Table 13. Occurrences and Probabilities of FT Events of US-R02b1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R02b1			$2.86 \cdot 10^{-1}$	1	US-R02a1
			$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R02b11	1 (a)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R02b12	0	0	Unknown	Unknown	Flight hour
US-R02b13	1 (n)	1 (n)	$3.97 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.3.4 End States.

The end states of the ESD are quantified using the quantification of the IE and the pivotal event; the results are given in table 14.

Table 14. Occurrences and Probabilities of End States of US-R02

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R02c1			$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R02c2			$1.99 \cdot 10^{-6}$	Unknown	Flight hour

5.4 US-R03: ESD AND FT DIAGRAMS.

The ESD and FT diagrams of US-R03, attempted flight with weight/center of gravity (CG) outside limits are shown in figures 9 through 11.

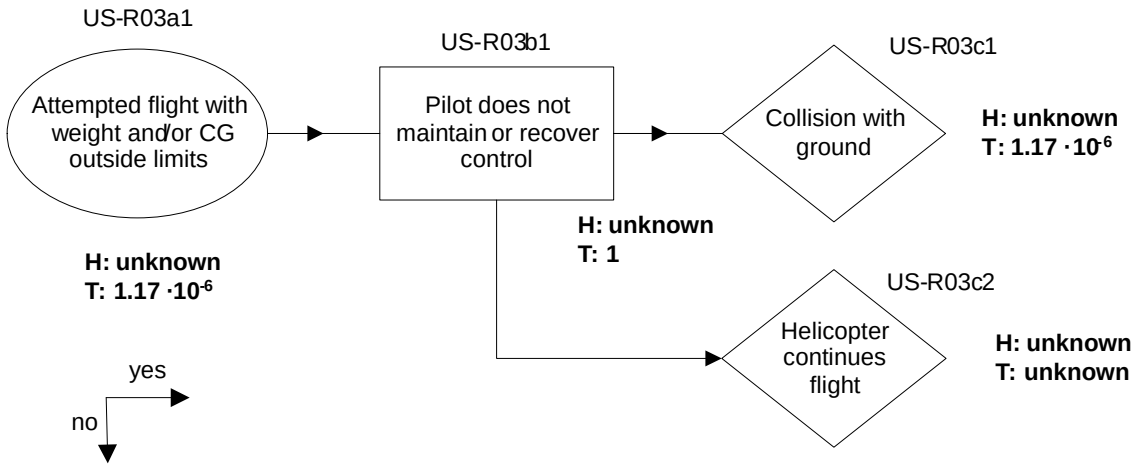


Figure 9. The ESD US-R03—Attempted Flight With Weight/CG Outside Limits

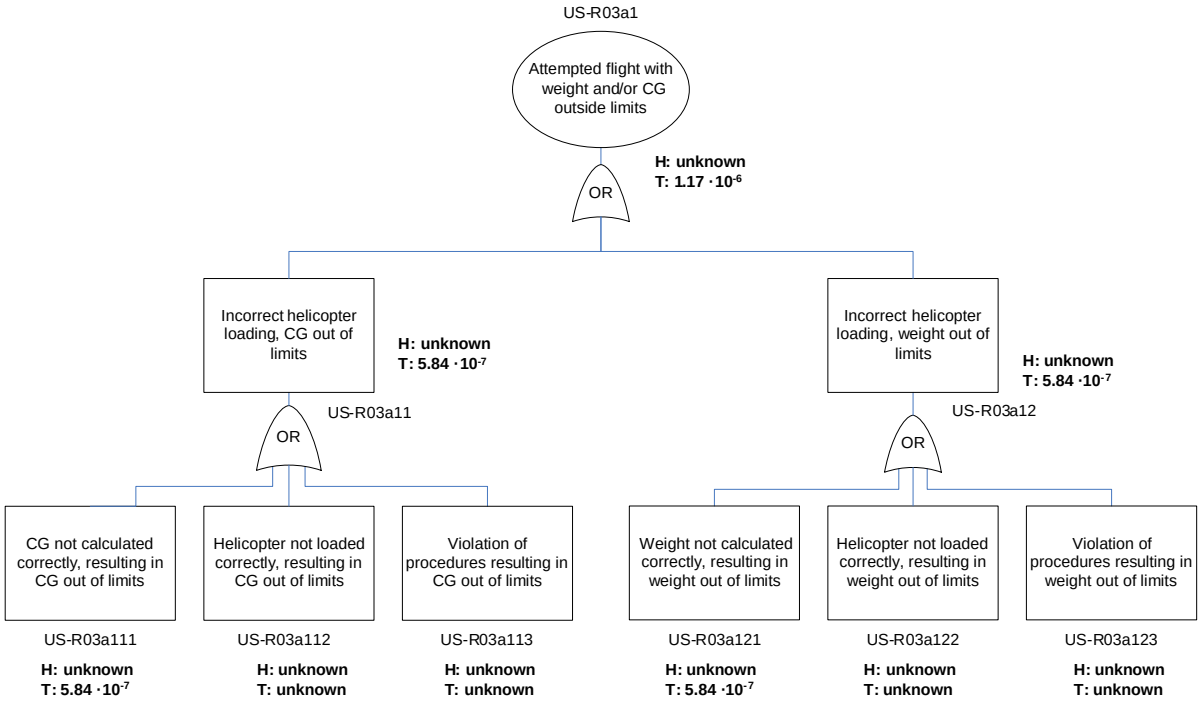


Figure 10. The FT US-R03a1—Attempted Flight With Weight/CG Outside Limits

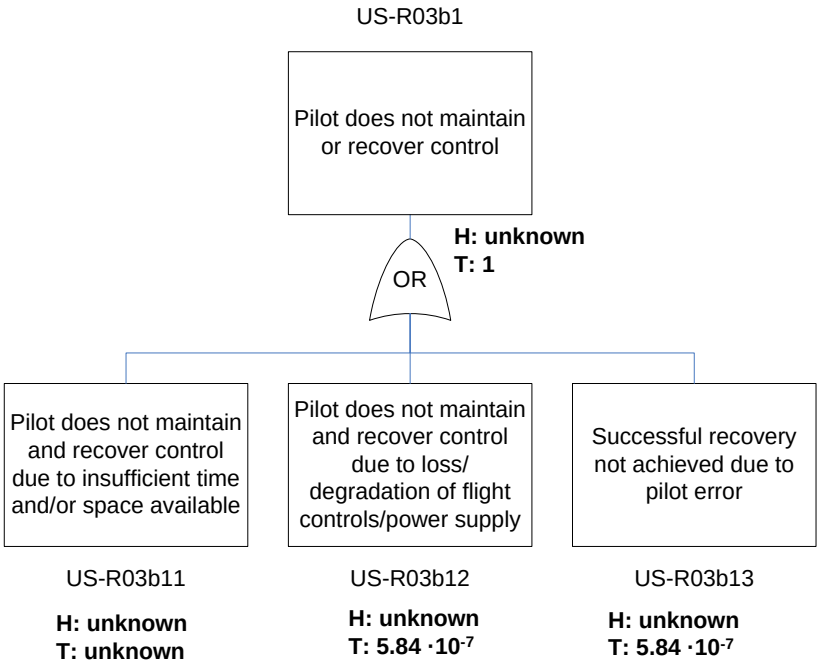


Figure 11. The FT US-R03b1—Pilot Does Not Maintain and Recover Control

5.4.1 Definitions.

Table 15. Definitions of ESD US-R03—Attempted Flight With Weight/CG Outside Limits

Event	Code	Definition
Attempted flight with weight/CG outside limits	US-R03a1	Flight is attempted with the weight/CG outside of helicopter limits. This includes winch operations. External load operations (Part 133) are excluded. Occurrences in which the actual overweight or incorrect CG manifests itself during the flight are included.
Pilot does not maintain or recover control	US-R03b1	The pilot is unable to maintain control after attempted flight with weight/CG outside limits.
Collision with ground	US-R03c1	The helicopter hits the ground after losing control. This includes dynamic rollovers, impact with terrain, and hard landings with damage.
Helicopter continues flight	US-R03c2	Helicopter continues flight with weight/CG outside limits.
FT–Initiating Event–US-R03a1		
Incorrect helicopter loading, CG out of limits	US-R03a11	The CG is out of limits, either in front or aft. This event can be caused by personnel loading the helicopter according to the incorrect load instructions or by inappropriately executing the correct load instructions.
CG not calculated correctly, resulting in CG out of limits	US-R03a111	CG not calculated correctly (e.g., incorrect loading instruction) resulting in CG out of limits.
Helicopter not loaded correctly, resulting in CG out of limits	US-R03a112	The helicopter is incorrectly loaded with correct load instruction, such that the CG is out of limits, either in front or aft.
Violation of procedures, resulting in CG out of limits	US-R03a113	Pilot is aware of the outside CG loading, but does attempt flight (i.e., the pilot is aware of a violation).
Incorrect helicopter loading; weight out of limits	US-R03a12	The weight is out of limits. This event can be caused either by personnel loading the helicopter according to the incorrect load instructions or by personnel inappropriately executing the correct load instructions.
Weight not calculated correctly, resulting in weight out of limits	US-R03a121	Weight not calculated correctly and incorrect loading instruction resulting in weight out of limits.
Aircraft not loaded correctly, resulting in weight out of limits	US-R03a122	The helicopter is incorrectly loaded such that the weight is out of limits, irrespective of a correct load instruction.
Violation of procedures, resulting in weight out of limits	US-R03a123	Pilot is aware of the outside weight limits loading, but does attempt flight (i.e., the pilot is aware of violation).
FT–Pivotal Event–US-R03b1		
Pilot does not maintain and recover control because of insufficient time/space available	US-R03b11	Pilot does not maintain and recover control because of insufficient time/space available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R03b12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R03b13	Successful recovery not achieved because of pilot error.

5.4.2 Quantification.

5.4.2.1 The IE.

The IE of the ESD is quantified using the NTSB, Concern Network, and ASRS databases. Two occurrences were found in the NTSB dataset related to tour operations, but no occurrences for HEMS. Table 16 shows the distribution of occurrences over the FT events for HEMS and tour operations and the corresponding probability per flight hour.

Table 16. Occurrences and Probabilities of FT Events of US-R03a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R03a1			Unknown	$1.17 \cdot 10^{-6}$	Flight hour
US-R03a11			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R03a111	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R03a112	0	0	Unknown	Unknown	Flight hour
US-R03a113	0	0	Unknown	Unknown	Flight hour
US-R03a12			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R03a121	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R03a122	0	0	Unknown	Unknown	Flight hour
US-R03a123	0	0	Unknown	Unknown	Flight hour
(n) = NTSB database					

5.4.2.2 Pivotal Event.

The only pivotal event, “pilot does not maintain or recover control,” (US-R03b1) can be quantified by using occurrences of collision with the ground after an attempted flight with weight/CG outside limits. In the data sample, two occurrences for tour operations were found; in one case, the LOC was due to a loss/degradation of flight controls, whereas, in the other case, successful recovery was not achieved because of pilot error. Table 17 shows the distribution of occurrences over the FT base events for HEMS and tour operations and the corresponding probability per flight hour. The conditional probability of the pivotal event is calculated from the base events divided by the IE probability.

Table 17. Occurrences and Probabilities of End States of US-R03b1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R03b1			Unknown	1	US-R03a1
			Unknown	$1.17 \cdot 10^{-6}$	Flight hour
US-R03b11	0	0	0	0	Flight hour
US-R03b12	0	1 (n)	0	$5.84 \cdot 10^{-7}$	Flight hour
US-R03b13	0	1 (n)	0	$5.84 \cdot 10^{-7}$	Flight hour
(n) = NTSB database					

5.4.2.3 End States.

The end states of the ESD are quantified using the quantification of the IE and the pivotal event; the results are given in table 18.

Table 18. Occurrences and Probabilities of End States of US-R03

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R03c1			Unknown	$1.17 \cdot 10^{-6}$	Flight hour
US-R03c2			Unknown	Unknown	Flight hour

5.5 US-R05: ESD AND FT DIAGRAMS.

Figures 12 through 15 show the ESD and FT diagrams of US-R05 conflict on taxiway or runway area.

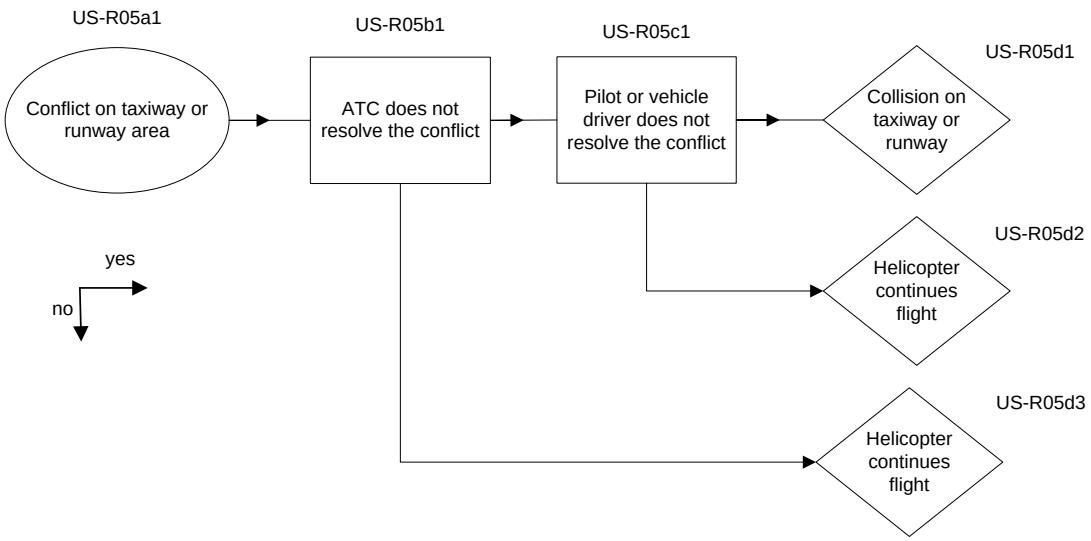


Figure 12. The ESD US-R05—Conflict on Taxiway or Runway Area

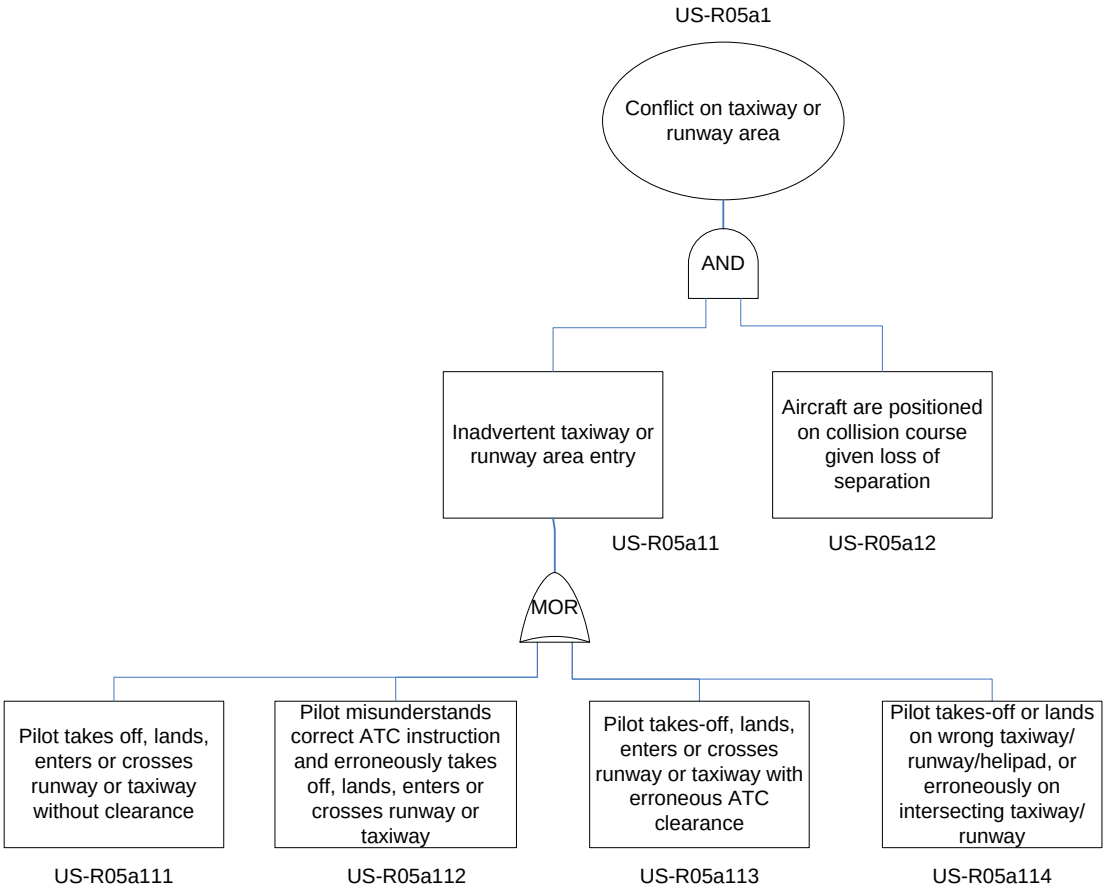
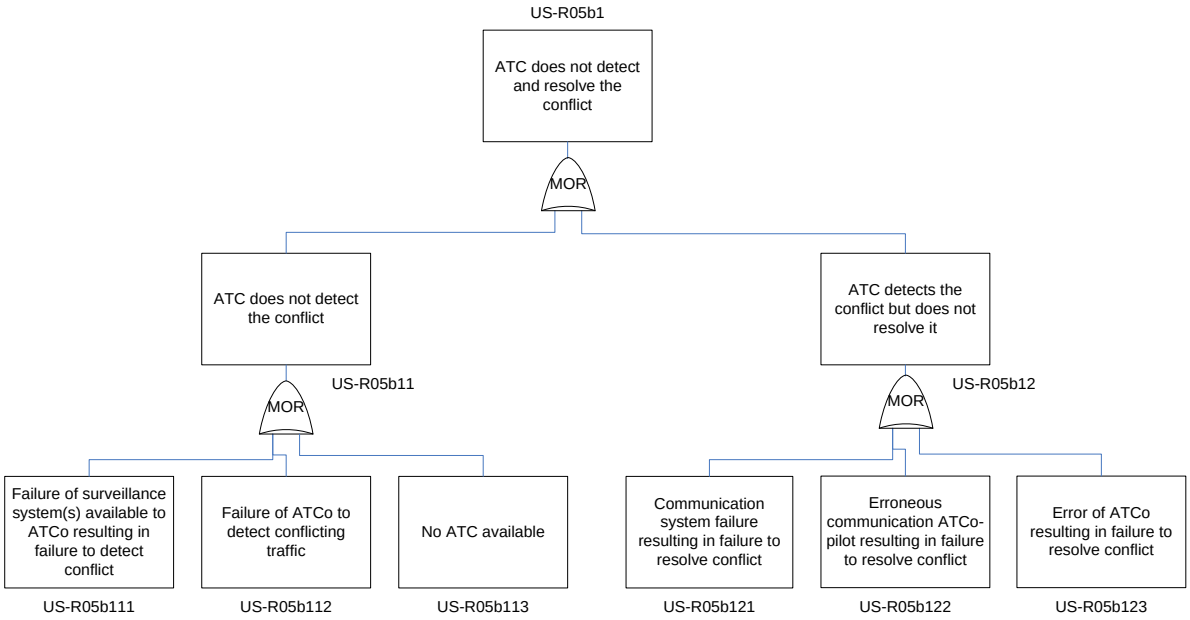


Figure 13. The FT US-R05a1—Conflict on Taxiway or Runway Area



ATC = Air Traffic Control
ATCO = Air Traffic Controller

Figure 14. The FT US-R05b1—ATC Does Not Resolve the Conflict

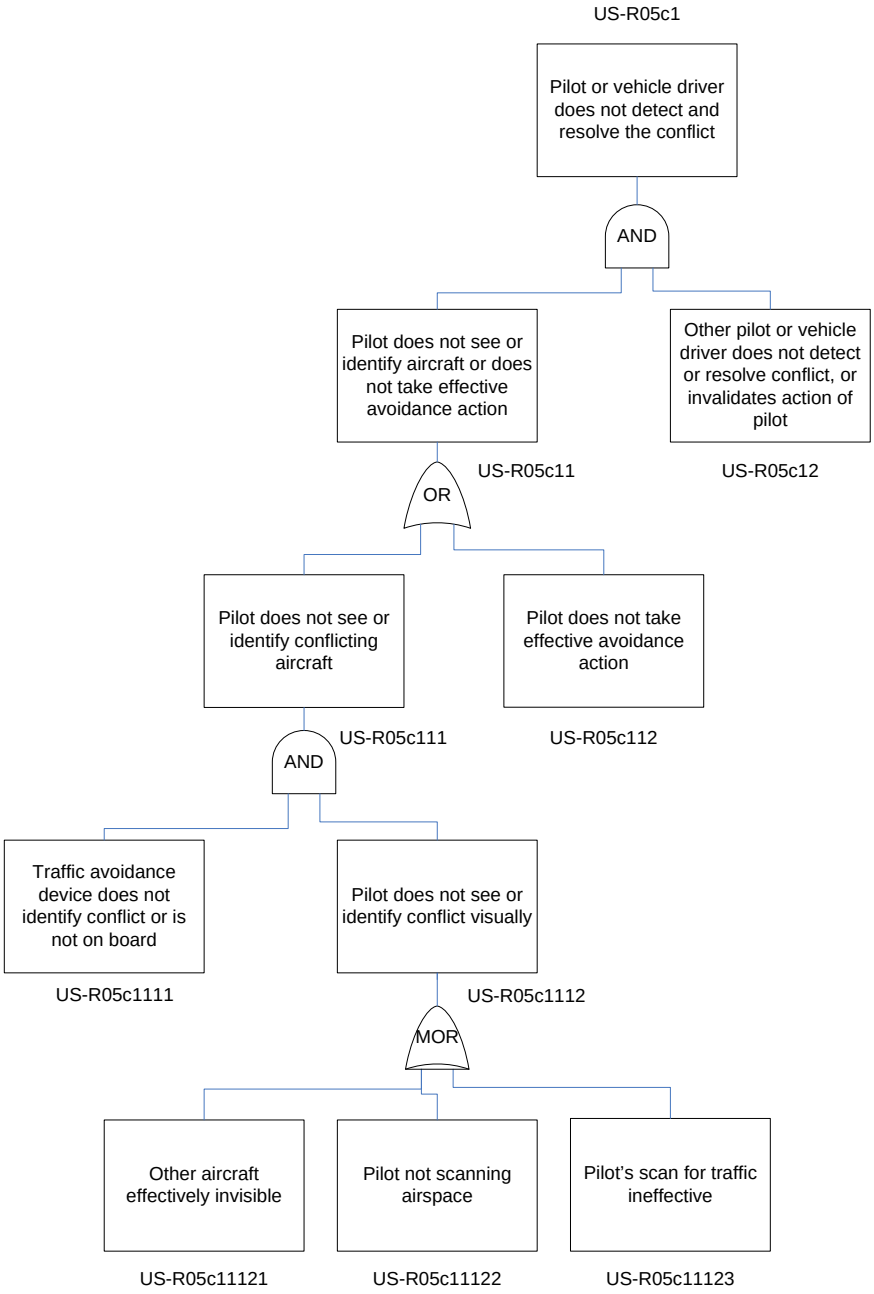


Figure 15. The FT US-R05c1—Pilot or Vehicle Driver Does Not Resolve the Conflict

5.5.1 Definitions.

Table 19 shows the definitions of US-R05 ESD and FT events.

Table 19. Definitions of ESD US-R05—Conflict on Taxiway or Runway Area

Event	Code	Definition
Conflict on taxiway or runway area	US-R05a1	The helicopter enters inadvertently the taxiway or runway (causing a runway incursion), leading to a conflict (i.e., separation recovery is required to avoid a collision). This ESD is applicable only to airports with runways and taxiways.
ATC does not resolve the conflict	US-R05b1	ATC fails to detect and/or provide separation/resolve the conflict.
Pilot or vehicle driver does not resolve the conflict	US-R05c1	Pilot fails to see and identify conflicting aircraft/vehicle, and/or fails to take recovery action in time, or takes an incorrect recovery action.
Collision on taxiway or runway	US-R05d1	Helicopter collides with other aircraft, helicopter, or vehicle.
Helicopter continues flight	US-R05d2	Helicopter continues flight.
Helicopter continues flight	US-R05d3	Helicopter continues flight.
FT—Initiating Event—US-R05a1		
Inadvertent taxiway or runway area entry	US-R05a11	The pilot enters the taxiway or runway area inadvertently. This could lead to a collision or conflict with other traffic.
Aircraft are positioned on collision course given loss of separation	US-R05a12	The recovery of the inadvertent taxiway or runway area entry is essential because the helicopter and another aircraft, vehicle, or helicopter are on trajectories that will lead to a collision.
Pilot takes off, lands, enters, or crosses runway or taxiway without clearance	US-R05a111	Pilot takes off, lands, enters or crosses runway or taxiway without clearance.
Pilot misunderstands ATC instruction and erroneously takes off, lands, enters, or crosses runway or taxiway	US-R05a112	Pilot misunderstands correct ATC instruction and erroneously takes off, lands, enters, or crosses runway or taxiway.
Pilot takes off, lands, enters, or crosses runway or taxiway with erroneous ATC clearance	US-R05a113	Pilot takes off, lands, enters, or crosses runway or taxiway with erroneous ATC clearance.

Table 19. Definitions of ESD US-R05—Conflict on Taxiway or Runway Area (Continued)

Event	Code	Definition
Pilot takes off or lands on wrong taxiway/runway/helipad, or erroneously on intersecting taxiway/runway	US-R05a114	Pilot takes off or lands on wrong taxiway/ runway/ helipad, or erroneously on intersecting taxiway/ runway.
FT—Pivotal Event—US-R05b1		
ATC does not detect the conflict	US-R05b11	The Air Traffic Controller (ATCo) does not detect the conflict. The ATCo includes all involved ATCos (executive, planner, supervisor) and failures in coordination and communications between them.
ATC detects the conflict but does not resolve it	US-R05b12	The ATCo does not recover separation, while aware of conflict. The ATCo includes all involved ATCos (executive, planner, supervisor) and failures in coordination and communications between them.
Failure of surveillance system(s) available to ATCo, resulting in failure to detect conflict	US-R05b111	Failure of the surveillance systems available to the ATCo, resulting in failure to detect the conflict.
Failure of ATCo to detect conflicting traffic	US-R05b112	The ATCo fails to detect the conflict while all systems function properly. The ATCo includes all involved ATCos (executive, planner, supervisor) and failures in coordination and communications between them.
No ATC available	US-R05b113	There is no ATCo available or present (e.g., because the ATCo left his/her position or because there are no ATC service provided).
Communication system failure, resulting in failure to resolve conflict	US-R05b121	Failure of communication systems available to the ATCo and pilot.
Erroneous communication ATCo pilot, resulting in failure to resolve conflict	US-R05b122	A failure/error in the communications between the ATCo and the pilot (e.g., call-sign confusion, misunderstanding, read back error, etc.).
Error of ATCo, resulting in failure to resolve conflict	US-R05b123	The ATCo fails to recover separation, while aware of conflict. This includes decision-making, judgment, or action errors.

Table 19. Definitions of ESD US-R05—Conflict on Taxiway or Runway Area (Continued)

Event	Code	Definition
FT—Pivotal Event—US-R05c1		
Pilot does not see or identify traffic or does not take effective avoidance action	US-R05c11	Pilot does not see or identify traffic (aircraft, helicopter, vehicle) or does not take effective avoidance action.
Other pilot or vehicle driver does not detect or resolve conflict, or invalidates the action of the pilot	US-R05c12	The pilot of the other traffic (aircraft, helicopter, etc.) or vehicle driver does not detect or resolve the conflict, or invalidates the action of pilot.
Pilot does not see or identify conflicting traffic	US-R05c111	Pilot does not see or identify conflicting traffic.
Pilot does not take effective avoidance action	US-R05c112	Pilot does not take effective avoidance action while aware of conflict. This includes avoidance action that induces a serious conflict, taking no action, or taking ineffective action (e.g., action is too late, insufficient, etc.).
Traffic-avoidance device does not identify conflict or is not on board	US-R05c1111	Traffic-avoidance device does not identify conflict and does not provide traffic/conflict alert to pilot because such a device is not installed on board, is switched off, or is not functioning properly.
Pilot does not see or identify conflict visually	US-R05c1112	The pilot does not detect conflicting traffic by using his/her vision.
Other traffic effectively invisible	US-R05c11121	Other traffic effectively invisible because of weather, glare, cockpit obstructions, other obstructions, poor contrast, aircraft too small to see, etc.
Pilot not scanning for traffic	US-R05c11122	Pilot does not detect conflicting traffic (aircraft, helicopter, vehicle) because he/she is not scanning the airspace, runway, taxiway areas.
Pilot's scan for traffic ineffective	US-R05c11123	Airspace and traffic scan by the pilot is not effective, object is not recognized as (conflicting) traffic, or traffic is not seen (e.g., scanning other part of airspace).

5.5.2 Quantification.

In the NTSB, ASRS, and Concern Network data sample that was analyzed, no occurrences involving HEMS or tour operations for this ESD were found. Therefore, this ESD and the corresponding FT events were not quantified.

Analysis of runway incursion data in the U.S. is recommended as is searching for occurrences related to this ESD; because of resource limitation in the current project, this task could not be undertaken.

5.6 US-R06: ESD AND FT DIAGRAMS.

Figures 16 through 18 show the ESD and FT diagrams of US-R06, loss of tail rotor effectiveness.

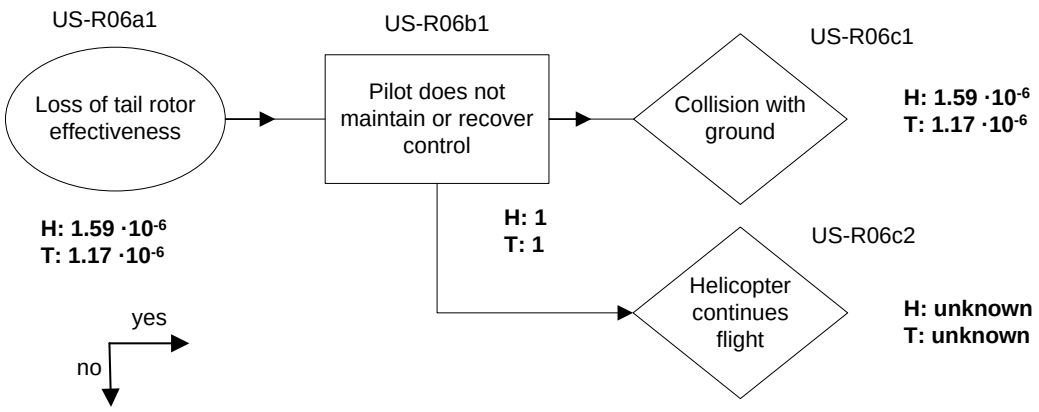


Figure 16. The ESD US-R06—Loss of Tail Rotor Effectiveness

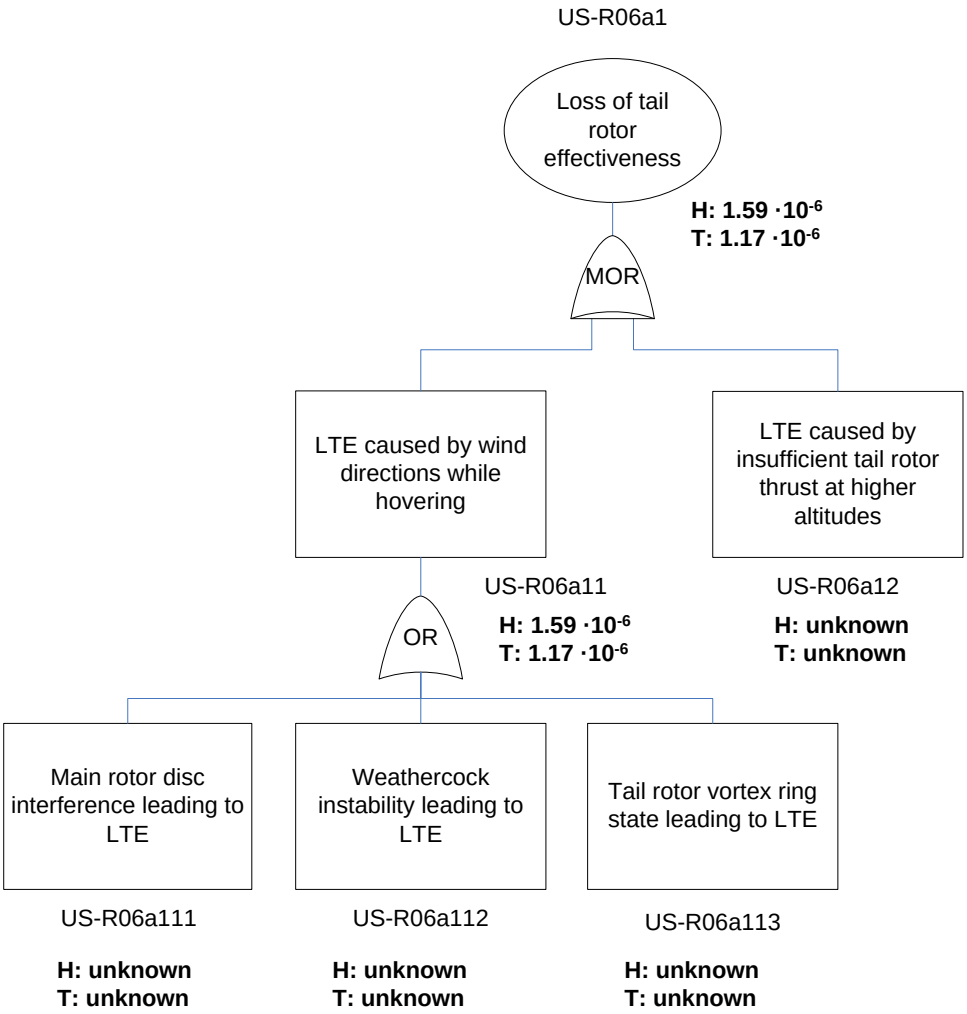


Figure 17. The FT US-R06a1—Loss of Tail Rotor Effectiveness

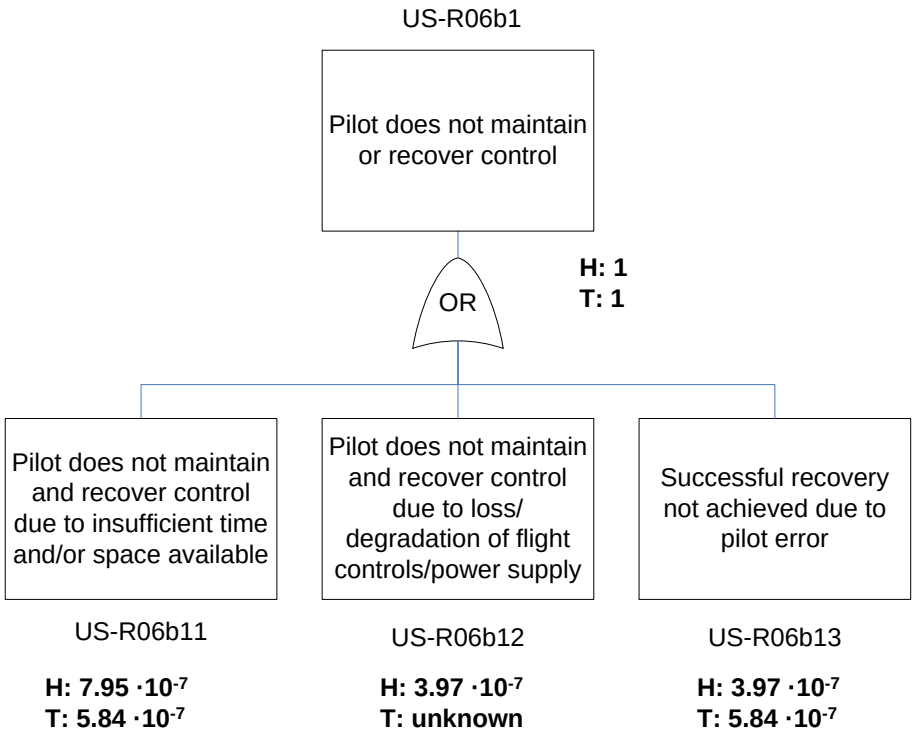


Figure 18. The FT US-R06b1—Pilot Does Not Maintain and Recover Control

5.6.1 Definitions.

Table 20 shows the definitions of US-R06, ESD and FT events.

Table 20. Definitions of ESD US-R06—Loss of Tail Rotor Effectiveness

Event	Code	Definition
LTE	US-R06a1	The occurrence of an uncommanded yaw rate that does not subside of its own accord and is not related to equipment or maintenance malfunction. For helicopter types without tail rotor, unanticipated yaw is also in scope of this initiating event.
Pilot does not maintain or recover control	US-R06b1	The pilot is unable to maintain or recover directional control of the helicopter.
Collision with ground	US-R06c1	The helicopter hits the ground after losing directional control.
Helicopter continues flight	US-R06c2	The pilot is able to continue the flight with a loss of tail rotor effectiveness.
FT—Initiating Event—US-R06b1		
LTE caused by wind directions while hovering	US-R06a11	The LTE is onset by wind that changes the tail rotor effective thrust while hovering.
Main rotor disc interference leading to LTE	US-R06a111	The main rotor vortex causes an extremely turbulent airflow into the tail rotor at relative winds between 285°-315°.
Weathercock instability leading to LTE	US-R06a112	Instability in tail rotor effectiveness when the helicopter attempts to weathervane its nose into the relative wind between 120°-240°.
Tail rotor vortex ring state leading to LTE	US-R06a113	A nonuniform, unsteady airflow into the tail rotor at relative winds between 210°-330°.
LTE caused by insufficient tail rotor thrust at higher altitudes	US-R06a12	The loss of tail rotor effectiveness is caused by insufficient tail rotor thrust because of operating at high altitude and high gross weight.
FT—Pivotal Event—US-R06b1		
Pilot does not maintain and recover control because of insufficient time and/or space available	US-R06b11	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R06b12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R06b13	Successful recovery not achieved because of pilot error.

LTE = Loss of tail rotor effectiveness

5.6.2 Quantification.

5.6.2.1 The IE.

The IE of the ESD is quantified using the NTSB, Concern Network, and ASRS databases. Four occurrences were found in the NTSB dataset and two in the Concern Network dataset for HEMS. The two occurrences in the Concern Network dataset are also in the NTSB dataset, making the total four. For tour operations, two occurrences were found in the NTSB dataset. The data contain insufficient detail to determine the initiating FT base events, but the next higher level FT events can be quantified. Table 21 shows the distribution of occurrences over the FT events for HEMS and tour operations and the corresponding probability per flight hour.

Table 21. Occurrences and Probabilities of FT Events of US-R06a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R06a1			$1.59 \cdot 10^{-6}$	$1.17 \cdot 10^{-7}$	Flight hour
US-R06a11	4 (c, n)	2 (c, n)	$1.59 \cdot 10^{-6}$	$1.17 \cdot 10^{-7}$	Flight hour
US-R06a111	Unknown	Unknown	Unknown	Unknown	Flight hour
US-R06a112	Unknown	Unknown	Unknown	Unknown	Flight hour
US-R06a113	Unknown	Unknown	Unknown	Unknown	Flight hour
US-R06a12	0	0	Unknown	Unknown	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.6.2.2 Pivotal Event.

The only pivotal event, “pilot does not maintain or recover control” (US-R06b1), can be quantified by using occurrences of collision with the ground after a loss of tail rotor effectiveness occurred. In the data sample, four occurrences were found for HEMS and two occurrences for tour operations. Table 22 shows the distribution of occurrences over the FT base events for HEMS and tour operations and the corresponding probability per flight hour. The conditional probability of the pivotal event is calculated from the base events divided by the IE probability.

Table 22. Occurrences and Probabilities of FT Events of US-R06b1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R06b1			1	1	US-R06a1
			$1.59 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R06b11	2 (c, n)	1 (n)	$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R06b12	1 (c, n)	0	$3.97 \cdot 10^{-7}$	unknown	Flight hour
US-R06b13	1 (n)	1 (n)	$3.97 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.6.2.3 End States.

The end states of the ESD are quantified using the quantification of the IE and the pivotal event; the results are shown in table 23.

Table 23. Occurrences and Probabilities of End States of US-R06

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R06c1			$1.59 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R06c2			Unknown	Unknown	Flight hour

5.7 THE ESD-R07: ESD AND FT DIAGRAMS.

Figures 19 through 23 show the ESD and FT diagrams of US-R07, fire, smoke, or burning odor onboard helicopter.

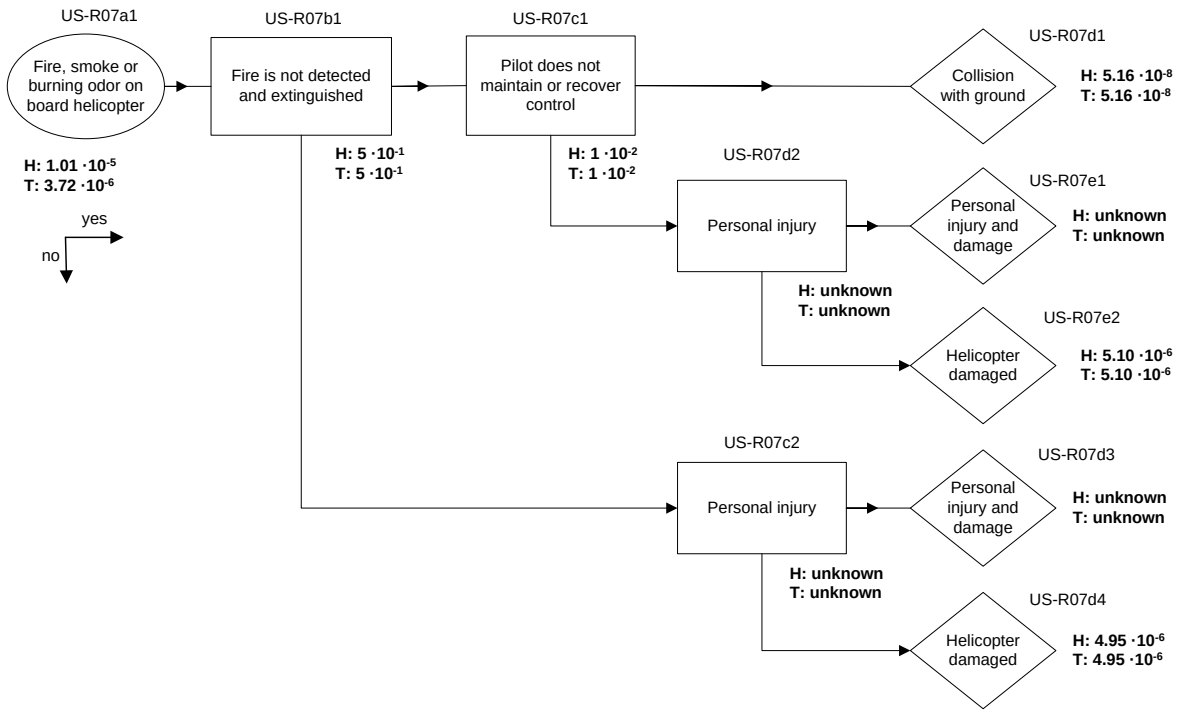


Figure 19. The ESD US-R07—Fire, Smoke, or Burning Odor Onboard Helicopter

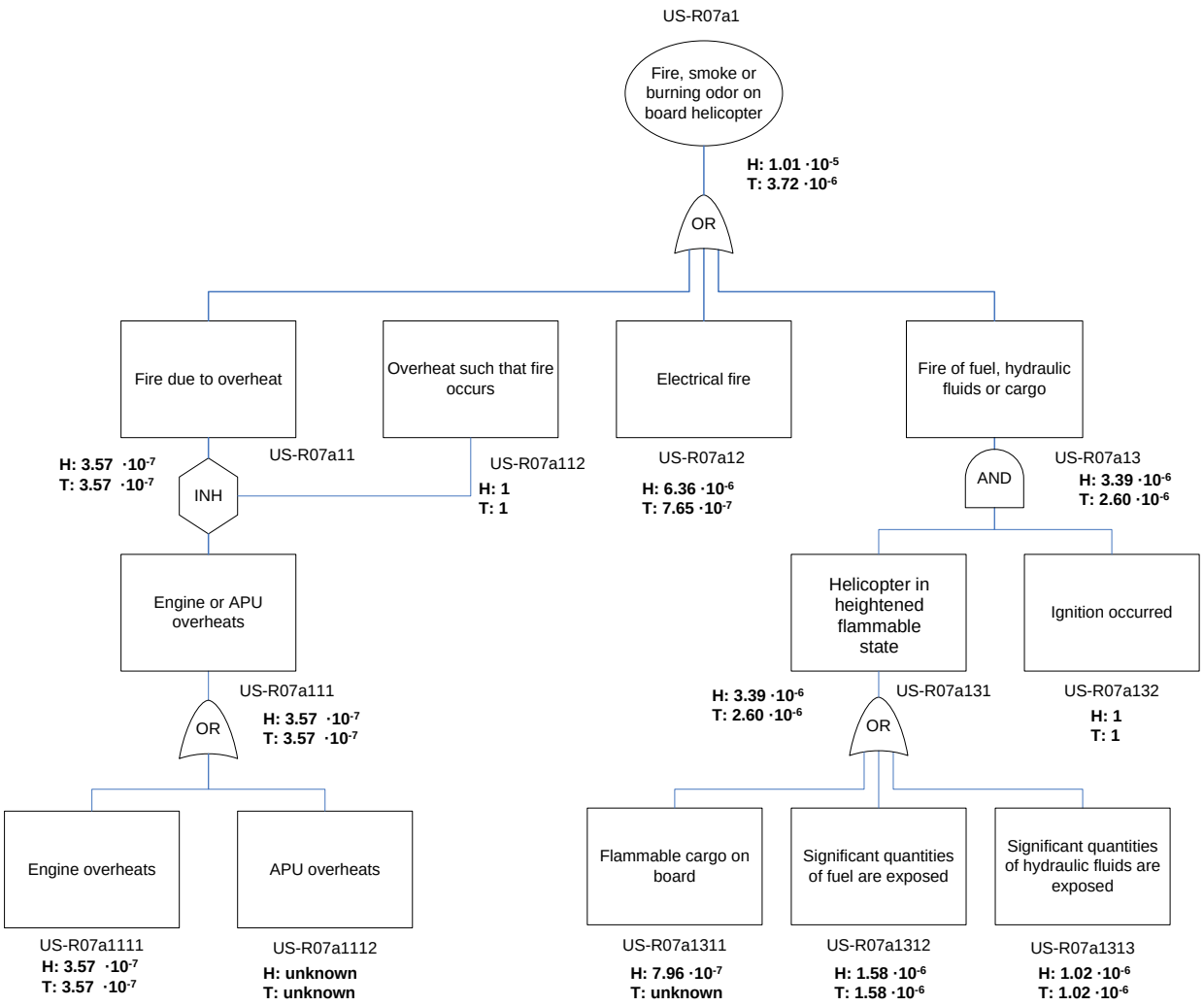


Figure 20. The FT US-R07a1—Fire, Smoke, or Burning Odor Onboard Helicopter

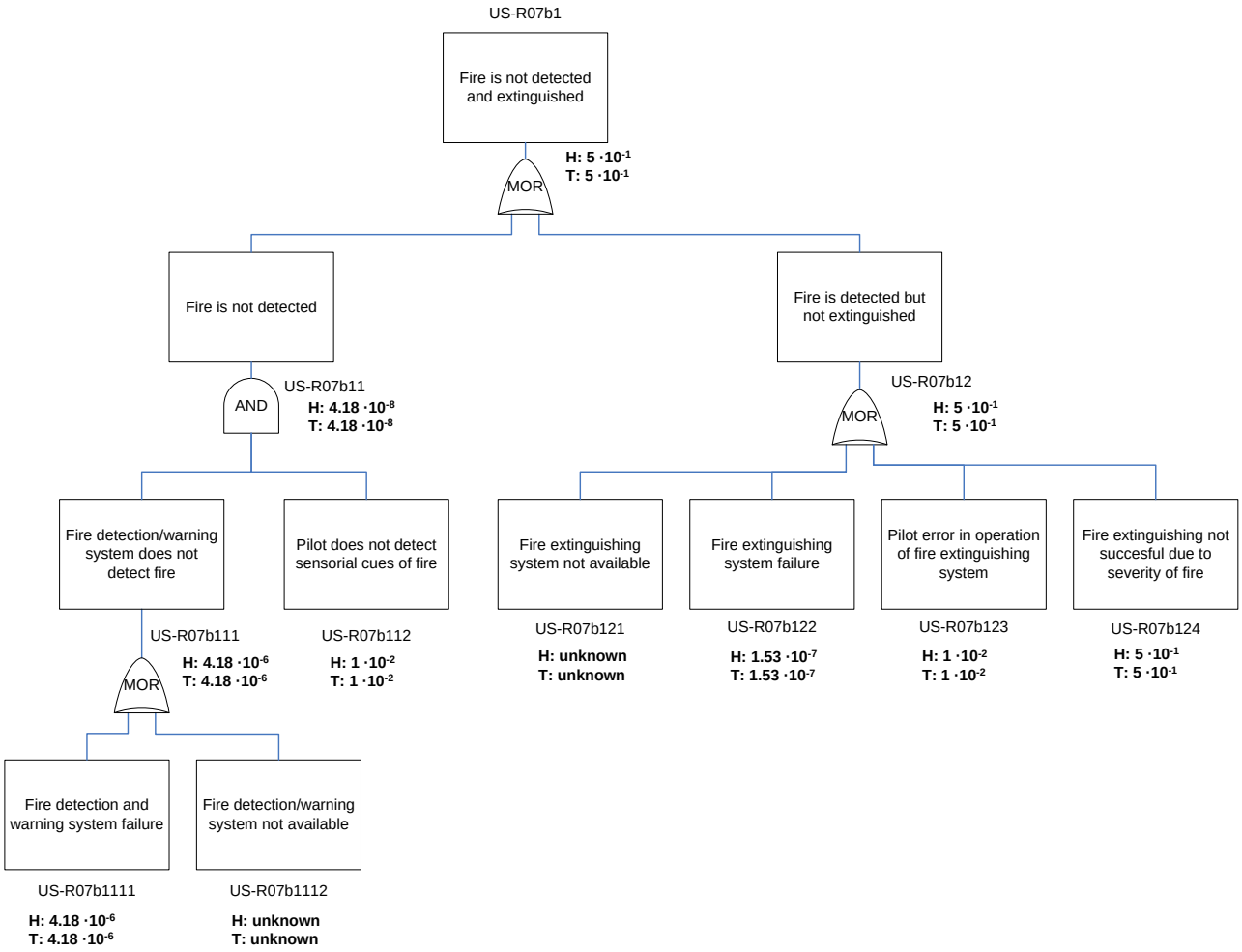


Figure 21. The FT US-R07b1—Fire Is Not Detected and Extinguished

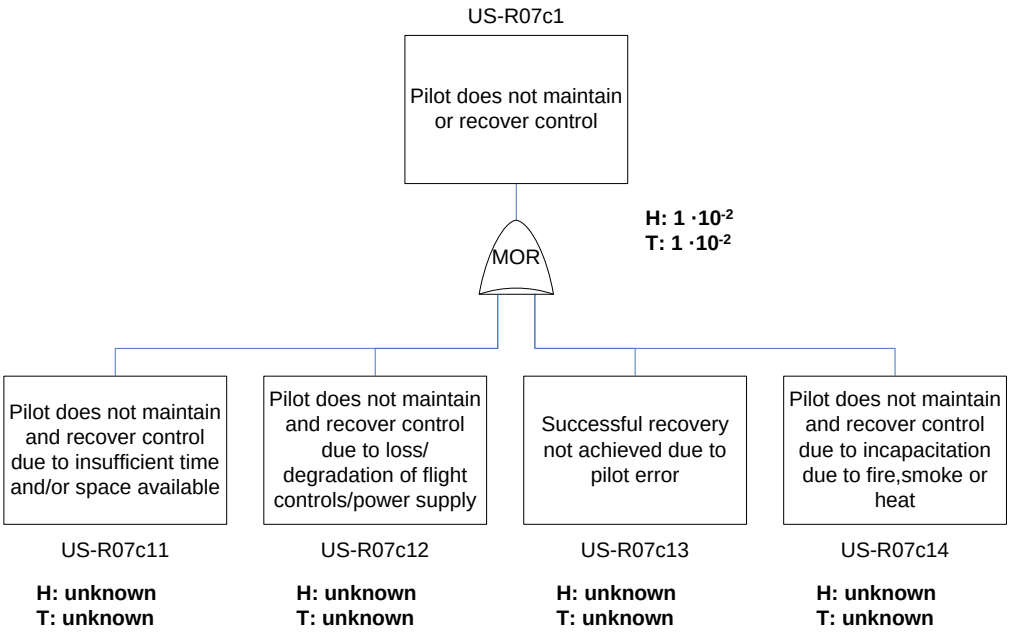


Figure 22. The FT US-R07c1—Pilot Does Not Maintain or Recover Control

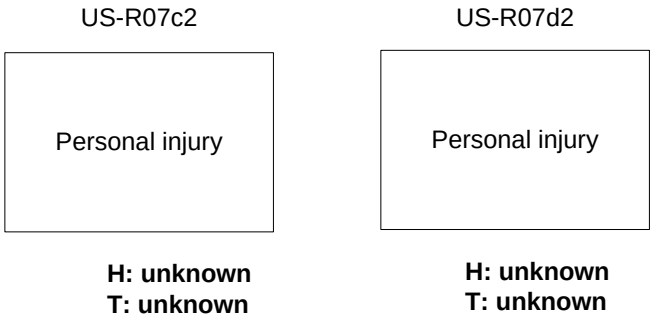


Figure 23. The FT US-R07c2 and US-R07d2—Personal Injury

5.7.1 Definitions.

Table 24 shows the definitions of US-R07, ESD and FT events.

Table 24. Definitions of ESD US-R07—Fire, Smoke, or Burning Odor Onboard Helicopter

Event	Code	Definition
Fire, smoke, or burning odor onboard helicopter	US-R07a1	A situation in which a combustible substance onboard the aircraft is burning (e.g., aircraft's payload, systems, or interior). Indicator of a fire is visible flames, but also visible smoke or a burning smell. The fire can start either on the ground or in the air.
Fire is not detected and extinguished	US-R07b1	Flight crew or ground crew are not aware of fire developing onboard or are not able to extinguish the fire.
Pilot does not maintain or recover control	US-R07c1	The pilot is unable to maintain or recover control after fire, smoke, or burning odor.
Personal injury	US-R07c2	Personal injury due to fire or smoke.
Collision with ground	US-R07d1	The helicopter hits the ground after losing control. This includes dynamic rollovers, impact with terrain, and hard landings with damage.
Personal injury	US-R07d2	Personal injury due to fire or smoke.
Personal injury and damage	US-R07d3	Personal injury due to fire or smoke and damage to the helicopter due to fire.
Helicopter damaged	US-R07d4	Damage to the helicopter due to fire.
Personal injury and damage	US-R07e1	Personal injury due to fire or smoke, and damage to the helicopter due to fire.
Helicopter damaged	US-R07e2	Damage to the helicopter because of fire.
FT—Initiating Event—US-R07a1		
Fire due to overheat	US-R07a11	A fire breaks out because of an overheated engine or APU.
Engine or APU overheats	US-R07a111	The engine or APU overheats.
Engine overheats	US-R07a1111	The engine overheats, including rotor drive and tail-rotor drive-system overheat.
APU overheats	US-R07a1112	The APU overheats.
Overheat such that causes fire	US-R07a112	The overheat of the engine or APU causes a fire. INH-gate: US-R07a111 is the necessary, but not always sufficient, single cause of US-R07a11. The portion of sufficient overheats is indicated by the condition US-R07a112.
Electrical fire	US-R07a12	A fire breaks out that has been ignited by an electrical fault.
Fire of fuel, hydraulic fluids, or cargo	US-R07a13	A fire breaks out with fuel, hydraulic fluids, or cargo as combustible substance.
Helicopter in heightened flammable state	US-R07a131	Elements of the helicopter are in a heightened flammable state.
Flammable cargo on board	US-R07a1311	The helicopter has flammable cargo onboard.
Significant quantities of fuel are exposed	US-R07a1312	Significant quantities of fuel or engine oil are exposed (e.g., a leak of fuel or engine oil that, when ignited, results in a fire in flight).

Table 24. Definitions of ESD US-R07—Fire, Smoke, or Burning Odor Onboard Helicopter (Continued)

Event	Code	Definition
Significant quantities of hydraulic fluids are exposed	US-R07a1313	Significant quantities of hydraulic fluids are exposed (e.g., a leak of hydraulic fluid that, when ignited, results in a fire in flight).
Ignition occurs	US-R07a132	When the aircraft is in a state of heightened flammability, ignition occurs and initiates a fire onboard.
FT—Pivotal Event—US-R07b1		
Fire is not detected	US-R07b11	Flight crew or ground crew is not aware of fire developing onboard.
Fire detection/warning system does not detect fire	US-R07b111	The fire detection/warning system does not detect the fire developing onboard
Fire detection system failure	US-R07b1111	Fire detection system failure.
Fire warning system failure	US-R07b1112	Fire warning system failure.
Fire detection/warning system not available	US-R07b1113	There is no fire detection/warning system installed in the helicopter.
Pilot does not detect sensorial cues of fire	US-R07b112	Pilot does not detect the fire by smell, vision, sound, or feel.
Fire is detected, but not extinguished	US-R07b12	Flight crew or ground crew is not able to extinguish the fire.
Fire extinction system not available	US-R07b121	There is no fire extinction system onboard the aircraft.
Fire extinction system failure	US-R07b122	Fire extinction system failure.
Pilot error in operation of fire extinction system	US-R07b123	Pilot error in operation of fire extinction system (e.g., delay in activation, incorrect operation, system not used).
Fire extinction not successful because of severity of fire	US-R07b124	The fire is so severe that proper extinction is not possible.
FT—Pivotal Event—US-R07c1		
Pilot does not maintain and recover control because of insufficient time and/or space available	US-R07c11	Pilot does not maintain and recover control because of insufficient time/space available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R07c12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R07c13	Successful recovery not achieved because of pilot error.
Pilot does not maintain and recover control because of incapacitation due to fire, smoke, or heat	US-R07c14	Pilot does not maintain and recover control because of incapacitation due to fire, smoke, or heat.
FT—Pivotal Event—US-R07c2		
No events defined		
FT—Pivotal Event—US-R07d2		
No events defined		

APU = Auxiliary power unit

5.7.2 Quantification.

5.7.2.1 The IE.

The IE of the ESD is quantified using the NTSB, Concern Network, and ASRS databases; and the SDR data. Data from the SDR database were used to estimate the probabilities of the base events related to system failures. Events US-R07a1111, US-R07a1112, US-R07a1312, and US-R07a1313 were quantified with SDR data. It is assumed that the type of operation does not affect the event probability and, therefore, that the probability derived from SDR data is applicable to all types of helicopter operations. Event US-R07a1311 was estimated by occurrence data from NTSB, Concern Network, and ASRS databases. The FT logic was applied to calculate the intermediate events. Table 25 shows the distribution of occurrences over the FT events for HEMS and tour operations and the corresponding probability per flight hour.

It is assumed that the probability of "overheat such that fire occurs" (US-R07a112) is 1, so that an engine or auxiliary power unit overheat always results in a fire. With this assumption, the branch of the FT with the current dataset can be quantified. However, it is expected that, in reality, there will be more overheat events that do not result in fires, but those are not reported in our data sample.

For "electrical fire" (US-R07b12), 16 occurrences for HEMS operations were found from the three databases, compared to 15 occurrences in the SDR database that represent all types of operations. It is believed that the estimate based on the 16 HEMS occurrences is better compared to an estimate using the SDR events because 16 events specifically relate to HEMS operations, whereas the SDR events relate to all types of helicopters and operations. Therefore, the 16 occurrences found for the HEMS operations were used to quantify this event. For tour operations, no occurrence was found and the estimate based on SDR events was used.

It was assumed that the probability of the event "ignition occurred" (US-R07a132) is 1. The occurrences include not only fire, but also events in which smoke or smell is reported. For the reported occurrences in this dataset, the event US-R07a132 occurred and, therefore, its probability equals 1.

Table 25 shows the results of FT event qualifications.

Table 25. Occurrences and Probabilities of FT Events of US-R07a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R07a1			$1.01 \cdot 10^{-5}$	$3.72 \cdot 10^{-6}$	Flight hour
US-R07a11			$3.57 \cdot 10^{-7}$	$3.57 \cdot 10^{-7}$	Flight hour
US-R07a111			$3.57 \cdot 10^{-7}$	$3.57 \cdot 10^{-7}$	Flight hour
US-R07a1111	7 (s)	7 (s)	$3.57 \cdot 10^{-7}$	$3.57 \cdot 10^{-7}$	Flight hour
US-R07a1112	0 (s)	0 (s)	Unknown	Unknown	Flight hour
US-R07a112			1 (*)	1 (*)	US-R07a111
US-R07a12	16 (a,c,n)	15 (s)	$6.36 \cdot 10^{-6}$	$7.65 \cdot 10^{-7}$	Flight hour
US-R07a13	4 (c)	0	$3.39 \cdot 10^{-6}$	$2.60 \cdot 10^{-6}$	Flight hour
US-R07a131			$3.39 \cdot 10^{-6}$	$2.60 \cdot 10^{-6}$	Flight hour
US-R07a1311	2 (c)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R07a1312	31 (s)	31 (s)	$1.58 \cdot 10^{-6}$	$1.58 \cdot 10^{-6}$	Flight hour
US-R07a1313	20 (s)	20 (s)	$1.02 \cdot 10^{-6}$	$1.02 \cdot 10^{-6}$	Flight hour
US-R07a132			1 (*)	1 (*)	US-R07a131
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (s) = SDR data; (*) = assumption					

5.7.2.2 Pivotal Event(s).

In all 21 occurrences for HEMS operations that were analyzed for this ESD, the crew detected the fire or smoke and made safe landings without personal injuries to the occupants. No occurrences were found for the pivotal events US-R07b1, US-R07d2, and US-R07c2. For air tour operations, no occurrences were found in the NTSB and ASRS datasets. Data from the SDR database also apply to tour operations; however, as with HEMS operations, there were no occurrences found for the pivotal events US-R07b1, US-R07d2, and US-R07c2.

There is not enough data to support the quantification of the FT bottom-up without making assumptions on certain event probabilities. The probability of the base events US-R07b1111 and US-R07b1112 are estimated based on SDR data. The probability "fire detection/warning system not available" (US-R07b1113) is estimated to be 0 because it is very likely that each HEMS and tour operator's helicopter has a fire detection and warning system onboard. Likewise, the probability of "fire extinction system not available" is estimated to be 0. The research team assumed that the probability of a pilot error in "detection of the fire" (US-R07b112) and "the operation of the fire extinction system" (US-R07b123) is in the order of magnitude of $1.0 \cdot 10^{-2}$. It is assumed that, in at least 50% of the occurrences with smoke, fire, etc., the fire extinction is not successful; US-R07b124 is $5.0 \cdot 10^{-1}$. The estimated probabilities for HEMS and tour operations are the same.

There is no data to support the quantification of the pivotal event "pilot does not maintain or recover control" (US-R07c1). It is assumed that this pivotal event has a probability of $1.0 \cdot 10^{-2}$.

Table 26 shows the frequency of the FT events and corresponding probability.

Table 26. Occurrences and Probabilities of Pivotal Events of US-R07

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R07b1			$5.10 \cdot 10^{-1}$	$5.10 \cdot 10^{-1}$	US-R07a1
US-R07b11			$4.18 \cdot 10^{-8}$	$4.18 \cdot 10^{-8}$	Flight hour
US-R07b111			$4.18 \cdot 10^{-6}$	$4.18 \cdot 10^{-6}$	Flight hour
US-R07b112			$1.0 \cdot 10^{-2}$ (*)	$1.0 \cdot 10^{-2}$ (*)	US-R07a1
US-R07b1111	79(s)+3(s)	79(s)+3(s)	$4.18 \cdot 10^{-6}$	$4.18 \cdot 10^{-6}$	Flight hour
US-R07b1112			0 (*)	0 (*)	Flight hour
US-R07b12			$5.10 \cdot 10^{-1}$	$5.10 \cdot 10^{-1}$	US-R07a1
US-R07b121			0 (*)	0 (*)	US-R07a1
US-R07b122	3 (s)	3 (s)	$1.53 \cdot 10^{-7}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R07b123			$1.0 \cdot 10^{-2}$ (*)	$1.0 \cdot 10^{-2}$ (*)	US-R07a1
US-R07b124			$5.0 \cdot 10^{-1}$ (*)	$5.0 \cdot 10^{-1}$ (*)	US-R07a1
US-R07c1			$1.0 \cdot 10^{-2}$ (*)	$1.0 \cdot 10^{-2}$ (*)	US-R07a1
US-R07c11			Unknown	Unknown	Flight hour
US-R07c12			Unknown	Unknown	Flight hour
US-R07c13			Unknown	Unknown	Flight hour
US-R07c14			Unknown	Unknown	Flight hour
US-R07c2			Unknown	Unknown	Flight hour
US-R07d2			Unknown	Unknown	Flight hour
(s) = SDR data; (*) = Assumption					

5.7.2.3 End States.

The end states of the ESD are quantified using the quantification of the IE and the pivotal events; the results are given in table 27.

Table 27. Occurrences and Probabilities of End States of US-R07

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R07d1			$5.16 \cdot 10^{-8}$	$5.16 \cdot 10^{-8}$	Flight hour
US-R07e1			Unknown	Unknown	Flight hour
US-R07e2			$5.10 \cdot 10^{-6}$	$5.10 \cdot 10^{-6}$	Flight hour
US-R07d3			Unknown	Unknown	Flight hour
US-R07d4			$4.95 \cdot 10^{-6}$	$4.95 \cdot 10^{-6}$	Flight hour

5.8 US-R08: ESD AND FT DIAGRAMS.

Figures 24 through 27 show the ESD and FT diagrams of US-R08: Loss of situational awareness in degraded visual environment.

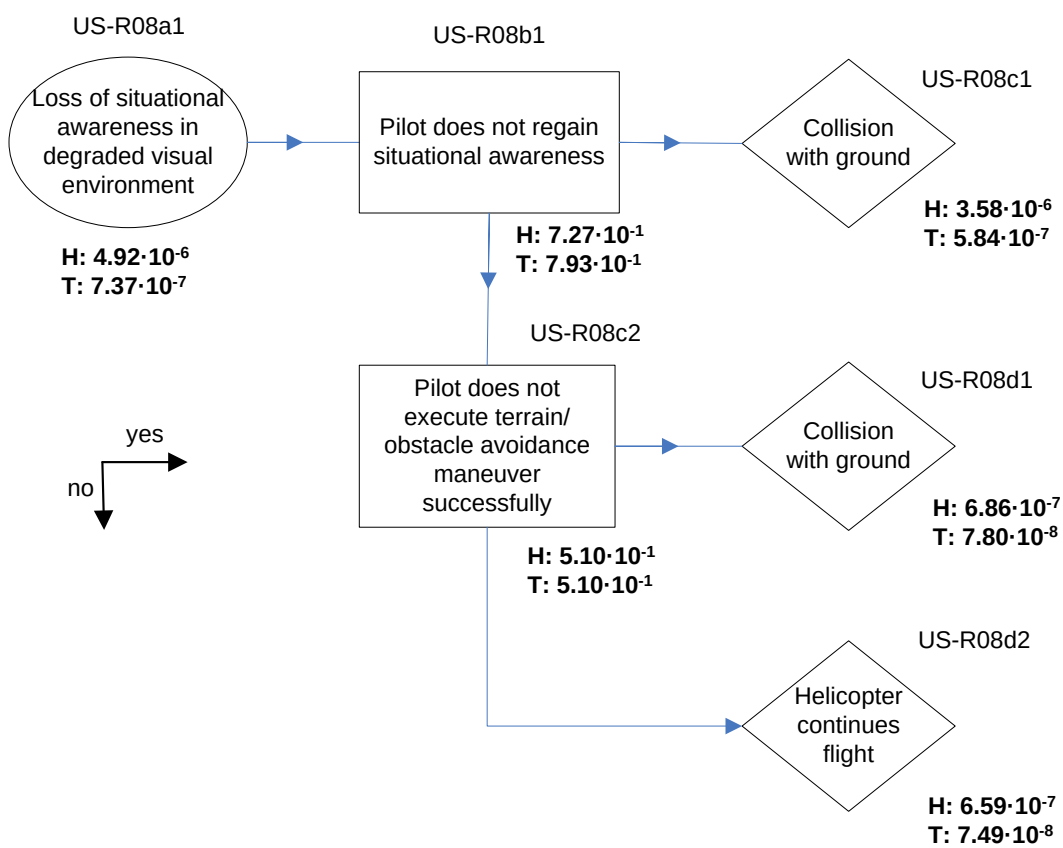


Figure 24. The ESD US-R08—Loss of Situational Awareness in Degraded Visual Environment

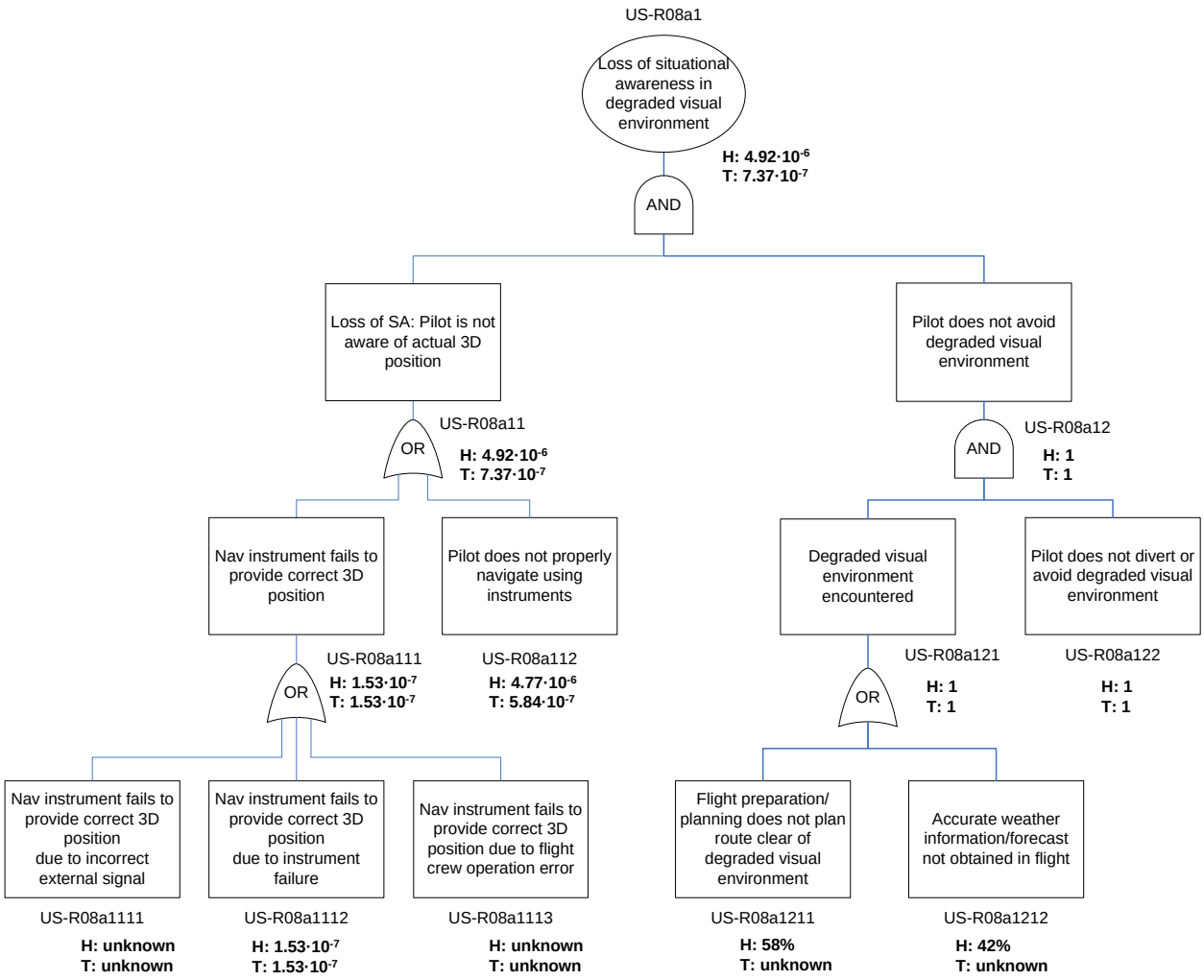


Figure 25. The FT US-R08a1—Loss of Situational Awareness in Degraded Visual Environment

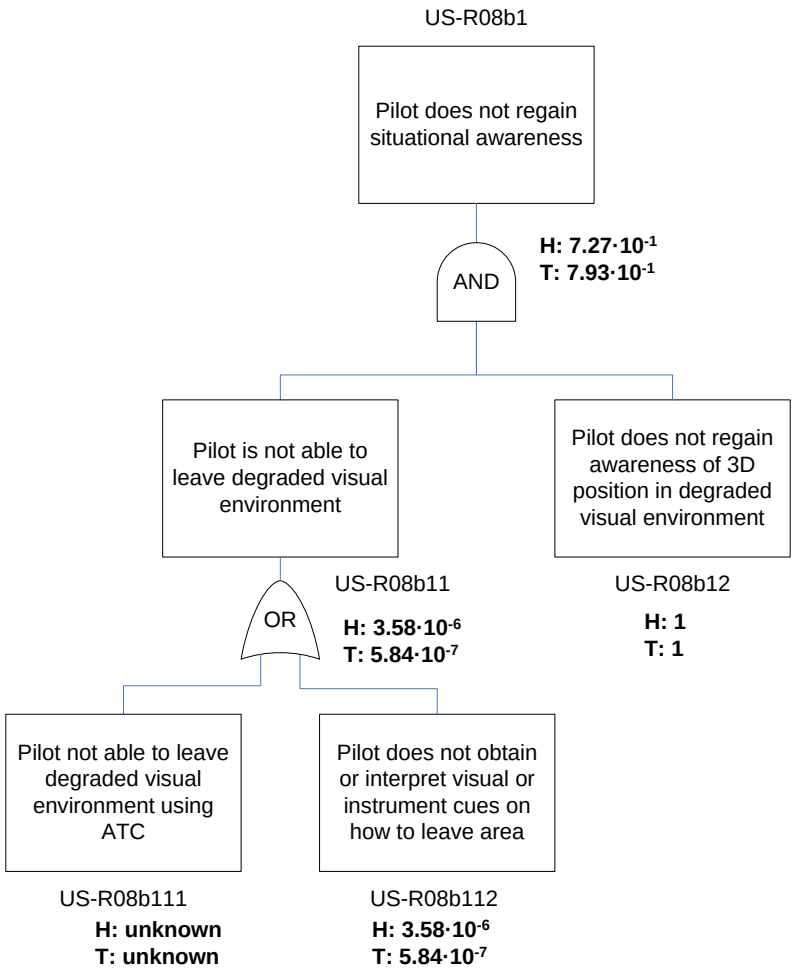


Figure 26. The FT US-R08b1—Pilot Does Not Regain Situational Awareness

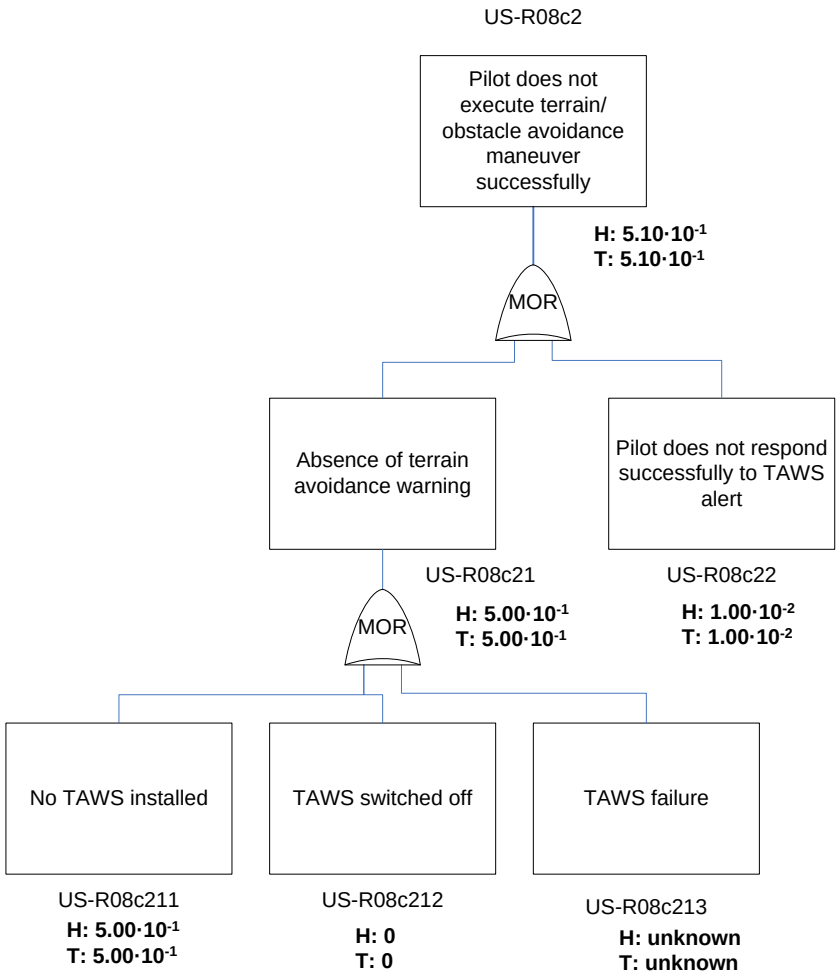


Figure 27. The FT US-R08c2—Pilot Does Not Execute Terrain/Obstacle Avoidance Maneuver Successfully

5.8.1 Definitions.

5.8.1.1 The Difference Between ESDs 8 and 9.

Both ESDs 8 and 9 occur in a degraded visual environment so the reader may wonder why they are separate ESDs. In the breakdown of accident archetypes, LOC and controlled flight into terrain (CFIT) are two different accident archetypes. There are various possible IEs for an LOC accident scenario; one is the loss of situational awareness (SA) in a degraded visual environment followed by pilot disorientation and an LOC. In a CFIT scenario—by definition—LOC does not occur. Therefore, both scenarios have been modeled as separate ESDs.

Table 28 shows definitions of ESD US-R08, ESD and FT events.

Table 28. Definitions of ESD US-R08—Loss of SA in Degraded Visual Environment

Event	Code	Definition
Loss of SA in degraded visual environment	US-R08a1	This scenario concerns a CFIT scenario and not a loss of control (the latter is covered by ESD US-R9). The pilot loses SA and becomes unaware of his/her position (location/altitude) because of a degraded visual environment, which includes low visibility conditions, inadvertent flight into IMC, night conditions, etc.
Pilot does not regain SA	US-R08b1	Pilot does not regain SA in degraded visual environment, despite possible assistance from ATC, TAWS, etc.
Collision with ground	US-R08c1	The helicopter hits the ground, terrain, water, or an obstacle after losing SA. This includes a hard landing with damage.
Pilot does not execute terrain/obstacle avoidance maneuver successfully	US-R08c2	Pilot does not execute terrain/obstacle avoidance maneuver successfully. This includes not executing such a maneuver at all.
Collision with ground	US-R08d1	The helicopter hits the ground, terrain, water, or an obstacle after losing SA. This includes a hard landing with damage.
Helicopter continues flight	US-R08d2	The pilot continues flight because SA is regained in degraded visual environment, or because the visual environment improves.
FT—Initiating Event—US-R08a1		
Loss of SA: Pilot is not aware of actual 3D position	US-R08a11	Pilot loses SA and is not aware of the helicopter's location/altitude.
Nav instrument fails to provide correct 3D position	US-R08a111	Nav instrument fails to provide a correct 3D position.
Nav instrument fails to provide correct 3D position because of incorrect external signal	US-R08a1111	Nav instrument fails to provide a correct 3D position because of an incorrect external signal (e.g., a GPS signal error).
Nav instrument fails to provide correct 3D position because of instrument failure	US-R08a1112	Nav instrument fails to provide a correct 3D position because of onboard instrument failure.
Nav instrument fails to provide correct 3D position because of flight crew operation error	US-R08a1113	Nav instrument fails to provide correct 3D position because of flight crew error of operation of instruments.
Pilot does not properly navigate using instruments	US-R08a112	Pilot does not properly navigate using instruments.
Pilot does not avoid degraded visual environment	US-R08a12	The pilot continues the flight into the degraded visual environment.
Degraded visual environment encountered	US-R08a121	The pilot encounters a degraded visual environment (e.g. clouds, darkness, brown-out, white-out).
Flight preparation/planning does not plan route clear of degraded visual environment	US-R08a1211	Flight preparation/planning does not plan route clear of degraded visual environment, which includes flying in the dark.

Table 28. Definitions of ESD US-R08—Loss of SA in Degraded Visual Environment (Continued)

Event	Code	Definition
Accurate weather information/forecast not obtained in flight	US-R08a1212	Accurate weather information/forecast is not obtained in flight. This includes occurrences involving brown-outs or white-outs.
Pilot does not divert or avoid degraded visual environment	US-R08a122	The pilot does not divert or initiate a maneuver to avoid the degraded visual environment. This includes cases for which no avoidance action is undertaken because the flight into IMC is intentional.
FT—Pivotal Event—US-R08b1		
Pilot is not able to leave degraded visual environment	US-R08b11	Pilot is not able to leave degraded visual environment.
Pilot not able to leave degraded visual environment using ATC	US-R08b111	Pilot is not able to leave degraded visual environment because he/she does not use available ATC instruction, or the instructions are not correct.
Pilot does not obtain or interpret visual or instrument cues on how to leave area	US-R08b112	Pilot does not obtain visual or instrument cues on how to leave area, or he/she does not interpret the available cues correctly to leave the area of degraded visual environment.
Pilot does not regain awareness of 3D position in degraded visual environment	US-R08b12	Pilot does not regain awareness of the 3D position in a degraded visual environment
FT—Pivotal Event—US-R08c2		
Absence of terrain awareness and avoidance warning	US-R08c21	There is no terrain awareness and avoidance alert provided to the pilot.
No TAWS installed	US-R08c211	The TAWS is not installed in the helicopter.
TAWS switched off	US-R08c212	The TAWS is installed, but switched off.
TAWS failure	US-R08c213	The TAWS is installed, but fails to work correctly. There is no timely warning given—failure of the database or failure of the system, for instance.
Pilot does not respond successfully to TAWS alert	US-R08c22	A warning is received, but the pilot fails to respond successfully (e.g., warning is not observed, warning is neglected, incorrect avoidance maneuver is flown, or there is no time left to avoid a collision).

IMC = instrument meteorological conditions; Nav = navigation; TAWS = terrain awareness and warning system

5.8.2 Quantification.

5.8.2.1 The IE.

The IE, “loss of situational awareness in degraded visual environment” (US-R08a1), is mainly quantified using the NTSB, ASRS, and Concern Network databases. The SDR database is used only to quantify, “nav instrument fails to provide correct 3D position because of instrument failure” (US-R08a1112), of which three occurrences were found.

From the databases used, it is not possible to determine the probability of “pilot does not avoid degraded visual environment” (US-R08a12). All occurrences found are cases of loss of SA

(US-R08a11) and "pilot does not avoid degraded visual environment" (US-R08a12) combined. Using these databases, it must therefore be assumed that the probability of the pilot not avoiding the degraded visual environment equals 1. The probabilities of the underlying base events are given as distributions; for HEMS, 58% of the cases were due to flight preparation error (US-R08a1211) and 42% were due to not obtaining weather information in-flight. For tour, no occurrences were found.

The probabilities of the left branch of the FT are determined from its base events. In total, 12 occurrences are found in the NTSB, ASRS, and Concern Network databases for HEMS operations and one occurrence is found for tour operations in the NTSB data. The event "pilot does not properly navigate using instruments" (US-R08a112) was found in the NTSB, ASRS, and Concern Network databases respectively in 9, 2, and 1 occurrence(s). Three occurrences of "nav instrument fails to provide correct 3D position because of instrument failure" (US-R08a1112) were found in the SDR dataset. Table 29 shows the breakdown of occurrences and the associated probabilities of the events.

Table 29. Occurrences and Probabilities of US-R8a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R08a1			$4.92 \cdot 10^{-6}$	$7.37 \cdot 10^{-7}$	Flight hour
US-R08a11			$4.92 \cdot 10^{-6}$	$7.37 \cdot 10^{-7}$	Flight hour
US-R08a111			$1.53 \cdot 10^{-7}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R08a1111	0	0	Unknown	Unknown	Flight hour
US-R08a1112	3 (s)	3 (s)	$1.53 \cdot 10^{-7}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R08a1113	0	0	Unknown	Unknown	Flight hour
US-R08a112	12 (a,c,n)	1 (n)	$4.77 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R08a12			1 (*)	1 (*)	US-R08a11
US-R08a121			1 (*)	1 (*)	US-R08a11
US-R08a1211	7 (n)	0	58%	Unknown	US-R08a121
US-R08a1212	5 (a,c,n)	0	42%	Unknown	US-R08a121
US-R08a122			1 (*)	1 (*)	US-R08a11
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (s) = SDR data; (*) = assumption					

5.8.2.2 Pivotal Event(s).

For the pivotal event, "pilot does not regain situational awareness" (US-R08b1), it is assumed that, when the pilot is not able to leave the degraded environment (US-R08b11), the probability that the pilot does not regain awareness (US-R08b12) equals 1. The left branch of the FT is quantified from occurrences found in the NTSB database.

For the pivotal event "pilot does not execute terrain/obstacle avoidance maneuver successfully" (US-R08c2), there are no occurrence data available in the dataset. Therefore, a few assumptions are made to be able to quantify the FT events. These assumptions are conditional on the preceding events (US-R08a1 occurring and US-R08b1 not occurring): in 50% of the helicopter fleet, terrain awareness and warning system (TAWS) is not installed (US-R08c211), and when installed, TAWS is never switched off (US-R08c212). The probability that the pilot does not respond successfully to a TAWS alert is assumed to be $1.0 \cdot 10^{-2}$. No occurrences of TAWS failure (US-R08c22) were found in the SDR dataset. Table 30 summarizes the quantification results.

Table 30. Occurrences and Probabilities of the Pivotal Events of ESD US-R08

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R08b1			$7.27 \cdot 10^{-1}$	$7.93 \cdot 10^{-1}$	US-R08a1
			$3.58 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R08b11			$3.58 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R08b111	0	0	Unknown	Unknown	Flight hour
US-R08b112	9 (n)	1 (n)	$3.58 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R08b12			1 (*)	1 (*)	US-R08b11
US-R08c2			$5.10 \cdot 10^{-1}$	$5.10 \cdot 10^{-1}$	US-R08a1/nb1
US-R08c21			$5.00 \cdot 10^{-1}$	$5.00 \cdot 10^{-1}$	US-R08a1/nb1
US-R08c211			$5.00 \cdot 10^{-1}$ *)	$5.00 \cdot 10^{-1}$ (*)	US-R08a1/nb1
US-R08c212			0 (*)	0 (*)	US-R08a1/nb1
US-R08c213			Unknown	Unknown	US-R08a1/nb1
US-R08c22			$1.00 \cdot 10^{-2}$ (*)	$1.00 \cdot 10^{-2}$ (*)	US-R08a1/nb1
(n) = NTSB database; (*) = assumption					

5.8.2.3 End States.

The end states are quantified using the quantification of the IE and the pivotal events; the results are given in table 31.

Table 31. Probabilities of End Events of ESD US-R08

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R08c1			$3.58 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R08d1			$6.86 \cdot 10^{-7}$	$7.80 \cdot 10^{-8}$	Flight hour
US-R08d2			$6.59 \cdot 10^{-7}$	$7.49 \cdot 10^{-8}$	Flight hour

5.9 US-R09: ESD AND FT DIAGRAMS.

Figures 28 through 31 show the ESD and FT diagrams of US-R09, loss of visual reference in degraded visual environment.

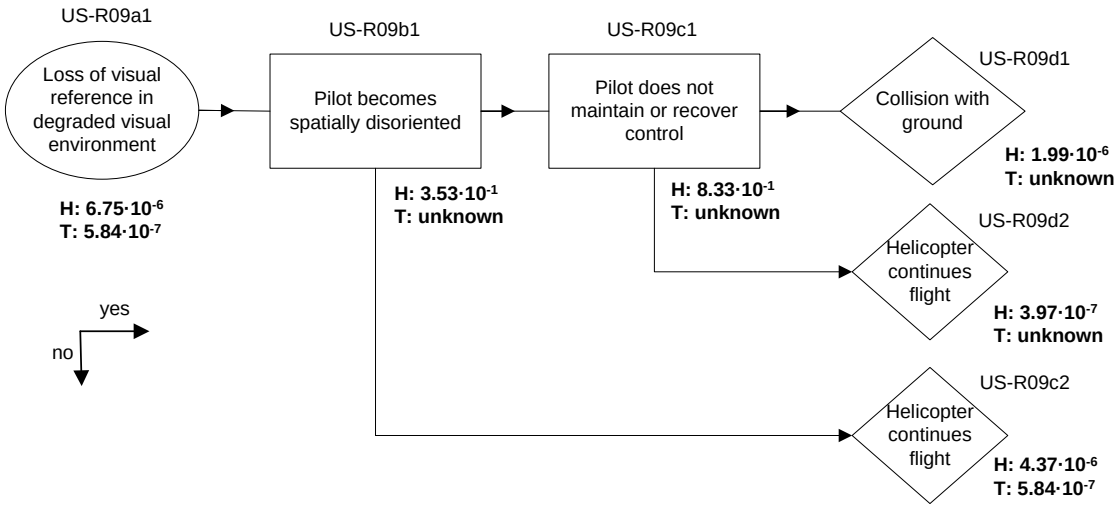


Figure 28. The ESD US-R09—Loss of Visual Reference in Degraded Visual Environment

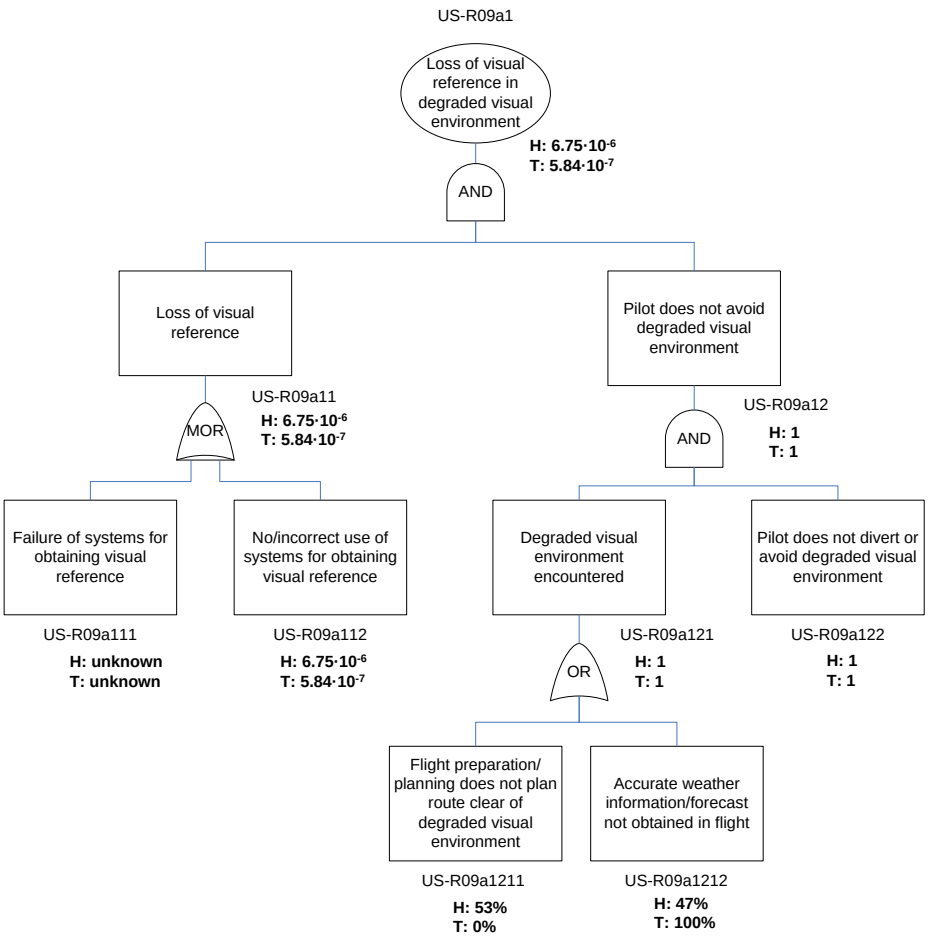


Figure 29. The FT US-R09a1—Loss of Visual Reference in Degraded Visual Environment

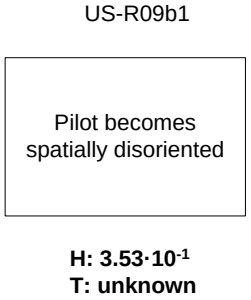


Figure 30. The FT US-R09b1—Pilot Becomes Spatially Disoriented

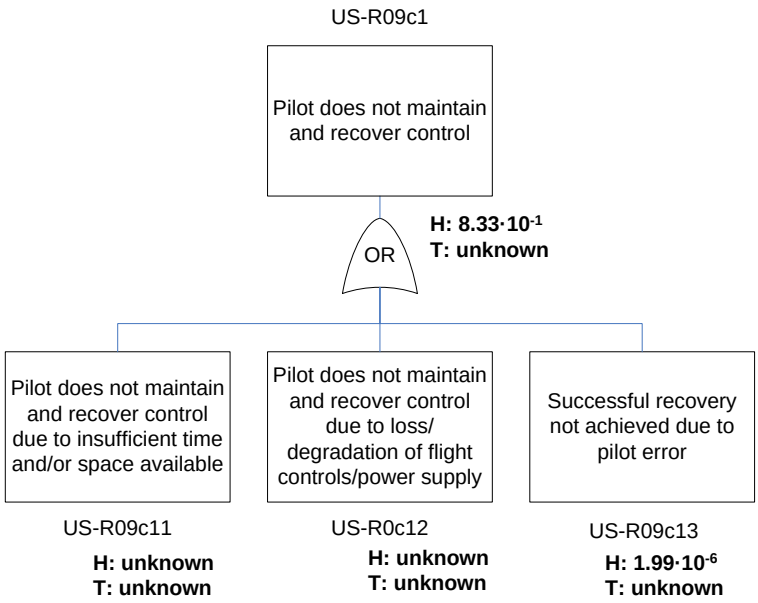


Figure 31. The FT US-R09c1—Pilot Does Not Maintain and Recover Control

5.9.1 Definitions.

5.9.1.1 The Difference Between ESDs 8 and 9.

Both ESDs 8 and 9 occur in degraded visual environments. However, they are treated as separate ESDs because, in the breakdown of accident archetypes, LOC and CFIT are two different accident archetypes. There are various possible IEs for an LOC accident scenario; one is the loss of SA in a degraded visual environment followed by pilot disorientation and an LOC. In a CFIT scenario, by definition, LOC does not occur. Therefore, both scenarios have been modeled as separate ESDs.

Table 32. Definitions of ESD US-R09—Loss of Visual Reference in Degraded Visual Environment

Event	Code	Definition
Loss of visual reference in degraded visual environment	US-R09a1	This scenario concerns an LOC and not a CFIT scenario (the latter is covered by ESD US-R8). The pilot becomes disoriented in a degraded visual environment. Degraded visual environment includes low visibility, brown-out, white-out, night conditions, climbing above or descending below clouds, inadvertent flight into IMC, etc. This event may lead to an LOC, including when attempting to avoid a region of degraded visual environment.
Pilot becomes spatially disoriented	US-R09b1	The pilot incorrectly perceives the helicopter motion, orientation, and altitude
Pilot does not maintain or recover control	US-R09c1	The pilot is unable to maintain or recover control of the helicopter with regard to speed, altitude, and attitude.
Helicopter continues flight	US-R09c2	The helicopter continues the flight with a loss of visual reference in a degraded visual environment.
Collision with ground	US-R09d1	The helicopter hits the ground after the pilot loses control.
Helicopter continues flight	US-R09d2	The helicopter continues the flight with a spatially disoriented pilot.
FT—Initiating Event—US-R09a1		
Loss of visual reference	US-R09a11	Loss of visual cues to determine the helicopter motion, orientation, and altitude.
Failure of systems for obtaining visual reference	US-R09a111	Failure of systems for obtaining visual reference (e.g., exterior lighting, night vision goggles, windscreen).
No/incorrect use of systems for obtaining visual reference	US-R09a112	No or incorrect use of exterior lighting, night vision goggles, a lack of training, etc.
Pilot does not avoid degraded visual environment	US-R09a12	The pilot continues the flight into the degraded visual environment.
Degraded visual environment encountered	US-R09a121	The pilot encounters a degraded visual environment (e.g. clouds, darkness, brown-out, white-out).
Flight preparation/planning does not plan route clear of degraded visual environment	US-R09a1211	Flight preparation/planning does not plan route clear of degraded visual environment, which includes flying in the dark.
Accurate weather information/forecast not obtained in flight	US-R09a1212	Accurate weather information/forecast not obtained in flight. This includes occurrences involving brown-outs or white-outs.
Pilot does not divert or avoid degraded visual environment	US-R09a122	The pilot does not divert or initiate a maneuver to avoid the degraded visual environment. This includes cases for which no avoidance action is undertaken because the flight into IMC is intentional.
FT—Pivotal Event—US-R09b1		
An FT has not been defined for “pilot becomes spatially disoriented” because the exact mechanics of that event are unknown and cannot be represented in an FT. Causal factors of spatial disorientation include: training, experience, aeromedical factors, and the dynamics of the helicopter at the moment of loss of visual reference.		

Table 32. Definitions of ESD US-R09—Loss of Visual Reference in Degraded Visual Environment (Continued)

Event	Code	Definition
FT—Pivotal Event—US-R09c1		
Pilot does not maintain and recover control because insufficient time/space is available	US-R09c11	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain or recover control because of loss/degradation of flight controls/power supply	US-R09c12	Pilot does not maintain or recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R09c13	Successful recovery not achieved because of pilot error.

5.9.2 Quantification.

5.9.2.1 The IE.

The IE "loss of visual reference in degraded visual environment" (US-R09a1) is quantified using the NTSB, ASRS, and Concern Network databases.

The probability of "pilot does not avoid degraded visual environment" (US-R09a12) cannot be determined from the databases used. All occurrences found are cases of loss of visual reference (US-R09a11) along with US-R09a12. Therefore, using these databases, it must be assumed that the probability of the pilot not avoiding the degraded visual environment equals 1. For HEMS, 53% of the cases of encountering degraded visual environment are due to a failure in flight preparation (US-R09a1211) and 47% are due to an in-flight failure to obtain weather information (US-R09a1212). For tour operations, these percentages are respectively 0% and 100%, but those are based on only one occurrence.

The probabilities of the left branch of the FT are determined from their base events. In total, 17 occurrences for HEMS are found in the NTSB, ASRS, and Concern Network databases—of which 5 are in the NTSB dataset, 10 in the ASRS, 1 in the Concern Network data, and 1 occurrence was recorded in both the NTSB and Concern Network databases. Only 1 occurrence was found for tour operations in the ASRS database. Table 33 shows the breakdown of occurrences and the associated probabilities of the events.

Table 33. Occurrences and Probabilities of US-R09a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R09a1			$6.75 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R09a11			$6.75 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R09a111	0	0	Unknown	Unknown	Flight hour
US-R09a112	17 (a,c,n)	1 (a)	$6.75 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R09a12			1 (*)	1 (*)	R09a11
US-R09a121			1 (*)	1 (*)	R09a11
US-R09a1211	9 (a,c,n)	0	53%	0%	R09a121
US-R09a1212	8 (a,c,n)	1 (a)	47%	100%	R09a121
US-R09a122			1 (*)	1 (*)	R09a11
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (*) = assumption					

5.9.2.2 Pivotal Event(s).

The only event found for tour operations results in a safe continuation of the flight (US-R09c2). Therefore, all probabilities of pivotal events are unknown. For HEMS, six occurrences of pilot disorientation (US-R09b1) were found, five of which resulted in a failure to maintain control (US-R09c1) and a subsequent collision with the ground. The results are summarized in table 34.

Table 34. Occurrences and Probabilities of the Pivotal Events of ESD US-R09

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R09b1	6 (c, n)	0	$3.53 \cdot 10^{-1}$	Unknown	US-R09a1
			$2.38 \cdot 10^{-6}$	Unknown	Flight hour
US-R09c1			$8.33 \cdot 10^{-1}$	Unknown	US-R09a1/b1
US-R09c1			$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R09c11	0	0	Unknown	Unknown	Flight hour
US-R09c12	0	0	Unknown	Unknown	Flight hour
US-R09c13	5 (c, n)	0	$1.99 \cdot 10^{-6}$	Unknown	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.9.2.3 End States.

The end states are quantified using the quantification of the IE and the pivotal events; the results are shown in table 35.

Table 35. Probabilities of End Events of ESD US-R09

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R09c2			$4.37 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R09d1			$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R09d2			$3.97 \cdot 10^{-7}$	Unknown	Flight hour

5.10 US-R10: ESD AND FT DIAGRAMS.

Figures 32 through 35 show the ESD and FT diagrams of US-R10, deviation from safe flight path toward obstacle.

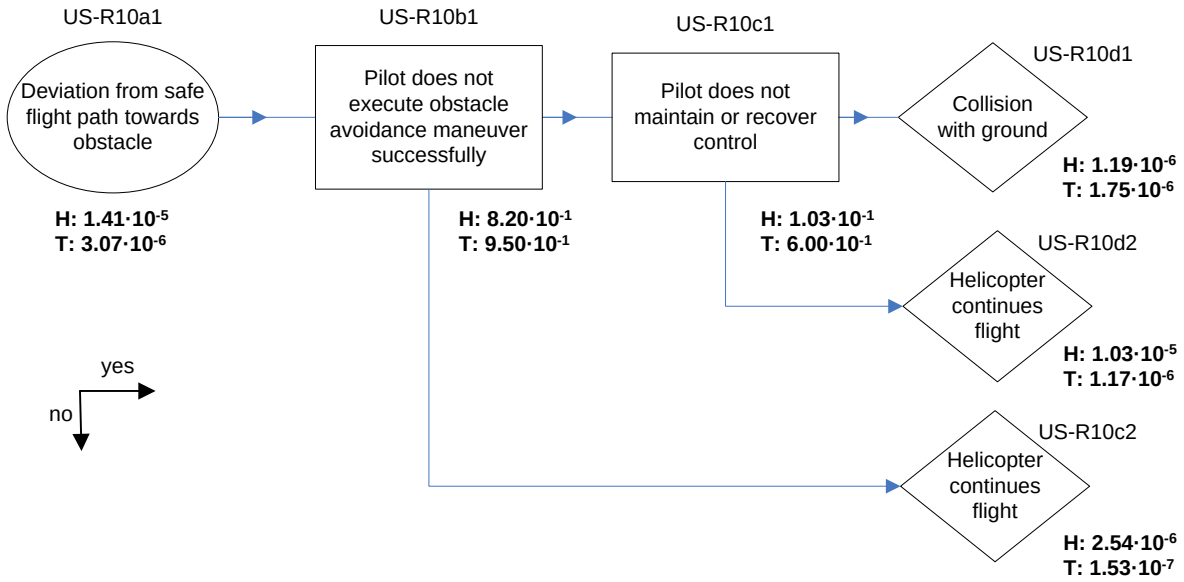


Figure 32. The ESD US-R10—Deviation From Safe Flight Path Toward Obstacle

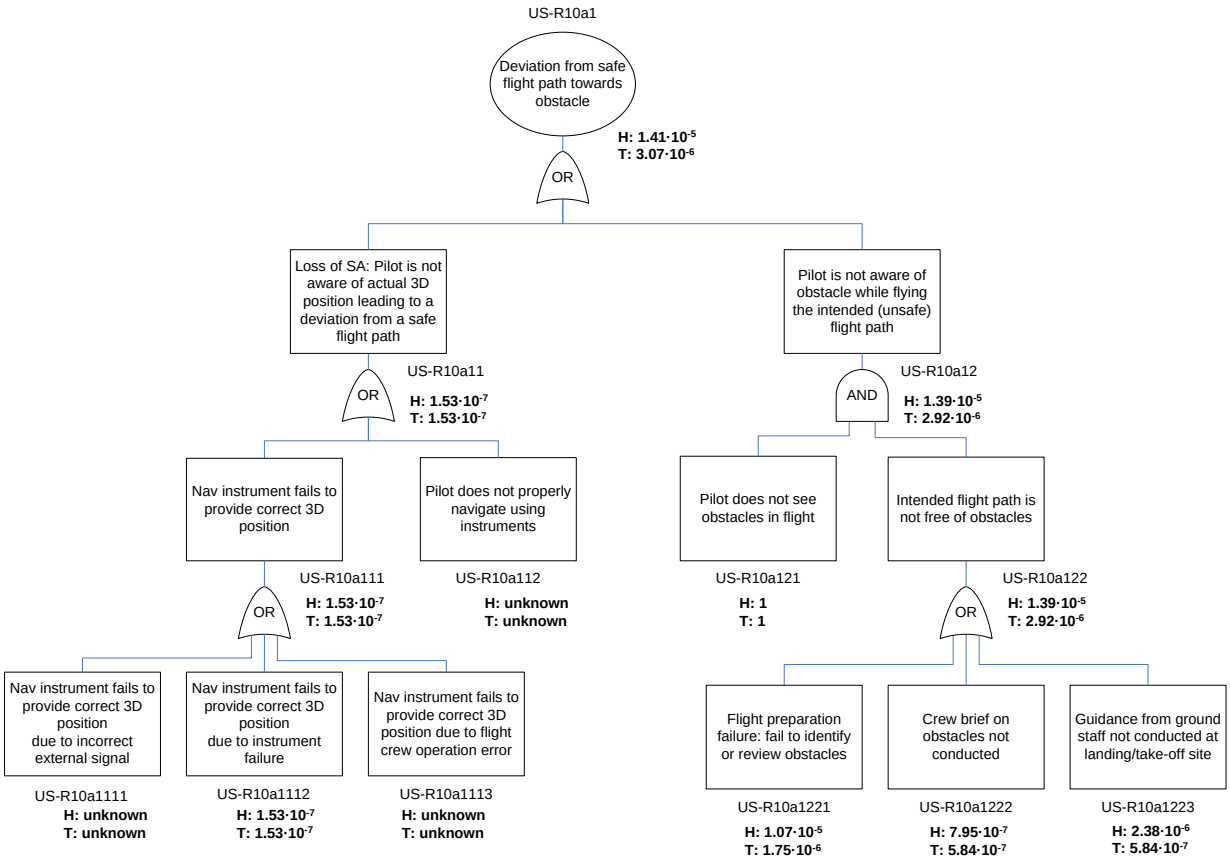


Figure 33. The FT US-R10a1—Deviation From Safe Flight Path Toward Obstacle

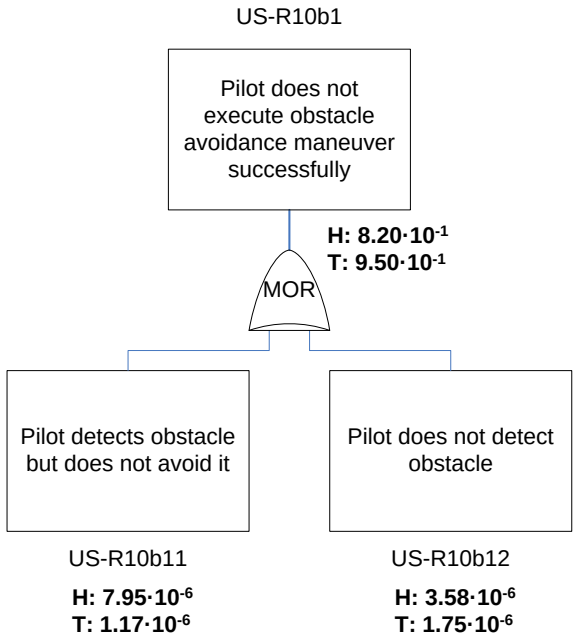


Figure 34. The FT US-R10b1—Pilot Does Not Execute Obstacle Avoidance Maneuver Successfully

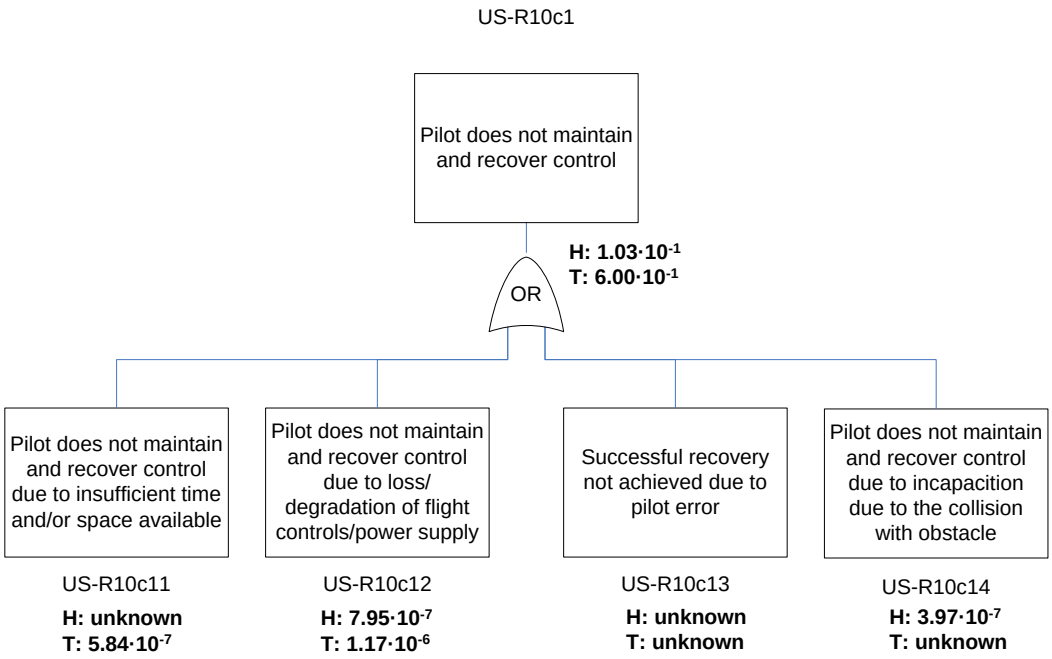


Figure 35. The FT US-R10c1—Pilot Does Not Maintain and Recover Control

5.10.1 Definitions.

Table 36 shows the definitions of US-R10, ESD and FT events.

Table 36. Definitions of ESD US-R10—Deviation From Safe Flight Path Toward Obstacle

Event	Code	Definition
Deviation from safe flight path toward obstacle	US-R10a1	Deviation from a safe flight path toward obstacle(s) likely to interfere with flight path. This ESD applies to all flight phases, except flight into a degraded visual environment (see ESD-R8). This event is related to a loss of SA/inadequate lookout in flight in good visibility conditions/a pilot failing to maintain adequate clearance with an obstacle (e.g., tree, pole, wire, crop, etc).
Pilot does not execute obstacle avoidance maneuver successfully	US-R10b1	Pilot does not execute obstacle avoidance maneuver successfully and collides with the obstacle. This includes collisions on the ground during hover/taxi (e.g., collision with other aircraft, buildings, etc).
Pilot does not maintain or recover control	US-R10c1	Pilot does not maintain or recover control after collision with the obstacle. This includes collisions on the ground during hover/taxi (e.g., collision with other aircraft, buildings, etc).
Helicopter continues flight	US-R10c2	The pilot continues the flight without a collision with the obstacle after a deviation from a safe flight path.
Collision with ground	US-R10d1	The helicopter hits the ground after losing control after a collision with the obstacle. This includes collisions on the ground during hover/taxi (e.g., collision with other aircraft, buildings etc).
Helicopter continues flight	US-R10d2	The pilot is able to continue the flight after a collision with the obstacle. This includes cases in which a safe landing is made.
FT—Initiating Event—US-R10a1		
Loss of SA: Pilot is not aware of actual 3D position leading to a deviation from a safe flight path	US-R10a11	Pilot loses SA and is not aware of the helicopter's location/altitude, leading to a deviation from a safe flight path. Hence, the flight path flown is unsafe because there are obstacles on the path.
Nav instrument fails to provide correct 3D position	US-R10a111	Nav instrument fails to provide a correct 3D position.
Nav instrument fails to provide correct 3D position because of incorrect external signal	US-R10a1111	Nav instrument fails to provide a correct 3D position because of incorrect external signal (e.g., a GPS signal error).
Nav instrument fails to provide correct 3D position because of instrument failure	US-R10a1112	Nav instrument fails to provide a correct 3D position because of an onboard instrument failure.
Nav instrument fails to provide correct 3D position because of flight crew operation error	US-R10a1113	Nav instrument fails to provide a correct 3D position because of a flight crew error of operation of instruments.
Pilot does not properly navigate using instruments	US-R10a112	Pilot does not properly navigate using instruments.

Table 36. Definitions of ESD US-R10—Deviation From Safe Flight Path Toward Obstacle (Continued)

Event	Code	Definition
Pilot is not aware of obstacle while flying the intended (unsafe) flight path	US-R10a12	The flight is planned with an unsafe flight path with obstacles of which the pilot is unaware.
Pilot does not see obstacles in flight	US-R10a121	The pilot does not see the obstacle because it is not visible from the cockpit or the pilot does not scan the airspace.
Intended flight path is not free of obstacles	US-R10a122	The intended flight path is unsafe because there are obstacles in the flight path.
Flight preparation failure: fail to identify or review obstacles	US-R10a1221	Obstacles are not identified or reviewed during flight preparation. This includes a failure of others to provide obstacle information (e.g., NOTAMs).
Crew brief on obstacles not conducted	US-R10a1222	Crew did not conduct briefing on obstacles during the flight. This includes inadequate visual lookout during the flight.
Guidance from ground staff not conducted at landing/takeoff site	US-R10a1223	Guidance from ground staff is not provided at the landing or takeoff site.
FT—Pivotal Event—US-R10b1		
Pilot detects obstacle but does not avoid it	US-R10b11	Pilot detects obstacle, but does not avoid it (e.g., because there is no time to avoid it or improper avoidance action).
Pilot does not detect obstacle	US-R10b12	Pilot does not detect obstacle (e.g., pilot is not scanning airspace because of work load or other distractions, pilot is unable to see obstacle).
FT—Pivotal Event—US-R10c1		
Pilot does not maintain and recover control because of insufficient time/space availability	US-R10c11	Pilot does not maintain and recover control because of insufficient time/space available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R10c12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R10c13	Successful recovery not achieved because of pilot error.
Pilot does not maintain and recover control because of incapacitation caused by collision with obstacle	US-R10c14	Pilot does not maintain and recover control because the pilot is incapacitated from the collision with the obstacle.

Nav = navigation; NOTAM = Notice to Airmen

5.10.2 Quantification.

5.10.2.1 The IE.

The IE "deviation from safe flight path towards obstacle" (US-R10a1) is quantified using all databases available. Specifically, the event "nav instrument fails to provide correct 3D position

because of instrument failure" (US-R10a1112) is quantified using the three occurrences found in the SDR database.

The base events of the event "intended flight path is not free of obstacles" (US-R10a122) is quantified using the NTSB, ASRS, and Concern Network databases. Regarding the latter event, it is noted that, because occurrence databases are used, only a subset is found. Clearly, every flight path is not free of obstacles. For the subset, it is assumed that the probability that pilot does not see the obstacle (US-R10a121) equals 1.

For HEMS operations, the following data were found. The event "flight preparation failure: fail to identify or review obstacles" (US-R10a1221) was found in 27 occurrences in the three databases mentioned. "Crew brief on obstacles not conducted" (US-R10a1222) was found in two occurrences in the NTSB dataset and the event "guidance from ground staff not conducted at landing/takeoff site" (US-R10a1223) was found in six occurrences in these three databases. For tour operations, less data were found. Three occurrences were found for US-R10a1221 in the NTSB and ASRS dataset. Two occurrences were found for US-R10a1222 and one for US-R10a1223 in the NTSB dataset. Table 37 shows the breakdown of occurrences and the associated probabilities of the events.

Table 37. Occurrences and Probabilities of US-R10a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R10a1			$1.41 \cdot 10^{-5}$	$3.07 \cdot 10^{-6}$	Flight hour
US-R10a11			$1.53 \cdot 10^{-7}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R10a111			$1.53 \cdot 10^{-7}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R10a1111	0	0	Unknown	Unknown	Flight hour
US-R10a1112	3 (s)	3 (s)	$1.53 \cdot 10^{-7}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R10a1113	0	0	Unknown	Unknown	Flight hour
US-R10a112	0	0	Unknown	Unknown	Flight hour
US-R10a12			$1.39 \cdot 10^{-5}$	$2.92 \cdot 10^{-6}$	Flight hour
US-R10a121			1 (*)	1 (*)	US-R10a12
US-R10a122			$1.39 \cdot 10^{-5}$	$2.92 \cdot 10^{-6}$	Flight hour
US-R10a1221	27 (a, c, n)	3 (a, n)	$1.07 \cdot 10^{-5}$	$1.75 \cdot 10^{-6}$	Flight hour
US-R10a1222	2 (n)	2 (n)	$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R10a1223	6 (a, c, n)	1 (n)	$2.38 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (s) = SDR database; (*) = assumption					

5.10.2.2 Pivotal Event(s).

The two pivotal events are quantified using occurrences found in the NTSB, ASRS, and Concern Network databases. For the pivotal event "pilot does not execute obstacle avoidance maneuver

successfully" (US-R10b1), engineering judgment was used in the review of the occurrences to assess if it was likely that the pilot saw the obstacle (e.g., trees) (US-R10b11) or did not see the obstacle (US-R10b12). It was assessed that, in 20 of the 29 occurrences found for HEMS in the three databases, the pilot detected the obstacle, but did not or could not avoid it, whereas in nine occurrences, the pilot probably did not see the obstacle. For tour operations, there was a total of five events. In two occurrences, the research team assumed the pilot detected the obstacle, but did not or could not avoid it; in three occurrences, the pilot probably did not see the obstacle.

The event "pilot does not maintain and recover control" after a collision with an obstacle was quantified with NTSB data (no occurrences were found in the other datasets). For HEMS, there were two occurrences of "pilot does not maintain and recover control because of loss/degradation of flight controls/power supply" after the collision (US-R10c12) and one of "pilot incapacitation due to the collision with obstacle" (US-R10c14). For tour operations, three occurrences were found: one for "pilot does not maintain and recover control due to insufficient time and/or space available" (US-R10c11) and two for "pilot does not maintain and recover control because of loss/degradation of flight controls/power supply" after the collision (US-R10c12). Table 38 provides the numbers of occurrences and associated probabilities.

Table 38. Occurrences and Probabilities of the Pivotal Events of ESD US-R10

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R10b1			$8.20 \cdot 10^{-1}$	$9.50 \cdot 10^{-1}$	R10a1
			$1.15 \cdot 10^{-5}$	$2.92 \cdot 10^{-6}$	Flight hour
US-R10b11	20 (a,c,n)	2 (n)	$7.95 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R10b12	9 (a,c,n)	3 (a,n)	$3.58 \cdot 10^{-6}$	$1.75 \cdot 10^{-6}$	Flight hour
US-R10c1			$1.03 \cdot 10^{-1}$	$6.00 \cdot 10^{-1}$	US-R10a1/b1
US-R10c1			$1.19 \cdot 10^{-6}$	$1.75 \cdot 10^{-6}$	Flight hour
US-R10c11	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R10c12	2 (n)	2 (n)	$7.95 \cdot 10^{-7}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R10c13	0	0	Unknown	Unknown	Flight hour
US-R10c14	1 (n)	0	$3.97 \cdot 10^{-6}$	Unknown	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.10.2.3 End States.

The three end states are quantified using the quantification of the IE and the pivotal events; the results are given in table 39.

Table 39. Probabilities of End Events of ESD US-R10

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R10c2			$2.54 \cdot 10^{-6}$	$1.53 \cdot 10^{-7}$	Flight hour
US-R10d1			$1.19 \cdot 10^{-6}$	$1.75 \cdot 10^{-6}$	Flight hour
US-R10d2			$1.03 \cdot 10^{-5}$	$1.17 \cdot 10^{-6}$	Flight hour

5.11 US-R11: ESD AND FT DIAGRAMS.

Figures 36 through 38 show the ESD and FT diagrams of US-R11, pilot incapacitation.

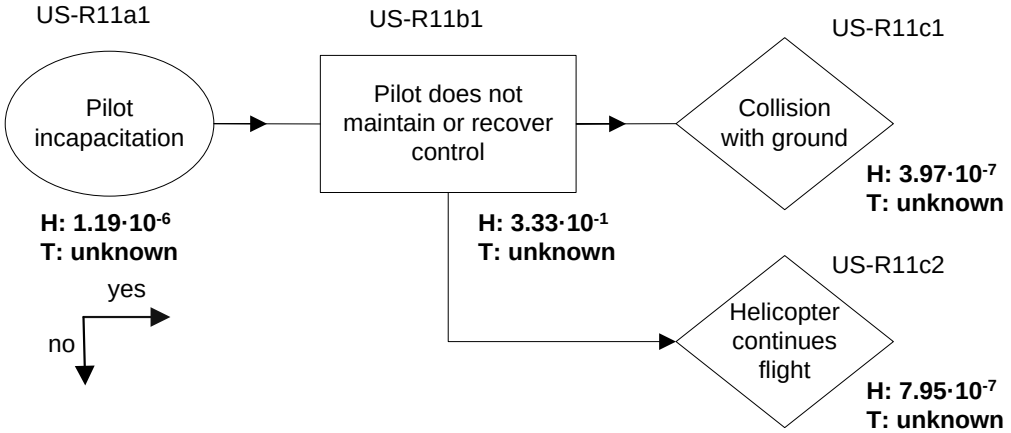


Figure 36. The ESD US-R11—Pilot Incapacitation

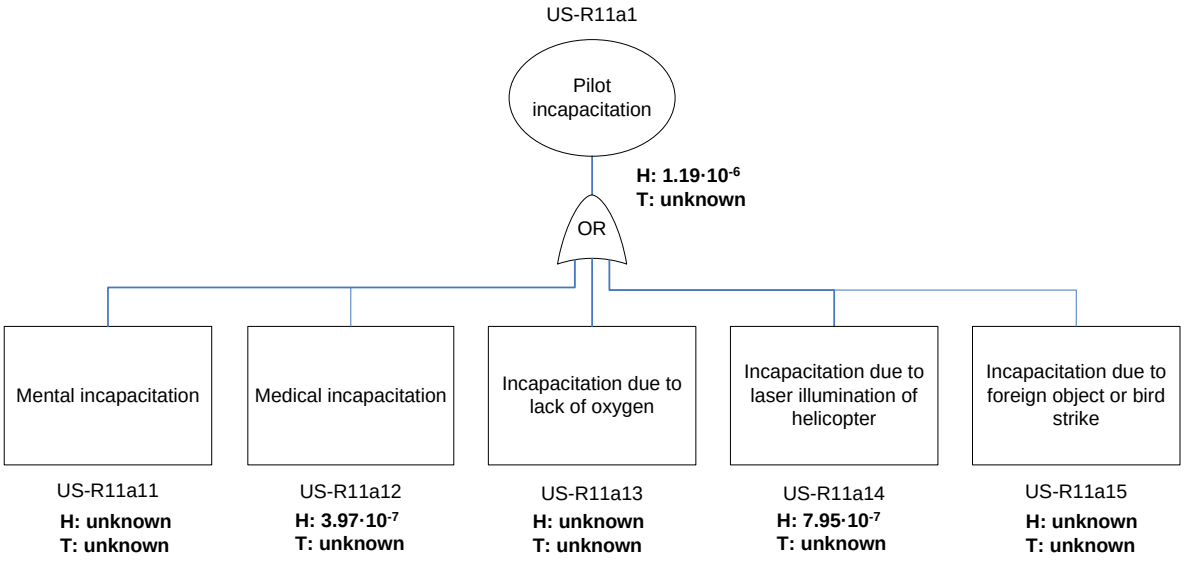


Figure 37. The FT US-R11a1—Pilot Incapacitation

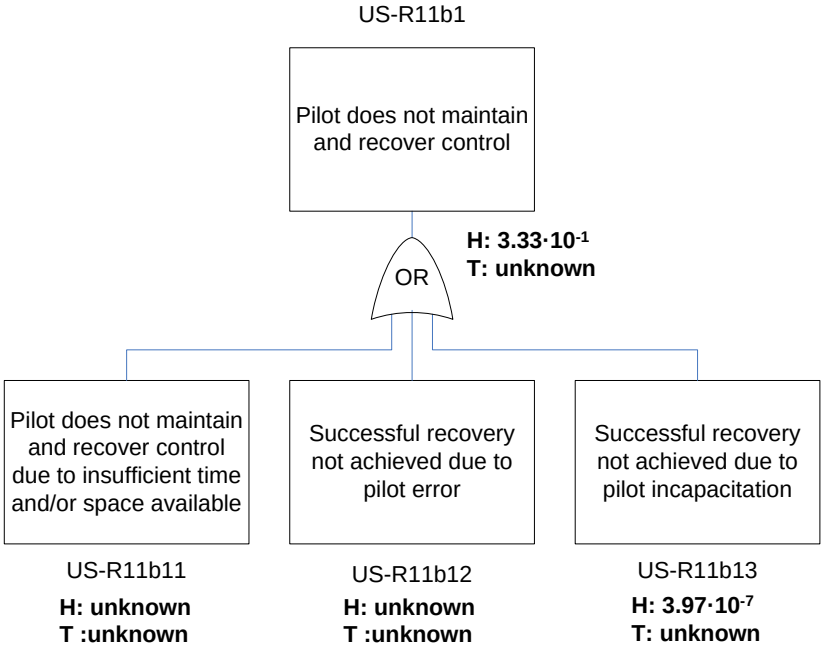


Figure 38. The FT US-R11b1—Pilot Does Not Maintain and Recover Control

5.11.1 Definitions.

Table 40 shows the definitions of US-R11, ESD and FT events.

Table 40. Definitions of ESD US-R11—Pilot Incapacitation

Event	Code	Definition
Pilot incapacitation	US-R11a1	The inability of the pilot to carry out normal duties because of the onset during flight of the effects of physiological or mental factors. Incapacitation is the inability of the pilot to perform prescribed flight duties as a result of reduced medical fitness. This event covers both impairment and incapacitation of the pilot. Incapacitation of the pilot due to asphyxiation (fire, smoke) is covered in ESD-R7 (fire on board).
Pilot does not maintain or recover control	US-R11b1	Helicopter control is not maintained or recovered after the pilot has been incapacitated.
Collision with ground	US-R11c1	The helicopter hits the ground after losing control after the pilot has become incapacitated. This includes hard landings with damage.
Helicopter continues flight	US-R11c2	The pilot is able to continue the flight after being incapacitated.
FT—Initiating Event—US-R11a1		
Mental incapacitation	US-R11a11	The inability of the pilot to carry out normal duties because of the onset during flight of the effects of mental factors.
Medical incapacitation	US-R11a12	The inability of the pilot to carry out normal duties because of the onset during flight of the effects of physiological factors.
Incapacitation due to lack of oxygen	US-R11a13	The inability of the pilot to carry out normal duties because of the onset during flight of the effects of a lack of oxygen.
Incapacitation due to laser illumination of helicopter	US-R11a14	The inability of the pilot to carry out normal duties because of the onset during flight of the effects of a laser illumination.
Incapacitation due to foreign object or bird strike	US-R11a15	Physical incapacitation due to impact with foreign object or bird. The inability of the pilot to carry out normal duties due to the onset during flight of the effects of a bird strike.
FT—Pivotal Event—US-R11b1		
Pilot does not maintain and recover control because insufficient time/space is available	US-R11b11	Pilot does not maintain and recover control because insufficient time/space is available. (Simultaneous) failure of flight control systems/propulsion system is excluded as a reason for LOC.
Successful recovery not achieved because of pilot error	US-R11b12	Successful recovery not achieved because of pilot error.
Successful recovery not achieved because of pilot incapacitation	US-R11b13	Successful recovery not achieved because of remaining incapacitation of the pilot.

5.11.2 Quantification.

5.11.2.1 The IE.

The IE "pilot incapacitation" (US-R11a1) is quantified using the NTSB and Concern Network databases. No occurrences of pilot incapacitation have been found for tour operations in the databases used for quantification. For HEMS, no occurrences are found in the ASRS database. Three occurrences of the IE are found: one occurrence of medical incapacitation (FT US-R11a12) and two of incapacitation due to laser illumination (FT US-R11a14). The probability of the IE is calculated from its base events. The results are given in table 41.

Table 41. Occurrences and Probabilities of US-R11a1 and Its Base Events

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R11a1			$1.19 \cdot 10^{-6}$	Unknown	Flight hour
US-R11a11	0	0	Unknown	Unknown	Flight hour
US-R11a12	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R11a13	0	0	Unknown	Unknown	Flight hour
US-R11a14	2 (c)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R11a15	0	0	Unknown	Unknown	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.11.2.2 Pivotal Event(s).

The only pivotal event, "pilot does not maintain and recover control" (US-R11b1), is quantified using occurrences of collision with the ground after pilot incapacitation. One such occurrence was found in the NTSB database. The conditional probability of the pivotal event is calculated using the probability of the base event, divided by the probability of the IE (see table 42).

Table 42. Occurrences and Probabilities of US-R11b1 and Its Base Events

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R11b1			$3.33 \cdot 10^{-1}$	Unknown	US-R11a1
			$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R11b11	0	0	Unknown	Unknown	Flight hour
US-R11b12	0	0	Unknown	Unknown	Flight hour
US-R11b13	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
(n) = NTSB database					

5.11.2.3 End States.

The two end states are quantified using the quantification of the IE and the pivotal event. The results are given in table 43.

Table 43. Probabilities of End States of ESD US-R11

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R11c1			$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R11c2			$7.95 \cdot 10^{-7}$	Unknown	Flight hour

5.12 US-R12: ESD AND FT DIAGRAMS.

The ESD and FT diagrams of US-R12, flight instrument failure, are shown in figures 39-41.

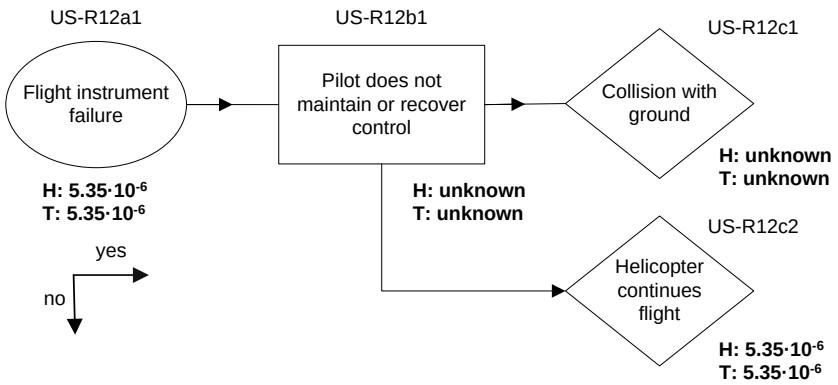


Figure 39. The ESD US-R12—Flight Instrument Failure

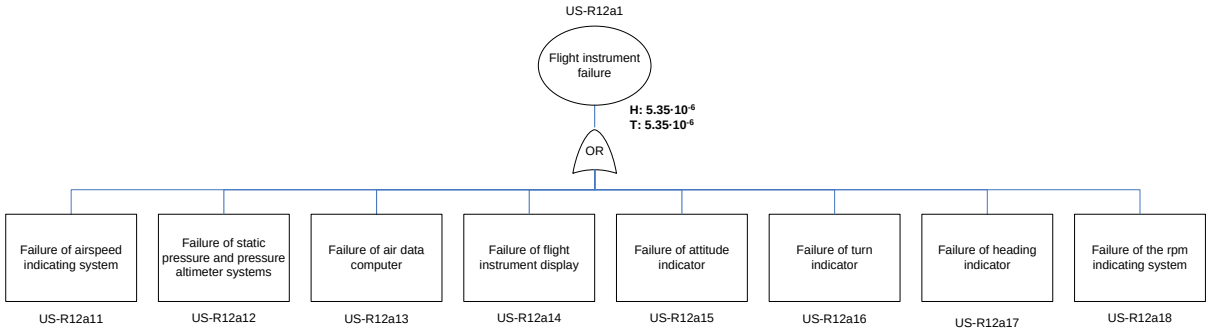


Figure 40. The FT US-R12a1—Flight Instrument Failure

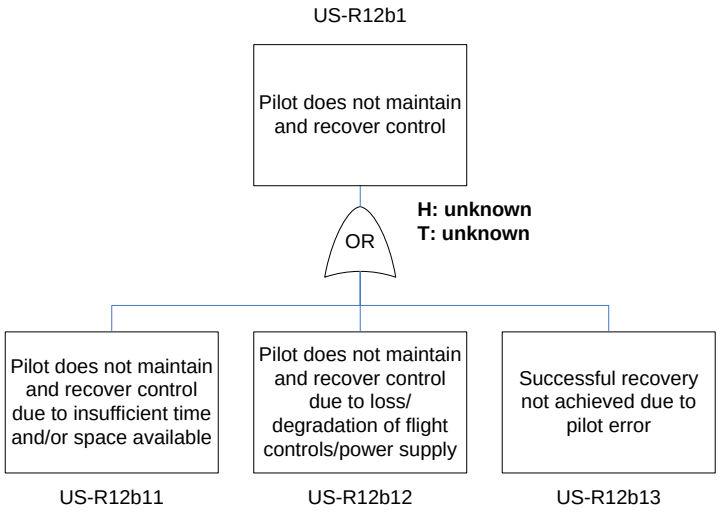


Figure 41. The FT US-R12b1—Pilot Does Not Maintain and Recover Control

5.12.1 Definitions.

Table 44 shows the definitions of US-R12 ESD and FT events.

Table 44. Definitions of ESD US-R12 – Flight Instrument Failure

Event	Code	Definition
Flight instrument failure	US-R12a1	Non-nominal operation of one or more of the flight instruments (ATA 3100, 3110, 3411-3425).
Pilot does not maintain control	US-R12b1	The pilot is unable to maintain control of the helicopter with regard to speed, altitude, and attitude.
Collision with ground	US-R12c1	The helicopter hits the ground after the pilot loses control. This includes hard landings with damage.
Helicopter continues flight	US-R12c2	The pilot is able to continue the flight with a flight instrument system failure.
FT—Initiating Event—US-R12a1		
Failure of airspeed-indicating systems	US-R12a11	Failure of the airspeed-indicating system.
Failure of static pressure and pressure altimeter systems	US-R12a12	Failure of the static pressure and pressure altitude system.
Failure of air data computer	US-R12a13	Failure of the computer that integrates data from various sensors (e.g., pitot-static system, GPS, accelerometers, gyro) and determines airspeed, altitude, vertical speed.
Failure of flight instrument display	US-R12a14	Failure of the display of flight instruments, LCD-type of display/screen with multiple instrument indications on one display.
Failure of attitude indicator	US-R12a15	Failure of the attitude-indicator system, including its display (indication) failure.
Failure of turn indicator	US-R12a16	Failure of the turn indicator system, including its display (indication) failure.
Failure of heading indicator	US-R12a17	Failure of the heading indicator system, including its display (indication) failure.
Failure of the rpm indicating system	US-R12a18	Failure of the rpm indication system, including its display (indication) failure.
FT—Pivotal Event—US-R12b1		
Pilot does not maintain and recover control because insufficient time/space is available	US-R12b11	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R12b12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R12b13	Successful recovery not achieved because of pilot error.

LCD = Liquid crystal display

5.12.2 Quantification.

5.12.2.1 The IE.

The IE, "flight instrument failure" (US-R12a1), is quantified using the SDR database. Because a distinction cannot be made between HEMS and tour operations in this database, it is assumed the probability for both operations is equal, using overall helicopter exposure. A total of 105 occurrences related to ATA codes 3100, 3110, and 3411 through 3425 have been found. Because the ATA codes used in the SDR database do not match the base events without overlap, only the top event is quantified. The quantification of US-R12a1 is shown in table 45.

Table 45. Occurrences and Probability of US-R12a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R12a1	105 (s)	105 (s)	$5.35 \cdot 10^{-6}$	$5.35 \cdot 10^{-6}$	Flight hour
(s) = SDR database					

5.12.2.2 Pivotal Event(s).

No occurrences have been found of collision with the ground caused by a failure to maintain and recover control after a flight instrument failure. Therefore, based on the databases used, the probability of pivotal event US-R12b1 is unknown.

5.12.2.3 End States.

The two end states are quantified using the quantification of the IE and the pivotal event. The results are given in table 46. It is noted that two occurrences of US-R12c2 are found in the ASRS database for HEMS operations. These are not used for quantification because the SDR database is more fit for system-failure-related events.

Table 46. Probabilities of End States of ESD US-R12

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R12c1			Unknown	Unknown	Flight hour
US-R12c2			$5.35 \cdot 10^{-6}$	$5.35 \cdot 10^{-6}$	Flight hour

5.13 US-R13: ESD AND FT DIAGRAMS.

Figures 42 through 44 show the ESD and FT diagrams of US-R13—Flight-control system failure.

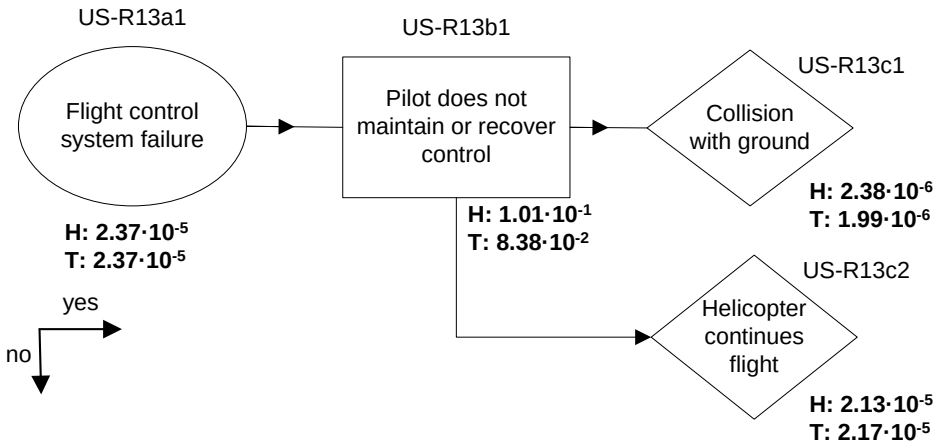


Figure 42. The ESD US-R13—Flight-Control System Failure

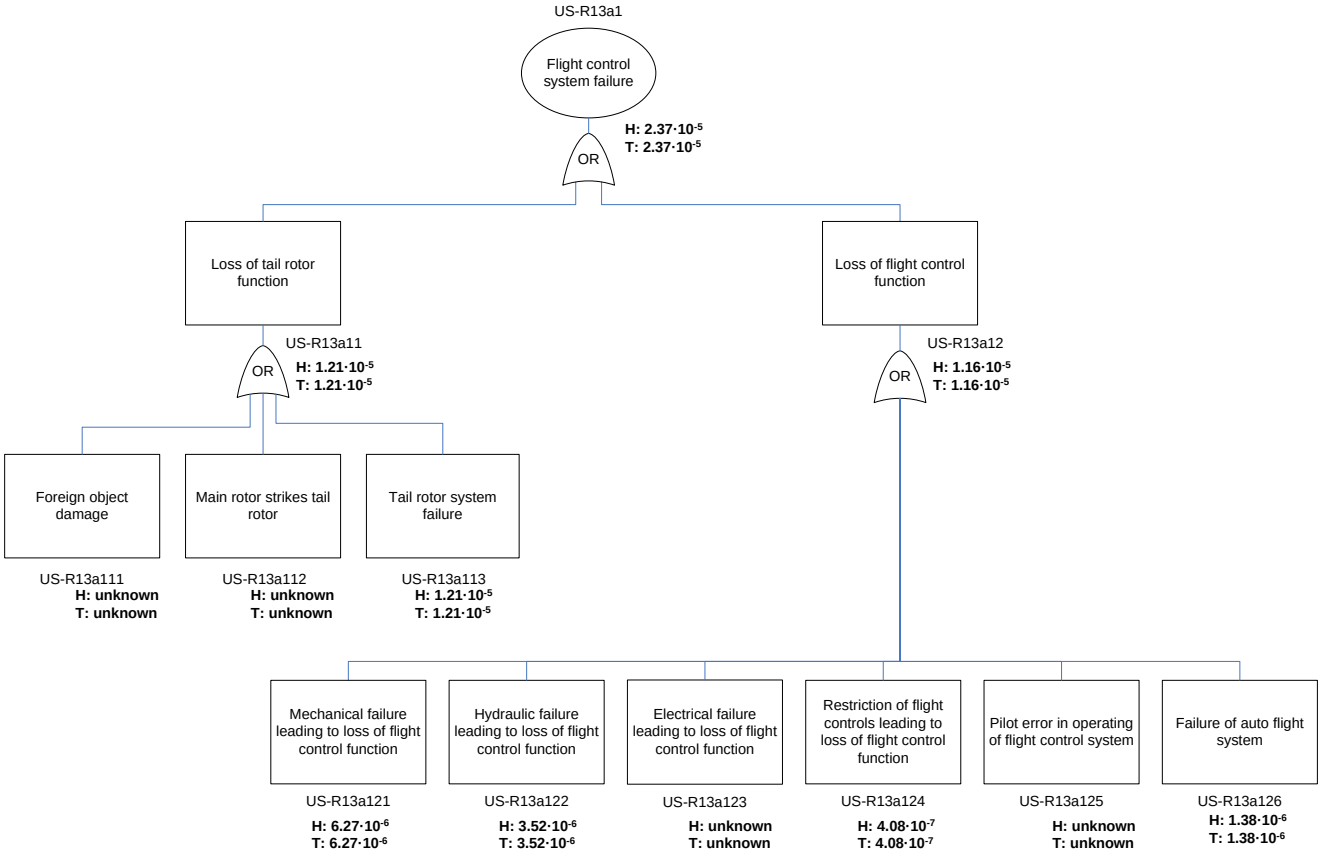


Figure 43. The FT US-R13a1—Flight-Control System Failure

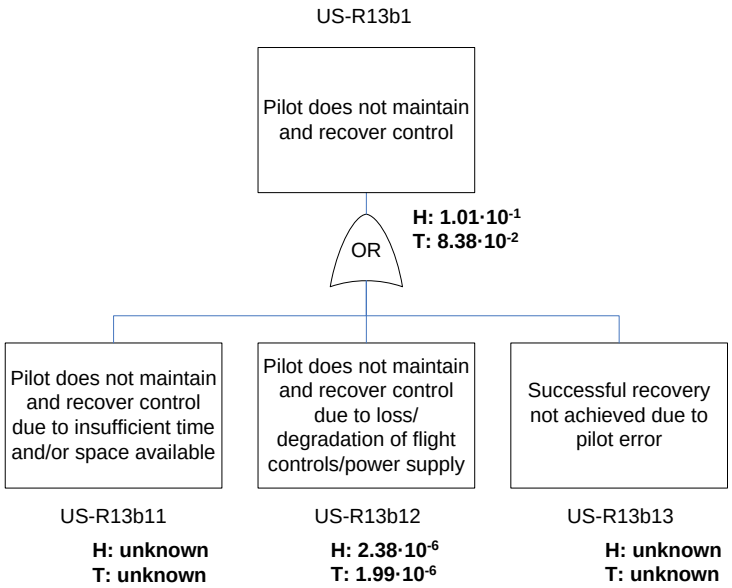


Figure 44. The FT US-R13b1—Pilot Does Not Maintain and Recover Control

5.13.1 Definitions.

Table 47 shows the definitions of US-R13 ESD and FT events.

Table 47. Definitions of ESD US-R13—Flight Control System Failure

Event	Code	Definition
Flight-control-system failure	US-R13a1	Non-nominal operation of one of the following systems: ATA 2700 flight controls, ATA 2900 hydraulic power system, ATA 6400 tail rotor system, ATA 6500 tail rotor drive system, ATA 6700 rotorcraft flight control.
Pilot does not maintain or recover control	US-R13b1	The pilot is unable to maintain control of the helicopter with regard to speed, altitude, and attitude.
Collision with ground	US-R13c1	The helicopter hits the ground after the pilot loses control. This includes hard landings with damage.
Helicopter continues flight	US-R13c2	The pilot is able to continue the flight with a flight-control system failure.
FT—Initiating Event—US-R13a1		
Loss of tail rotor function	US-R13a11	Loss of directional control.
Foreign object damage	US-R13a111	The tail rotor is damaged by a foreign object.
Main rotor strikes tail rotor	US-R13a112	Main rotor strikes the tail rotor.
Tail rotor system failure	US-R13a113	Failure of the tail rotor system or drive system (ATA 6400, ATA 6500, ATA 6720) caused by maintenance, fatigue, or manufacture, but excluding foreign object damage as a cause. Includes failure or loss of a tail rotor blade.
Loss of flight-control function	US-R13a12	Inability to transfer flight-control inputs to the flight-control surfaces.

Table 47. Definitions of ESD US-R13—Flight Control System Failure (Continued)

Event	Code	Definition
Mechanical failure leading to loss of flight control function	US-R13a121	(Partial) inability to transfer flight control inputs to the flight control surfaces because of a mechanical failure caused by maintenance or manufacturing issue (ATA 2700, excluding stuck or frozen surfaces; ATA 6700, excluding 6720).
Hydraulic failure leading to loss of flight control function	US-R13a122	(Partial) inability to transfer flight-control inputs to the flight-control surfaces because of a hydraulic failure due to maintenance or manufacturing issue (ATA 2900, excluding a leak, which is part of ESD US-R7).
Electrical failure leading to loss of flight control function	US-R13a123	(Partial) inability to transfer flight-control inputs to the flight-control surfaces because of electrical failure due to maintenance or manufacturing issue.
Restriction of flight controls leading to loss of flight control function	US-R13a124	(Partial) restriction of flight-control movement because of blockage, friction, frozen surface.
Pilot error in operating of flight control system	US-R13a125	Inappropriate operation of the flight-control system by the pilot (e.g., leaving the friction on).
Failure of auto flight system	US-R13a126	Failure of the auto flight system (ATA 2200).
FT—Pivotal Event—US-R13b1		
Pilot does not maintain and recover control because of insufficient time/space available	US-R13b11	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R13b12	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R13b13	Successful recovery not achieved because of pilot error.

5.13.2 Quantification.

5.13.2.1 The IE.

The IE, “flight control system failure” (US-R13a1), is quantified using the SDR database. Occurrences of nonsystem-failure-related events were not found in the other databases. In total, 465 occurrences of base events of the IE are found in the SDR database. The breakdown and associated probabilities are given in table 48.

Table 48. Occurrences and Probabilities of Events of US-R13a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R13a1			$2.37 \cdot 10^{-5}$	$2.37 \cdot 10^{-5}$	Flight hour
US-R13a11			$1.21 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$	Flight hour
US-R13a111	0	0	Unknown	Unknown	Flight hour
US-R13a112	0	0	Unknown	Unknown	Flight hour
US-R13a113	238 (s)	238 (s)	$1.21 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$	Flight hour
US-R13a12			$1.16 \cdot 10^{-5}$	$1.16 \cdot 10^{-5}$	Flight hour
US-R13a121	123 (s)	123 (s)	$6.27 \cdot 10^{-6}$	$6.27 \cdot 10^{-6}$	Flight hour
US-R13a122	69 (s)	69 (s)	$3.52 \cdot 10^{-6}$	$3.52 \cdot 10^{-6}$	Flight hour
US-R13a123	0	0	Unknown	Unknown	Flight hour
US-R13a124	8 (s)	8 (s)	$4.08 \cdot 10^{-7}$	$4.08 \cdot 10^{-7}$	Flight hour
US-R13a125	0	0	Unknown	Unknown	Flight hour
US-R13a126	27 (s)	27 (s)	$1.38 \cdot 10^{-6}$	$1.38 \cdot 10^{-6}$	Flight hour
(s) = SDR database					

5.13.2.2 Pivotal Event(s).

The only pivotal event ("pilot does not maintain or recover control" (US-R13b1)) is quantified by analyzing events of a collision with the ground after a flight control system failure. For HEMS, six of these events are found in the NTSB database, of which two are also found in the Concern Network database. Five occurrences are found in the NTSB database for tour operations. In all these events, the pilot did not maintain or recover control because of the degradation of the flight controls. The associated probabilities are given in table 49.

Table 49. Probabilities of Pivotal Events of ESD US-R13

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R13b1			$1.01 \cdot 10^{-1}$	$8.38 \cdot 10^{-2}$	US-R13a1
			$2.38 \cdot 10^{-6}$	$1.99 \cdot 10^{-6}$	Flight hour
US-R13b11	0	0	Unknown	Unknown	Flight hour
US-R13b12	6 (n)	5 (n)	$2.38 \cdot 10^{-6}$	$1.99 \cdot 10^{-6}$	Flight hour
US-R13b13	0	0	Unknown	Unknown	Flight hour
(n) = NTSB database					

5.13.2.3 End States.

The two end states are quantified using the quantification of the IE and the pivotal event. The results are given in table 50.

Table 50. Probabilities of End States of ESD US-R13

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R13c1			$2.38 \cdot 10^{-6}$	$1.99 \cdot 10^{-6}$	Flight hour
US-R13c2			$2.13 \cdot 10^{-5}$	$2.17 \cdot 10^{-5}$	Flight hour

5.14 US-R14 ESD AND FT DIAGRAMS.

The ESD and FT diagrams of US-R14: Engine malfunction or loss of power is shown in figures 45-50.

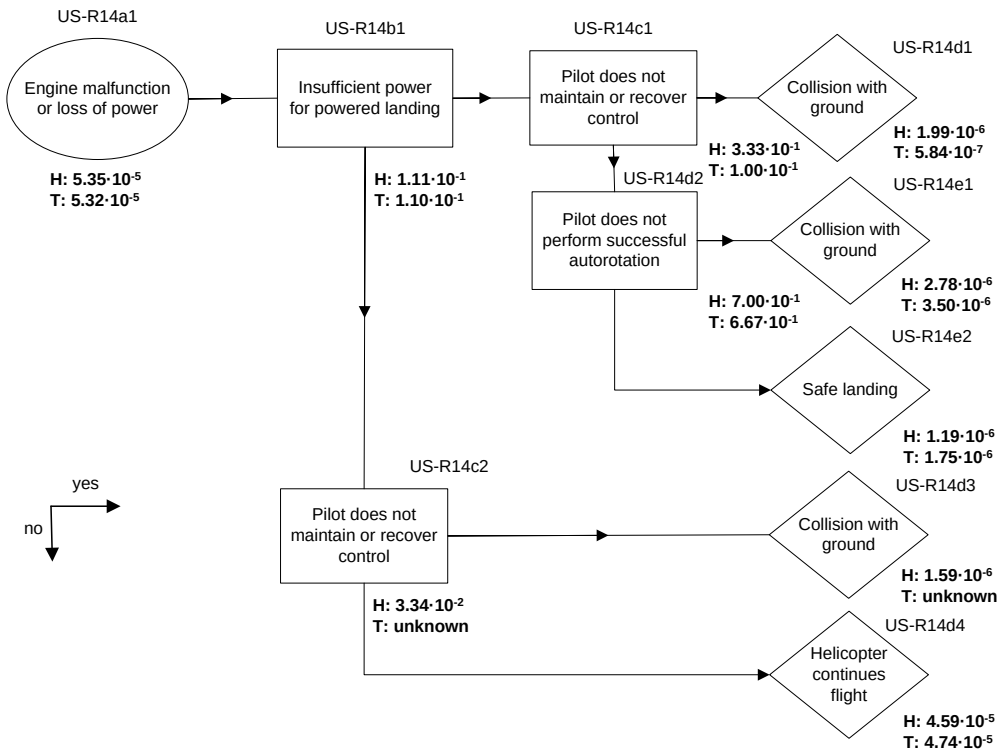


Figure 45. The ESD US-R14—Engine Malfunction or Loss of Power

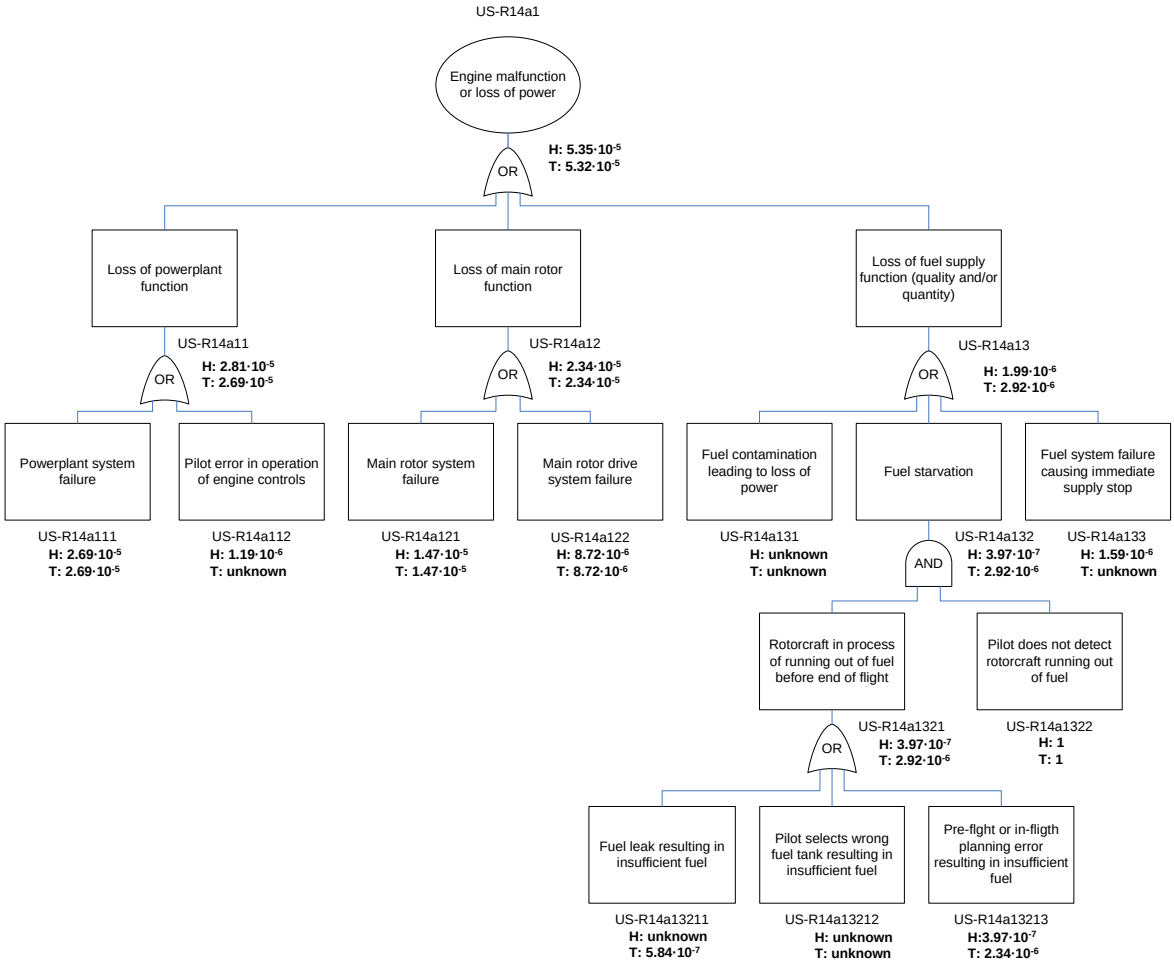


Figure 46. The FT US-R14a1—Engine Malfunction or Loss of Power

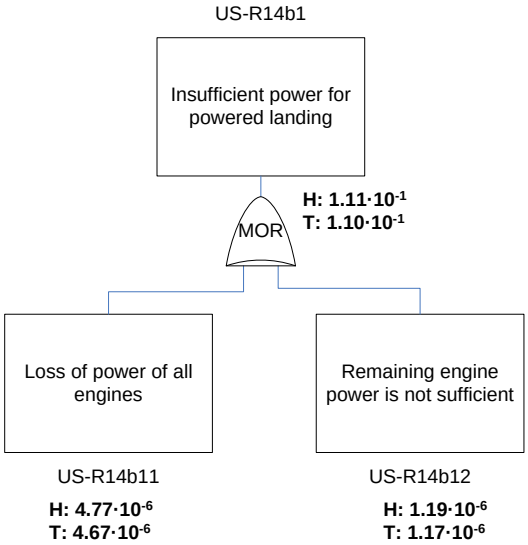


Figure 47. The FT US-R14b1—Insufficient Power for Powered Landing

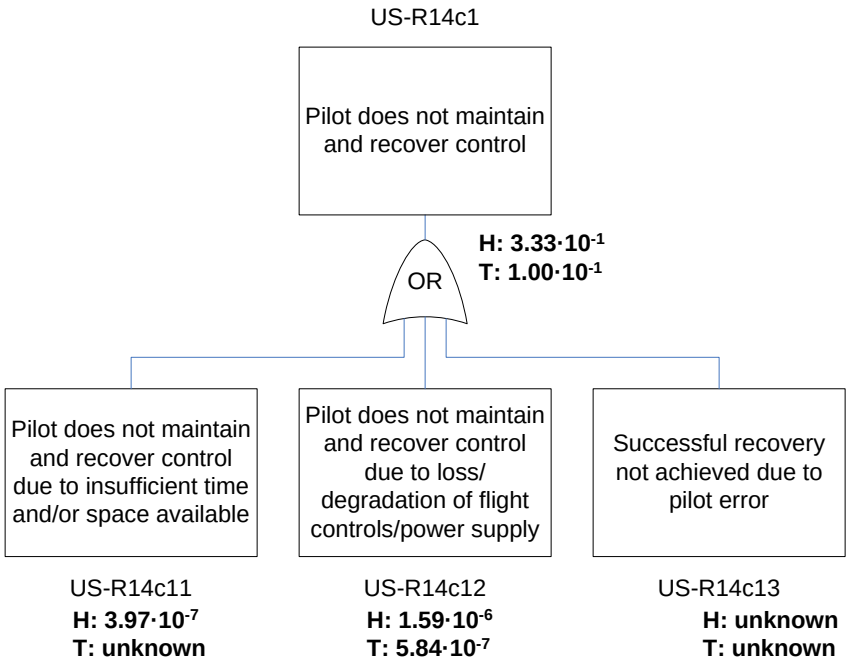


Figure 48. The FT US-R14c1—Pilot Does Not Maintain and Recover Control

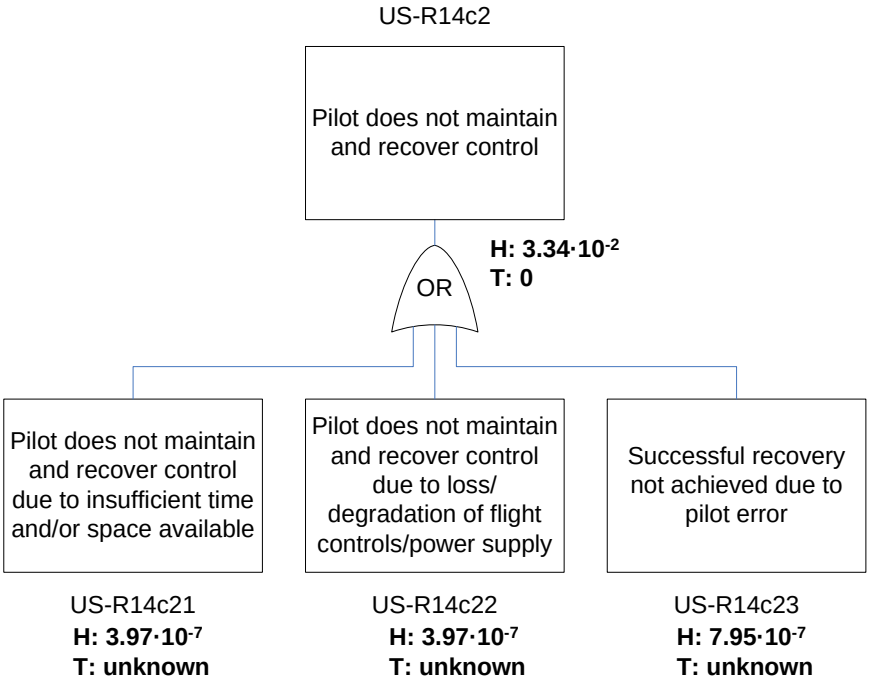


Figure 49. The FT US-R14c2—Pilot Does Not Maintain and Recover Control

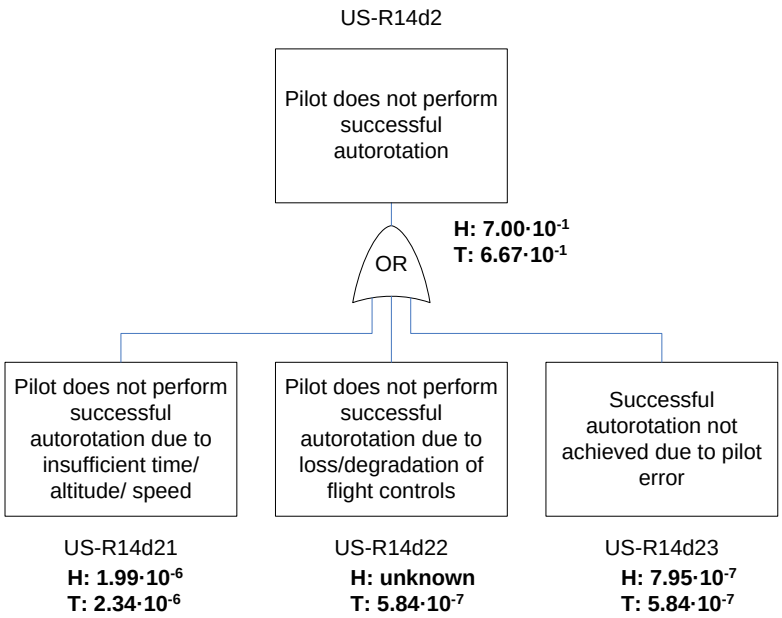


Figure 50. The FT US-R14d2—Pilot Does Not Perform Successful Autorotation

5.14.1 Definitions.

The definitions of US-R14 ESD and FT events are shown in table 51.

Table 51. Definitions of ESD US-R14—Loss of Power

Event	Code	Definition
Engine malfunction or loss of power	US-R14a1	Engine malfunction or loss of power can be the result of a failure of any of the following systems: ATA 6200 Main rotor ATA 6300 Main rotor drive ATA 7100 Powerplant system ATA 7200 Turbine/turboprop engine ATA 7300 Engine fuel & control system ATA 7400 Ignition system ATA 7500 Engine bleed air system ATA 7600 Engine controls ATA 7700 Engine indicating system ATA 7800 Engine exhaust system ATA 7900 Engine oil system-airframe ATA 8000 Engine starting system ATA 8100 Turbocharging ATA 8500 Reciprocating engine Causal factors of a system failure can be: manufacturing, maintenance, or impact damage (foreign object damage) related. Additional causes of loss of power are: fuel starvation, fuel exhaustion, fuel contamination, and incorrect operation of engine controls by the pilot.
Insufficient power for powered landing	US-R14b1	The remaining power after a power loss is insufficient for a powered landing.

Table 51. Definitions of ESD US-R14—Loss of Power (Continued)

Event	Code	Definition
Pilot does not maintain or recover control	US-R14c1	The pilot is unable to maintain or recover control of the helicopter because of a loss of power, such that there is insufficient power to hover.
Pilot does not maintain or recover control	US-R14c2	The pilot is unable to maintain or recover control of the helicopter because of a loss of power, such that there is sufficient power to hover.
Collision with ground	US-R14d1	The helicopter hits the ground after the pilot loses control. This includes cases of hard landings with damage.
Pilot does not perform successful autorotation	US-R14d2	An autorotation is initiated, but the pilot does not perform it successfully. This includes occurrences in which an adequate landing site is not available.
Collision with ground	US-R14d3	The helicopter hits the ground after the pilot loses control. This includes cases of hard landings with damage.
Helicopter continues flight	US-R14d4	The pilot is able to continue flight. This includes cases of safe landings with (partially) powered landings.
Collision with ground	US-R14e1	The helicopter hits the ground after a failure to perform a successful autorotation. This includes cases of hard landings with damage.
Safe landing	US-R14e2	Safe landing after successful autorotation.
FT—Initiating Event—US-R14a1		
Loss of powerplant function	US-R14a11	The function of the powerplant to generate power is lost.
Powerplant system failure	US-R14a111	Failure of: ATA 7100 Powerplant system ATA 7200 Turbine/turboprop engine ATA 7400 Ignition system ATA 7500 Engine bleed air system ATA 7600 Engine controls ATA 7700 Engine indicating system ATA 7800 Engine exhaust system ATA 7900 Engine oil system-airframe (excluding oil leaks, which are part of ESD US-R7) ATA 8000 Engine starting system ATA 8100 Turbocharging ATA 8500 Reciprocating engine
Pilot error in operation of engine controls	US-R14a112	Pilot error in operation of engine controls (e.g., throttles, power flight control switch).
Loss of main rotor function	US-R14a12	The function of the rotor to generate lift is lost.
Main rotor system failure	US-R14a121	Failure of: ATA 6200 Main rotor
Main rotor drive system failure	US-R14a122	Failure of: ATA 6300 Main rotor drive
Loss of fuel supply function	US-R14a13	The function to supply fuel to the powerplant is lost.
Fuel contamination leading to loss of power	US-R14a131	Fuel contamination leads to a loss of power.
Fuel starvation	US-R14a132	The helicopter runs out of fuel, leading to a loss of power.

Table 51. Definitions of ESD US-R14—Loss of Power (Continued)

Event	Code	Definition
Rotorcraft in process of running out of fuel before end of flight	US-R14a1321	There is a non-nominal situation that causes the helicopter to start running out of fuel before a possible landing.
Fuel leak resulting in insufficient fuel	US-R14a13211	Fuel leak leading to insufficient fuel for the flight and likely fuel starvation, failure of (parts of): ATA 2800 Fuel ATA 7300 Engine fuel and control The relevant parts are those that hold the fuel and can leak.
Pilot selects wrong fuel tank, resulting in insufficient fuel	US-R14a13212	Pilot selects wrong tank, leading to insufficient fuel for the flight and likely fuel starvation.
Pre-flight or in-flight planning error resulting in insufficient fuel	US-R14a13213	Pre-flight planning error resulting in insufficient fuel (e.g., improper fuel consumption calculation, inadequate fuel upload, improper forecast of conditions).
Pilot does not detect rotorcraft running out of fuel	US-R14a1322	Pilot does not monitor fuel state properly during flight, allowing the helicopter to run out of fuel before landing, or the pilot gets erroneous information from fuel quantity indications.
Fuel system failure causing immediate supply stop	US-R14a133	Failure that leads to stoppage of the fuel supply, excluding a fuel leak. Failure of (parts of): ATA 2800 fuel; ATA 7300 engine fuel and control. The parts are those that supply the fuel to the powerplant (e.g., pumps). In this case, there is sufficient fuel, but it does not reach the engine.
FT—Pivotal Event—US-R13b1		
Loss of power of all engines	US-R14b11	There is a loss of power of all engines (one or more). This includes cases in which the wrong engine is shut down.
Remaining engine power is not sufficient	US-R14b12	The power loss is so severe that there is not sufficient power for a powered landing.
FT—Initiating Event—US-R14c1/c2		
Pilot does not maintain and recover control because of insufficient time/space available	US-R14c11 & US-R14c21	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R14c12 & US-R14c22	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R14c13 & US-R14c23	Successful recovery not achieved because of pilot error.
FT—Initiating Event—US-R14d2		
Pilot does not perform successful autorotation because of insufficient time/altitude/speed	US-R14d21	A successful autorotation is not possible (e.g., because of proximity to the ground). This includes cases in which a suitable landing spot is not available.
Pilot does not perform successful autorotation because of loss/degradation of flight controls	US-R14d22	Although an autorotation is possible, the execution by the pilot of the autorotation is not successful because of loss of or degradation of flight controls (other than the normal degradation as result of a power loss).
Successful autorotation not achieved because of pilot error	US-R14d23	Although an autorotation is possible, the execution by the pilot of the autorotation is not successful.

5.14.2 Quantification.

5.14.2.1 The IE.

The IE, "engine malfunction or loss of power" (US-R14a1), is quantified using several databases: SDR, NTSB, ASRS, and Concern Network. All events are quantified using the probabilities of the base events.

The SDR database was used for HEMS and tour operations to quantify the base events of "loss of powerplant function" (US-R14a11) and "loss of main rotor function" (US-R14a12). A total of 527 occurrences of the event "powerplant system failure" (US-R14a111) was found in the SDR dataset. Two occurrences of the event "pilot error in operation of engine controls" (US-R14a112) were found in the NTSB dataset. The SDR dataset contained 289 cases related to "main rotor system failure" (US-R14a121) and 171 occurrences related to "main rotor drive system failure" (US-R14a122).

The base events of the intermediate event "fuel starvation" (US-R14a132) are quantified using occurrences of actual fuel starvations, implying the probability of the pilot not detecting the aircraft is running out of fuel (US-R14a1322), given the aircraft is actually running out of fuel (US-R14a1321) equals 1.

For HEMS, one occurrence of "preflight or inflight planning error resulting in insufficient fuel" (US-R14a13213) was found in the NTSB dataset and four events related to "fuel system failure causing immediate supply stop" (US-R14a133) were present in the NTSB and Concern Network datasets. It is noted that the SDR database was not used for the system failure events "fuel system failure causing immediate supply stop" (US-R14a113) and "fuel leak resulting in insufficient fuel" (US-R14a13211), because the database does not provide details regarding the consequences of the failure.

For tour operations, one occurrence of a "fuel leak resulting in insufficient fuel" (US-R14a13211) was recorded in the NTSB dataset and four occurrences of a "preflight or inflight planning error resulting in insufficient fuel" (US-R14a13213) were found in the NTSB and ASRS datasets.

The breakdown of occurrences, including the database used and associated probabilities, are given in table 52.

Table 52. Occurrences and Probabilities of Events of US-R14a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R14a1			$5.35 \cdot 10^{-5}$	$5.32 \cdot 10^{-5}$	Flight hour
US-R14a11			$2.81 \cdot 10^{-5}$	$2.69 \cdot 10^{-5}$	Flight hour
US-R14a111	527 (s)	527 (s)	$2.69 \cdot 10^{-5}$	$2.69 \cdot 10^{-5}$	Flight hour
US-R14a112	2 (n)	0	$1.19 \cdot 10^{-6}$	Unknown	Flight hour
US-R14a12			$2.34 \cdot 10^{-5}$	$2.34 \cdot 10^{-5}$	Flight hour
US-R14a121	289 (s)	289 (s)	$1.47 \cdot 10^{-5}$	$1.47 \cdot 10^{-5}$	Flight hour
US-R14a122	171 (s)	171 (s)	$8.72 \cdot 10^{-6}$	$8.72 \cdot 10^{-6}$	Flight hour
US-R14a13			$1.99 \cdot 10^{-6}$	$2.92 \cdot 10^{-6}$	Flight hour
US-R14a131	0	0	Unknown	Unknown	Flight hour
US-R14a132			$3.97 \cdot 10^{-7}$	$2.92 \cdot 10^{-6}$	Flight hour
US-R14a1321			$3.97 \cdot 10^{-7}$	$2.92 \cdot 10^{-6}$	Flight hour
US-R14a13211	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R14a13212	0	0	Unknown	Unknown	Flight hour
US-R14a13213	1 (n)	4 (a, n)	$3.97 \cdot 10^{-7}$	$2.34 \cdot 10^{-6}$	Flight hour
US-R14a1322			1	1	US-R14a1321
US-R14a133	4 (c, n)	0	$1.59 \cdot 10^{-6}$	Unknown	Flight hour
(a) = ASRS database; (c) = Concern database; (n) = NTSB database; (s) = SDR database					

5.14.2.2 Pivotal Event(s).

The ESD US-R14 has four pivotal events. The base events are quantified using the NTSB, ASRS, and Concern Network databases.

In the NTSB and Concern Network datasets, 12 occurrences of “loss of power of all engines” (US-R14b11) and three cases of “remaining engine power was not sufficient for a powered landing” (US-R14b12) were found. For tour operations, the NTSB and ASRS dataset showed a loss of power of all engines in eight cases (US-R14b11), while, in two cases, the “remaining engine power was not sufficient for a powered landing” (US-R14b12).

The pivotal event “pilot does not maintain or recover control” (US-R14c1) after “insufficient power for powered landing” was quantified for HEMS with NTSB data. In one case, the loss of control was due to “insufficient time and/or space available” (US-R14c11) and in four occurrences, it was related to “pilot does not maintain and recover control because of loss/degradation of flight controls/power supply” (US-R14c12). For tour operations, only one occurrence was available in the NTSB dataset; it was related to a loss of control due to “loss/degradation of flight controls/power supply” (US-R14c12).

The pivotal event “pilot does not maintain or recover control” (US-R14c2) after a loss of power, but with sufficient power remaining for a powered landing, was quantified for HEMS with the NTSB dataset. One occurrence was related to the base event “insufficient time/space available for recovery” (US-R14c21), one was related to the base event “loss/degradation of flight controls/power supply” (US-R14c22), and two occurrences were related to “pilot error” (US-R14c23). For tour operations, this event was not observed in the data sample.

The base events of the pivotal event “pilot does not perform successful autorotation” (US-R14d2) were quantified for HEMS and tour operations with NTSB data. Four HEMS 5 cases were due to the base event “insufficient time/altitude/speed” (US-R14d21) and two were related to “pilot error” (US-R14d23). For tour operations, four occurrences were found to be related to the base event US-R14d21, one was related the base event US-R14d22, and one was related to US-R14d23.

The breakdown of occurrences and associated probabilities are given in table 53.

Table 53. Probabilities of Pivotal Events of ESD US-R14

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R14b1			$1.11 \cdot 10^{-1}$	$1.10 \cdot 10^{-1}$	R14a1
			$5.96 \cdot 10^{-6}$	$5.84 \cdot 10^{-6}$	Flight hour
US-R14b11	12 (c,n)	8 (a,n)	$4.77 \cdot 10^{-6}$	$4.67 \cdot 10^{-6}$	Flight hour
US-R14b12	3 (c,n)	2(a,n)	$1.19 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R14c1			$3.33 \cdot 10^{-1}$	$1.00 \cdot 10^{-1}$	US-R14a1/b1
			$1.99 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R14c11	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R14c12	4 (n)	1 (n)	$1.59 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R14c13	0	0	Unknown	Unknown	Flight hour
US-R14c2			$3.34 \cdot 10^{-2}$	Unknown	US-R14a1/nb1
			$1.59 \cdot 10^{-6}$	Unknown	Flight hour
US-R14c21	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R14c22	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R14c23	2 (n)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R14d2			$7.00 \cdot 10^{-1}$	$6.67 \cdot 10^{-1}$	US-R14a1/b1/nc1
			$2.78 \cdot 10^{-6}$	$3.50 \cdot 10^{-6}$	Flight hour
US-R14d21	5 (n)	4 (n)	$1.99 \cdot 10^{-6}$	$2.34 \cdot 10^{-6}$	Flight hour
US-R14d22	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R14d23	2 (n)	1 (n)	$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.14.3 End States.

The five end states are quantified using the quantification of the IE and the pivotal events. The results are given in table 54.

Table 54. Probabilities of End States of ESD US-R14

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R14d1			$1.99 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R14d3			$1.59 \cdot 10^{-6}$	Unknown	Flight hour
US-R14d4			$4.59 \cdot 10^{-5}$	$4.74 \cdot 10^{-5}$	Flight hour
US-R14e1			$2.78 \cdot 10^{-6}$	$3.50 \cdot 10^{-6}$	Flight hour
US-R14e2			$1.19 \cdot 10^{-6}$	$1.75 \cdot 10^{-6}$	Flight hour

5.15 US-R15: ESD AND FT DIAGRAMS.

Figures 51 through 55 show the ESD and FT diagrams of US-R15, Helicopter Enters Adverse Weather.

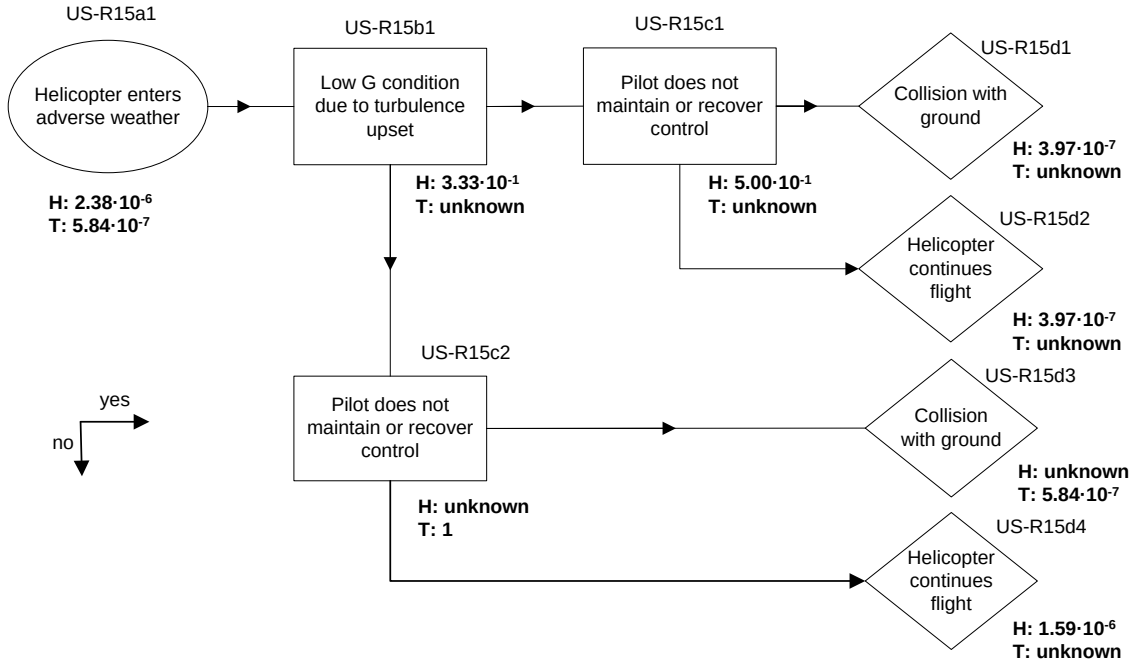


Figure 51. The ESD US-R15—Helicopter Enters Adverse Weather

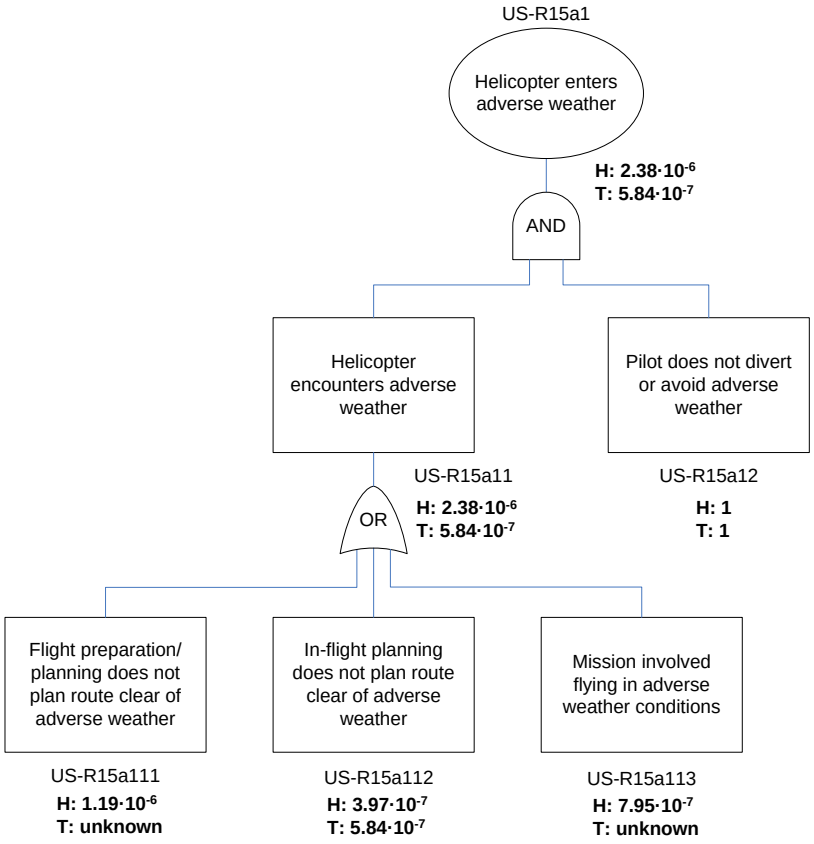


Figure 52. The FT US-R15a1—Helicopter Enters Adverse Weather

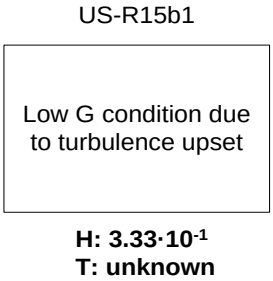


Figure 53. The FT US-R15b1—Low G Condition Due to Turbulence Upset

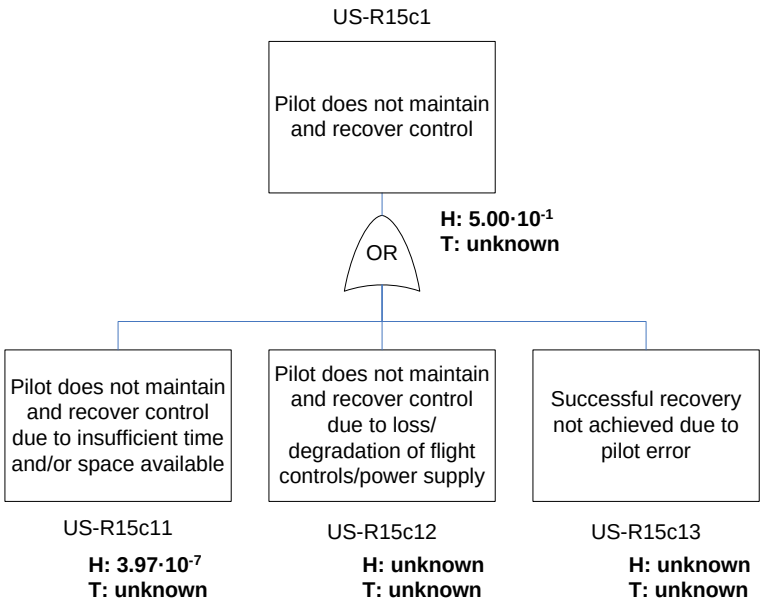


Figure 54. The FT US-R15c1/c2—Pilot Does Not Maintain and Recover Control

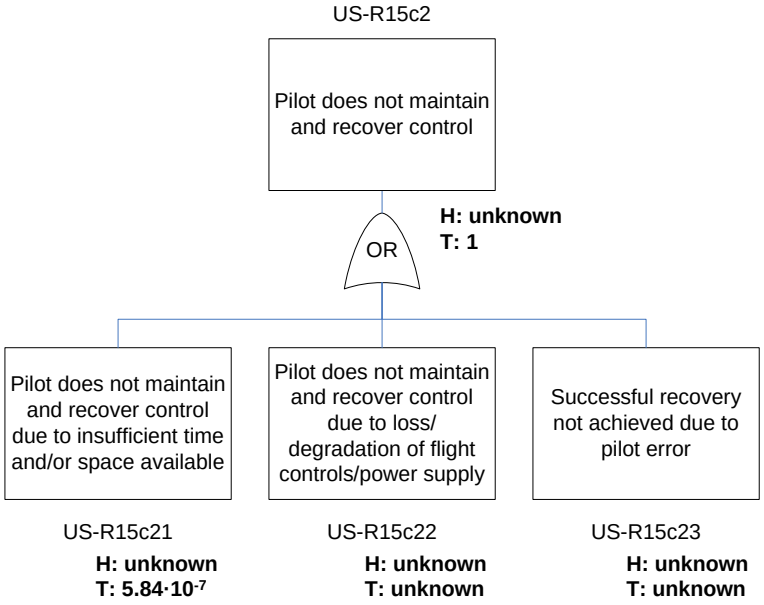


Figure 55. The FT US-R15c1/c2—Pilot Does Not Maintain and Recover Control

5.15.1 Definitions.

Table 55 shows the definition of US-R15, ESD and FT events.

Table 55. Definitions of ESD US-R15—Helicopter Enters Adverse Weather

Event	Code	Definition
Helicopter enters adverse weather	US-R15a1	Helicopter encounters and enters adverse weather. Adverse weather includes heavy precipitation (rain or snow), severe turbulence, thunderstorms, microburst/downdrafts, unexpected strong wind, gusts, etc. Loss of visual reference or loss of situational awareness in adverse weather is considered part of ESD US-R8 and -R9.
Low G condition due to turbulence upset	US-R15b1	A low G condition occurs because of a turbulence upset. Note: "In a low G (weightless) flight condition, improper corrective action could lead to the main rotor hub contacting the rotor mast. The result could be a severely damaged rotor mast, or the main rotor system could separate from the helicopter" [17].
Pilot does not maintain or recover control	US-R15c1	The pilot does not maintain or recover control after a low G condition because of a turbulence upset.
Pilot does not maintain or recover control	US-R15c2	The pilot does not maintain or recover control after an encounter with adverse weather without a low G condition.
Collision with the ground	US-R15d1	Helicopter collision with ground; rotor system may have separated because of mast bumping.
Helicopter continues flight	US-R15d2	Helicopter continues flight, possibly with damage due to mast bumping. Helicopter continues flight into adverse weather, which may lead to loss of visual reference and continues with ESD US-R8 and -R9.
Collision with the ground	US-R15d3	Helicopter collision with ground.
Helicopter continues flight	US-R15d4	Helicopter continues flight into adverse weather, which may lead to loss of visual reference and continues with ESD US-R8 and -R9.
FT—Initiating Event—US-R15a1		
Helicopter encounters adverse weather	US-R15a11	Helicopter encounters adverse weather en route or at destination. A diversion or precautionary landing is still possible before entering adverse weather.
Flight preparation/planning does not plan route clear of adverse weather	US-R15a111	Pilot or dispatch does not plan flight clear of adverse weather during preflight preparation. This can be caused by a pilot/dispatch error, unavailability of accurate or actual weather information, not conducting a proper weather briefing, etc.
In-flight planning does not plan route clear of adverse weather	US-R15a112	Pilot does not plan flight clear of adverse weather while in flight. This can be caused by a pilot error or unavailability of accurate or actual weather information.
Mission involved flying in adverse weather conditions	US-R15a113	The flight is conducted in adverse weather from the beginning.

Table 55. Definitions of ESD US-R15—Helicopter Enters Adverse Weather (Continued)

Event	Code	Definition
Pilot does not divert or avoid adverse weather	US-R15a12	Pilot does not avoid adverse weather and enters adverse weather intentionally or unintentionally; does not execute a precautionary landing or diversion to avoid adverse weather.
FT—Pivotal Event—US-R15b1		
Not further detailed.		
FT—Pivotal Event—US-R15c1/c2		
Pilot does not maintain and recover control because of insufficient time/space is available	US-R15c11 & US-R15c21	Pilot does not recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R15c12 & US-R15c22	Pilot does not maintain or recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R15c13 & US-R15c23	Successful recovery not achieved because of pilot error.

5.15.2 Quantification.

5.15.2.1 The IE.

The IE "helicopter enters adverse weather" (US-R15a1) is quantified using the NTSB, ASRS, and Concern Network databases. Because a helicopter entering adverse weather in itself is not a reportable occurrence, the use of the databases results in a significant underestimate of the IEs. In total, six occurrences were found for HEMS, one of which was covered by two databases. One occurrence for tour operations was found in the ASRS dataset. It is assumed that when adverse weather is encountered, the pilot does not divert to avoid the weather; hence, the probability of "pilot does not divert or avoid adverse weather" (US-R15a12) equals 1. The breakdown of occurrences and the associated probabilities of the events are given in table 56.

Table 56. Occurrences and Probability of US-R15a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R15a1			$2.38 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R15a11			$2.38 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R15a111	3 (a,n)	0	$1.19 \cdot 10^{-6}$	Unknown	Flight hour
US-R15a112	1 (a)	1 (a)	$3.97 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R15a113	2 (a,c)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R15a12			1 (*)	1 (*)	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (*) = assumption					

5.15.2.2 Pivotal Event(s).

The three pivotal events are quantified using occurrences found in the NTSB, ASRS, and Concern Network databases. The pivotal event "low G condition due to turbulence upset" (US-R15b1) does not have FT events and is quantified for HEMS directly from the two occurrences found in the databases: one is from the ASRS and one was covered by both Concern Network and NTSB databases. The other two pivotal events are quantified using the occurrences found in the NTSB dataset (no data were found in the other databases). The results are given in table 57.

Table 57. Occurrences and Probabilities of the Pivotal Events of ESD US-R15

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R15b1	2 (a,c,n)	0	$3.33 \cdot 10^{-1}$	Unknown	US-R15a1
			$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R15c1			$5.00 \cdot 10^{-1}$	Unknown	US-R15a1/b1
			$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R15c11	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R15c12	0	0	Unknown	Unknown	Flight hour
US-R15c13	0	0	Unknown	Unknown	Flight hour
US-R15c2			Unknown	1	R15a1/nb1
			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R15c21	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R15c22	0	0	Unknown	Unknown	Flight hour
US-R15c23	0	0	Unknown	Unknown	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.15.3 End States.

The four end states are quantified using the quantification of the IE and the pivotal events. The results are given in table 58.

Table 58. Probabilities of End Events of ESD US-R15

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R15d1			$3.97 \cdot 10^{-7}$	unknown	Flight hour
US-R15d2			$3.97 \cdot 10^{-7}$	unknown	Flight hour
US-R15d3			unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R15d4			$1.59 \cdot 10^{-6}$	unknown	Flight hour

5.16 US-R16: ESD AND FT DIAGRAMS.

Figures 56 through 59 show the ESD and FT diagrams of US-R16.

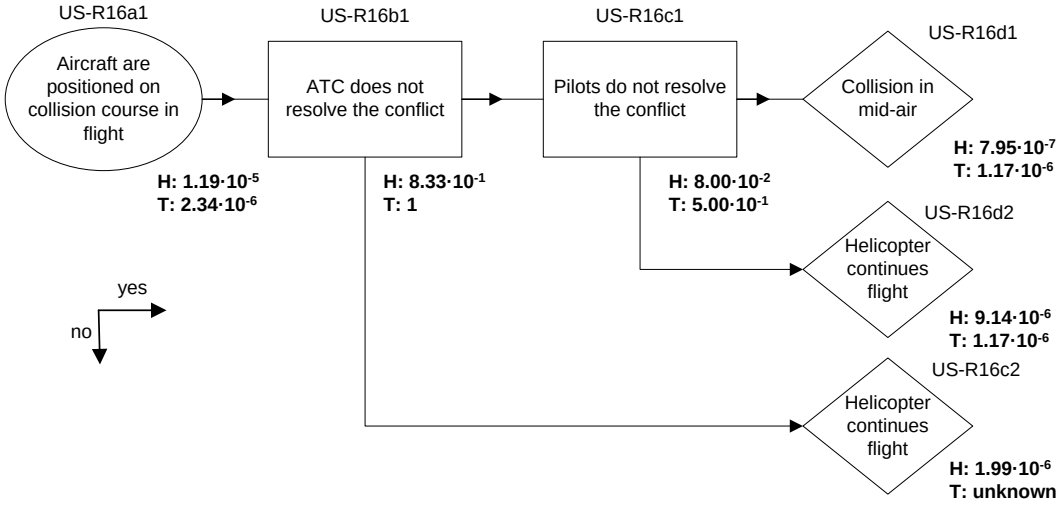


Figure 56. The ESD US-R16—Aircraft Are Positioned on Collision Course in Flight

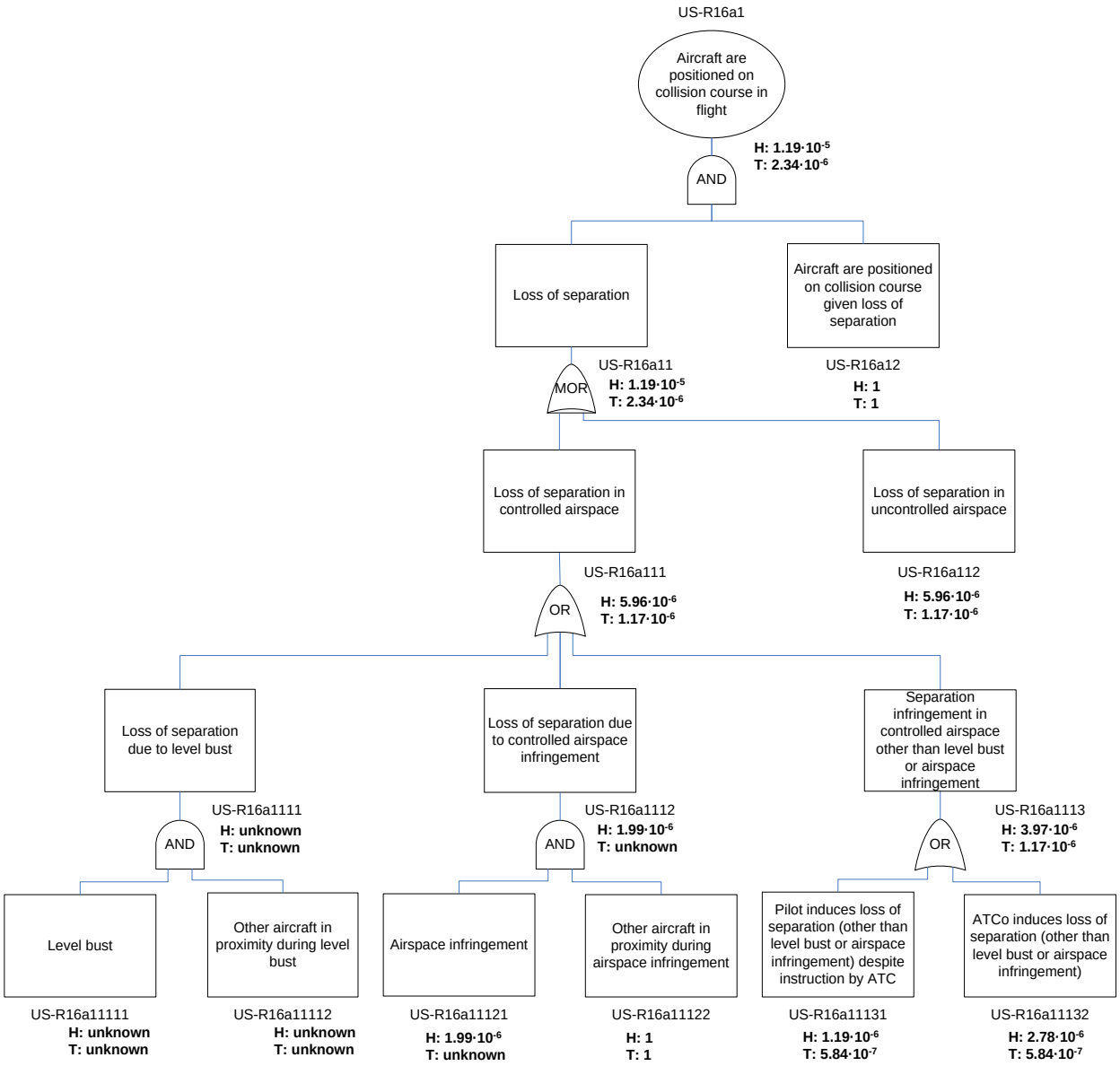


Figure 57. The FT US-R16a1—Aircraft Are Positioned on Collision Course in Flight

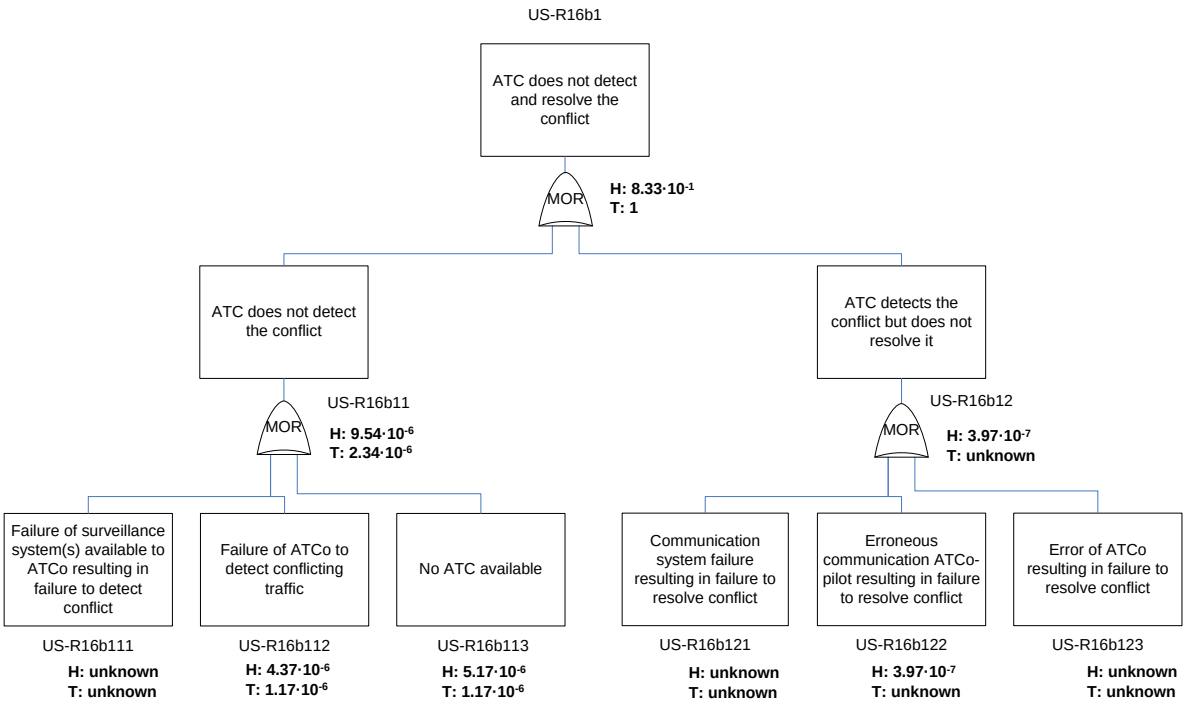


Figure 58. The FT US-R16b1—ATC Does Not Detect and Resolve the Conflict

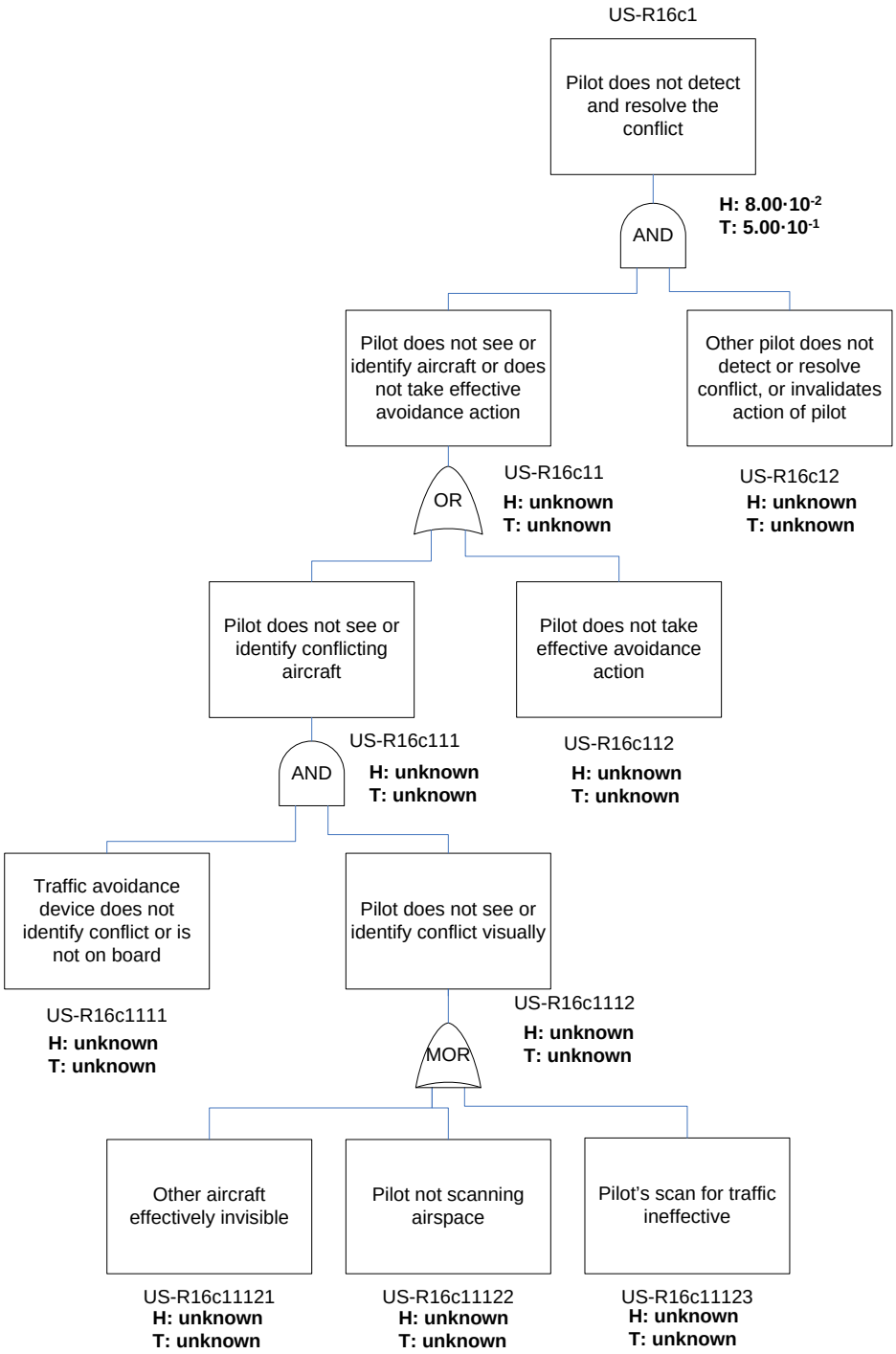


Figure 59. The FT US-R16c1—Pilot Does Not Detect and Resolve the Conflict

5.16.1 Definitions.

The definitions of US-R16: ESD and FT events are shown in table 59.

Table 59. Definitions of ESD US-R16—Aircraft Are Positioned on Collision Course in Flight

Event	Code	Definition
Aircraft are positioned on collision course in flight	US-R16a1	Airborne aircraft, at least one of which is a helicopter, are positioned such that their trajectories, if unaltered, will bring the aircraft close together, leading to a risk of collision.
ATC does not resolve the conflict	US-R16b1	The ATC fails to see and identify conflicting aircraft, fails to take recovery action in time, takes incorrect recovery action, or does not take action to resolve the conflict.
Pilots do not resolve the conflict	US-R16c1	Pilots of both aircraft (at least one of which is a helicopter) fail to see and identify the conflicting aircraft, fail to take recovery action in time, take incorrect recovery action, or do not take action to resolve the conflict.
Helicopter continues flight	US-R16c2	The helicopter continues flight after ATC resolves the conflict.
Collision in midair	US-R16d1	Two aircraft (at least one of which is a helicopter) collide in midair.
Helicopter continues flight	US-R16d2	The helicopter continues flight after the pilot resolves the conflict.
FT—Initiating Event—US-R16a1		
Loss of separation	US-R16a11	Separation between two airborne aircraft (at least one of which is a helicopter) is lost. Separation minimal criteria depend on airspace class. This includes loss of separation where the aircraft flight paths do not intersect (i.e., they do not fly on a collision course).
Loss of separation in controlled airspace	US-R16a111	Loss of separation in controlled airspace.
Loss of separation due to level bust	US-R16a1111	Level bust causes loss of separation because of the proximity of another aircraft. Note: The term “level bust” is used to describe a “noncompliance with an altitude constraint.”
Level bust	US-R16a11111	Level bust (i.e., vertical deviation from intended trajectory).
Other aircraft in proximity during level bust	US-R16a11112	Another aircraft is in proximity during the level bust.
Loss of separation due to controlled airspace infringement	US-R16a1112	Airspace infringement causes a loss of separation because of the proximity of another aircraft.
Airspace infringement	US-R16a11121	Airspace infringement (i.e., an aircraft penetrates an area for which special clearance is required without having such clearance).
Other aircraft in proximity during airspace infringement	US-R16a11122	Another aircraft is in proximity during the airspace infringement.

Table 59. Definitions of ESD US-R16—Aircraft Are Positioned on Collision Course in Flight (Continued)

Event	Code	Definition
Separation infringement in controlled airspace other than level bust or airspace infringement	US-R16a1113	Separation infringement in controlled airspace other than level bust or airspace infringement.
Pilot induces loss of separation (other than level bust or airspace infringement) despite instruction by ATC	US-R16a11131	Pilot is instructed by ATC, but does not follow instructions, resulting in a loss of separation due to the proximity of another aircraft. Airspace infringement and level bust are excluded.
ATCo induces loss of separation (other than level bust or airspace infringement)	US-R16a11132	The actions of the ATCo induce a loss of separation. Airspace infringement and level bust are excluded.
Loss of separation in uncontrolled airspace	US-R16a112	Separation is lost in uncontrolled airspace. This can be due to a failure of the pilot to follow procedures or guidelines for separation in uncontrolled airspace.
Aircraft are positioned on collision course, given loss of separation	US-R16a12	This is an event to introduce the probability that a loss of separation results in a situation in which aircraft are on a collision course. The recovery of the loss of separation is essential because the two aircraft (of which at least one is a helicopter) are positioned such that their trajectories will bring the aircraft together, leading to a collision.
FT—Pivotal Event—US-R16b1		
ATC fails to detect the conflict	US-R16b11	The ATC fails in its task to detect the conflicting aircraft.
Failure of surveillance system(s) available to ATCo, resulting in failure to detect conflict	US-R16b111	Failure of surveillance system(s) available to the ATCo (e.g., radar) resulting in failure to detect the conflict.
Failure of ATCo to detect conflicting traffic	US-R16b112	Failure of the ATCo to detect the conflicting traffic while surveillance systems are functioning correctly. This may include cases where short-term conflict alert is not functioning properly.
No ATC available	US-R16b113	No ATC available.
ATC detects the conflict, but fails to resolve it	US-R16b12	The ATC detects conflicting aircraft, but fails to resolve the conflict.
Communication system failure resulting in failure to detect conflict	US-R16b121	Communication system failure (airborne or land) resulting in a failure to detect the conflict. Failure includes blocked frequency or incorrect frequency selected by pilot.
Erroneous communication between ATCo and pilot, resulting in failure to detect conflict	US-R16b122	Erroneous communication between the ATCo and the pilot, resulting in a failure to detect the conflict (e.g., improper phraseology used or call-sign confusion).
Error of ATCo resulting in failure to resolve conflict	US-R16b123	The ATCo fails to recover separation while aware of the conflict. This includes decision-making, judgment, or action errors.

Table 59. Definitions of ESD US-R16—Aircraft Are Positioned on Collision Course in Flight (Continued)

Event	Code	Definition
FT—Pivotal Event—US-R16c1		
Pilot does not see or identify aircraft or does not take effective avoidance action	US-R16c11	Pilot does not see or identify aircraft, or does not take effective avoidance action.
Pilot does not see or identify conflicting aircraft	US-R16c111	Pilot does not see or identify the conflicting aircraft.
Traffic avoidance device does not identify conflict or is not on board	US-R16c1111	Traffic avoidance device does not identify conflict and does not provide traffic/conflict alert to the pilot because such a device is not installed on board, is switched off, or is not functioning properly.
Pilot does not see or identify conflict visually	US-R16c1112	Pilot does not detect the conflicting aircraft by using his or her vision.
Other aircraft effectively invisible	US-R16c11121	Other aircraft effectively invisible because of weather, glare, cockpit obstructions, other obstructions, poor contrast, aircraft too small to see, etc.
Pilot not scanning airspace	US-R16c11122	Pilot does not detect the conflicting aircraft because he or she is not scanning the airspace.
Pilot's scan for traffic ineffective	US-R16c11123	Airspace scan is not effective, the object is not recognized as a (conflicting) aircraft, or aircraft is not seen (e.g., scanning other part of airspace).
Pilot does not take effective avoidance action	US-R16c112	Pilot does not take effective avoidance action while aware of conflict. This includes inducing a serious conflict, taking no action, or taking ineffective action (e.g., too late, insufficient, or opposite action to ATC instruction).
Other pilot does not detect or resolve conflict, or invalidates action of pilot	US-R16c12	The pilot of the other aircraft does not detect or resolve conflict, or invalidates the action of the pilot.

5.16.2 Quantification.

5.16.2.1 The IE.

The IE “aircraft are positioned on collision course in flight” (US-R16a1) is quantified using the NTSB, ASRS, and Concern Network databases. Considering that these databases contain only occurrences of actual conflict situations, it is assumed that the probability that another aircraft is present (US-R16a11122) is 1 for airspace infringements (US-R16a11121). In the same manner, it is assumed that, given a loss of separation, the aircraft are positioned on collision course (US-R16a12). In other words, it is assumed that a loss of separation without risk of collision is not reported in the datasets used. An occurrence found in the NTSB dataset was not used because information was missing.

Five occurrences of the base event “airspace infringement” (US-R16a11121) were found in the ASRS and Concern Network datasets for HEMS. Three occurrences of the event “pilot induces loss of separation (other than level bust or airspace infringement) despite instruction by ATC”

(US-R16a11131) were recorded in the Concern Network dataset and seven occurrences of the base event "ATCo induces loss of separation (other than level bust or airspace infringement)" (US-R16a11132) were found for HEMS operations in the NTSB, ASRS, and Concern Network databases. For tour operations, one occurrence was found for "pilot induces loss of separation (other than level bust or airspace infringement) despite instruction by ATC" (US-R16a11131) and also one case of "ATCo induces loss of separation (other than level bust or airspace infringement)" (US-R16a11132).

A "loss of separation in uncontrolled airspace" (US-R16a112) for HEMS was reported 15 times in the NTSB, ASRS, and Concern Network datasets. Two occurrences of the latter event were found for tour operations in the NTSB and ASRS datasets.

The number of occurrences found in the databases and the associated probabilities of the events are given in table 60.

Table 60. Occurrences and Probability of US-R16a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R16a1			$1.19 \cdot 10^{-5}$	$2.34 \cdot 10^{-6}$	Flight hour
US-R16a11			$1.19 \cdot 10^{-5}$	$2.34 \cdot 10^{-6}$	Flight hour
US-R16a111			$5.96 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16a1111			Unknown	Unknown	Flight hour
US-R16a11111	0	0	Unknown	Unknown	Flight hour
US-R16a11112			Unknown	Unknown	Flight hour
US-R16a1112			$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R16a11121	5 (a,c)	0	$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R16a11122			1 (*)	1 (*)	US-R16a11121
US-R16a1113			$3.97 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16a11131	3 (c)	1 (a)	$1.19 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R16a11132	7 (a,c,n)	1 (n)	$2.78 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R16a112	15 (a,c,n)	2 (a,n)	$5.96 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16a12			1 (*)	1 (*)	Loss of separation
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (*) = assumption					

5.16.3 Pivotal Event(s).

The two pivotal events are quantified using occurrences found in the NTSB, ASRS, and Concern Network databases. For the pivotal event "ATC does not resolve the conflict" (US-R16b1), 25

occurrences were found for HEMS and four for tour operations that can be used to quantify the base events of that pivotal event.

The base events of the pivotal event “ATC does not resolve the conflict” (US-R16b1) were quantified for HEMS by using the NTSB, Concern Network, and ASRS datasets. There were 11 occurrences of “failure of surveillance system(s) available to ATCo resulting in failure to detect conflict” (US-R16b111) found as well as 13 occurrences related to “failure of ATCo to detect conflicting traffic” (US-R16b112). For tour operations, two occurrences were found for each of these two base events. The base event “erroneous communication ATCo-pilot resulting in failure to detect conflict” (US-R16b122) was found in one occurrence in HEMS that was recorded in both the ASRS and Concern Network dataset.

For occurrences in which the pilot did not detect and resolve the conflict (US-R16c1), an actual collision took place. In total, two midair collisions are found in the NTSB database for both HEMS and tour operations. These occurrence records do not contain enough information to quantify the events of the FT of US-R16c1. Therefore, only the pivotal event US-R16c1 is quantified by dividing the two occurrences by the relevant exposure. The results are summarized in table 61.

Table 61. Occurrences and Probabilities of the Pivotal Events of ESD US-R16

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R16b1			$8.33 \cdot 10^{-1}$	1	US-R16a1
			$9.93 \cdot 10^{-6}$	$2.34 \cdot 10^{-6}$	Flight hour
US-R16b11			$9.54 \cdot 10^{-6}$	$2.34 \cdot 10^{-6}$	Flight hour
US-R16b111	0	0	Unknown	Unknown	Flight hour
US-R16b112	11 (a,c,n)	2 (a,n)	$4.37 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16b113	13 (a,c,n)	2 (a,n)	$5.17 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16b12			$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R16b121	0	0	Unknown	Unknown	Flight hour
US-R16b122	1 (a,c)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R16b123	0	0	Unknown	Unknown	Flight hour
US-R16c1			$8.00 \cdot 10^{-2}$	$5.00 \cdot 10^{-1}$	US-R16a1/b1
			$7.95 \cdot 10^{-7}$	$1.17 \cdot 10^{-6}$	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.16.4 End States.

The three end states are quantified using the quantification of the IE and the pivotal events. The results are given in table 62.

Table 62. Probabilities of End States of ESD US-R16

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R16d1			$7.95 \cdot 10^{-7}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16d2			$9.14 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R16c2			$1.99 \cdot 10^{-6}$	Unknown	Flight hour

5.17 US-R17: ESD AND FT DIAGRAMS.

The ESD and FT diagrams of US-R17: Pilot judgment, decision, or action error are shown in figures 60-66.

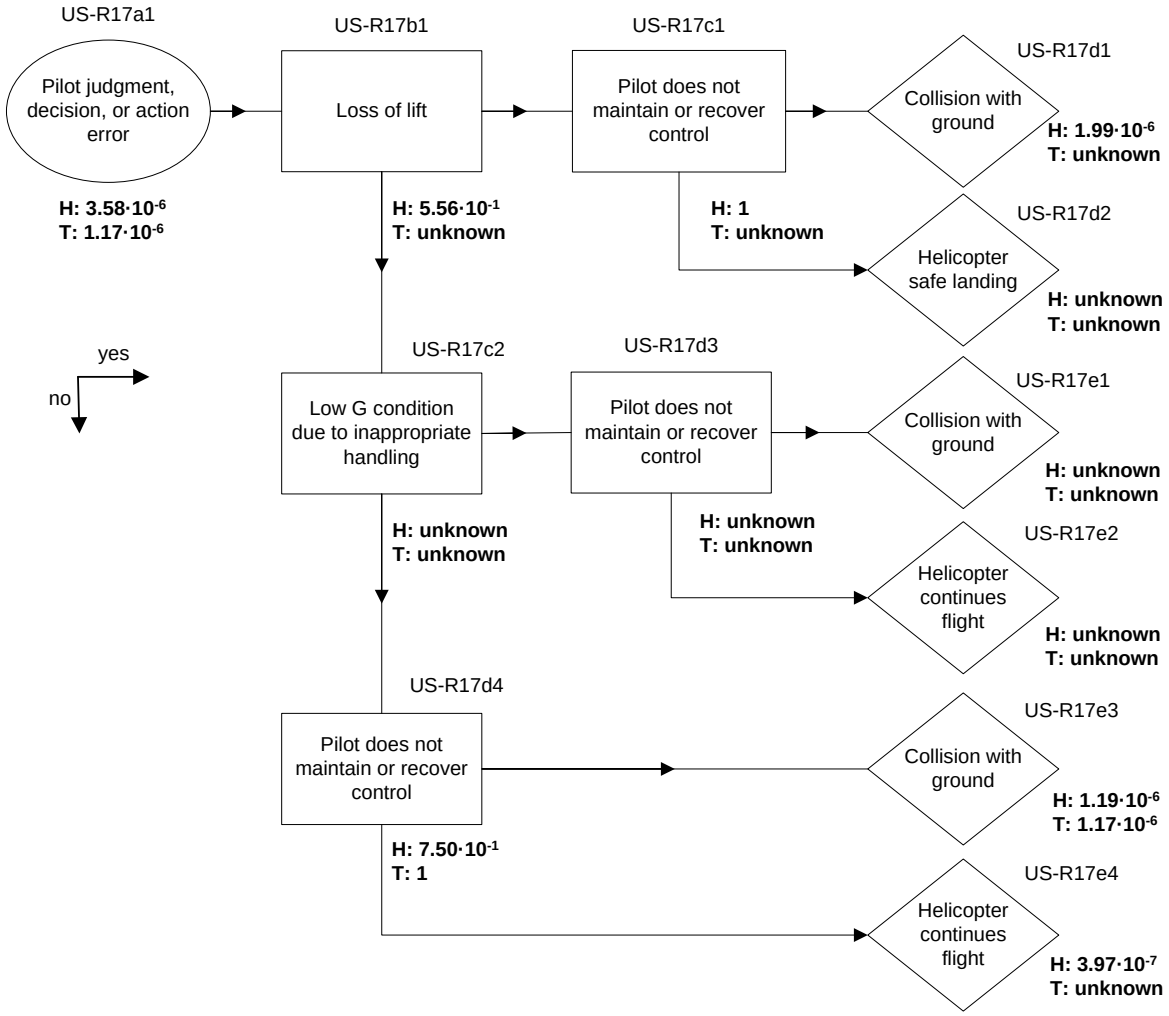


Figure 60. The ESD US-R17—Pilot Judgment, Decision, or Action Error

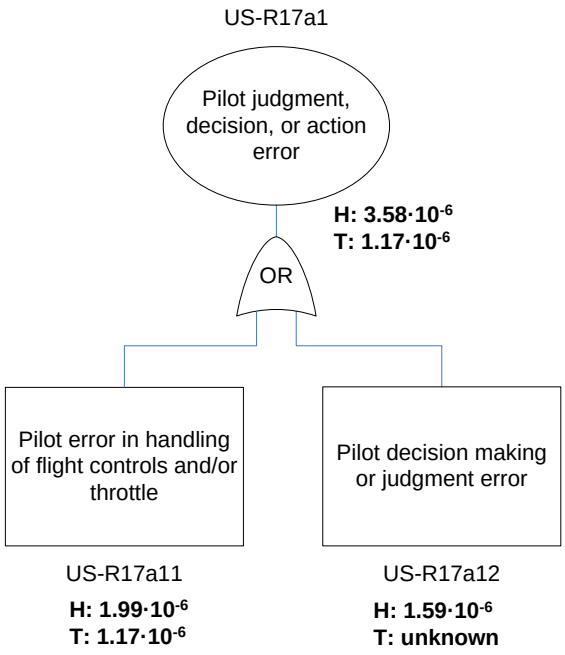


Figure 61. The FT US-R17a1—Pilot Judgment, Decision, or Action Error

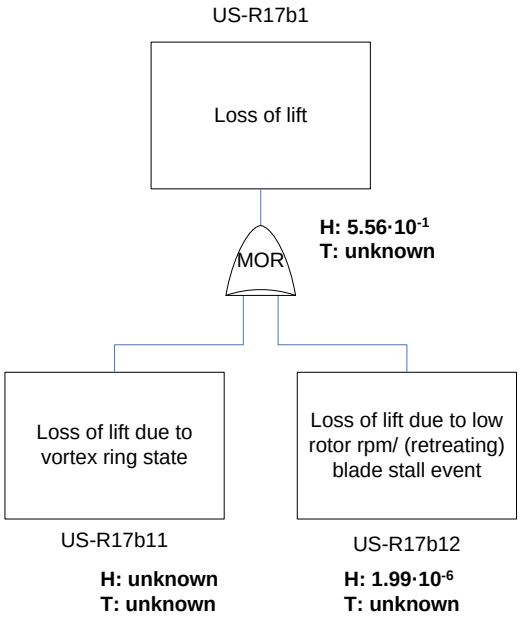


Figure 62. The FT US-R17b1—Loss of Lift

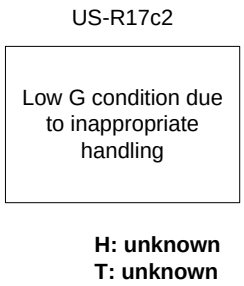


Figure 63. The FT US-R17c2—Low G Condition Due to Inappropriate Handling

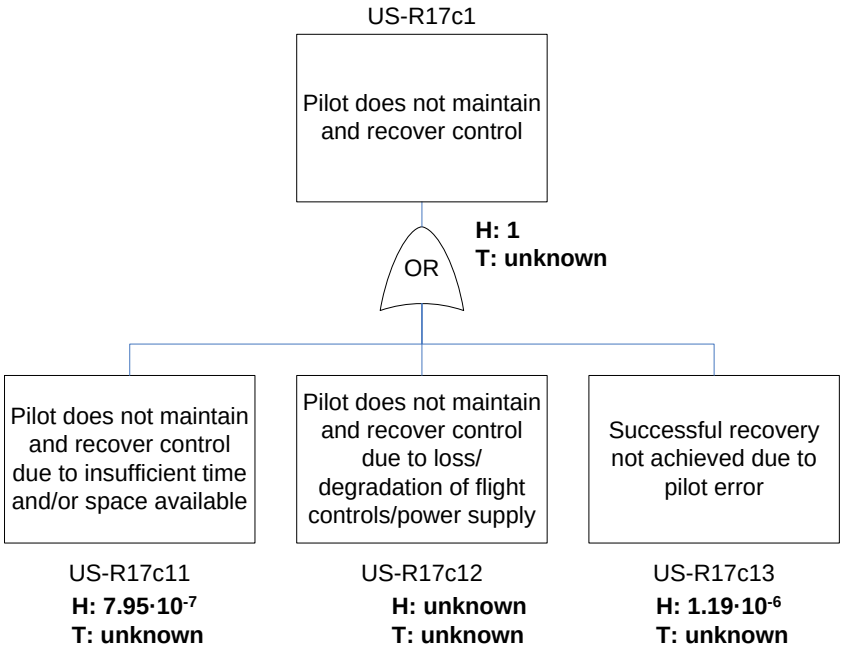


Figure 64. The FT US-R17c1—Pilot Does Not Maintain and Recover Control

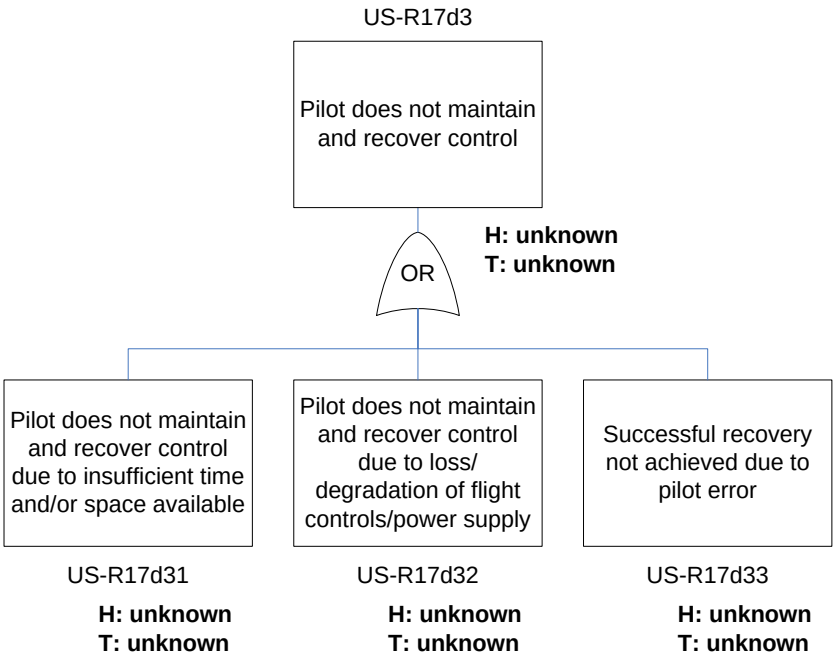


Figure 65. The FT US-R17d3—Pilot Does Not Maintain and Recover Control

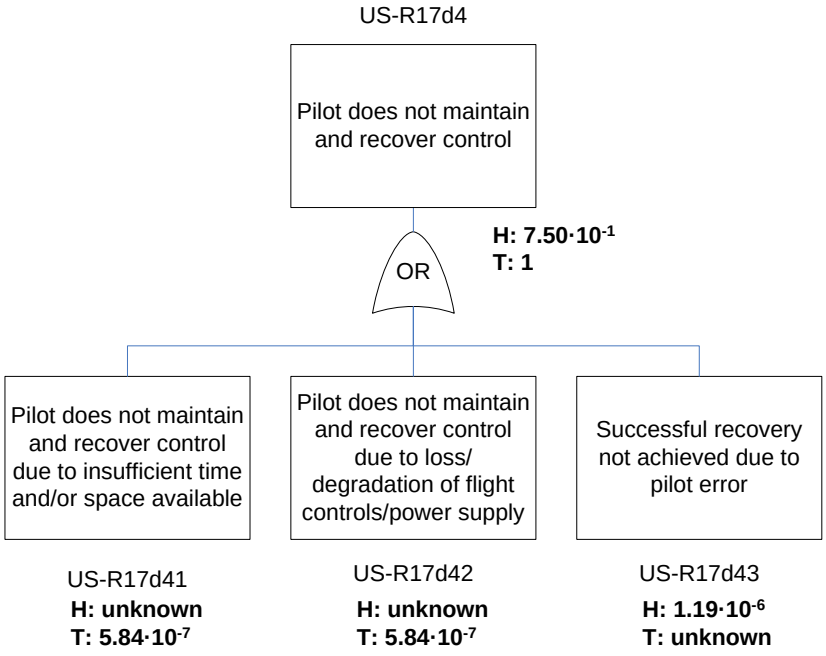


Figure 66. The FT US-R17d4—Pilot Does Not Maintain and Recover Control

5.17.1 Definitions.

The definitions of US-R17 ESD and FT events are shown in table 63.

Table 63. Definitions of ESD US-R17—Pilot Judgment, Decision, or Action Error

Event	Code	Definition
Pilot judgment, decision, or action error	US-R17a1	Pilot does not display appropriate competency and judgment. Pilot makes judgment or decision-making error or demonstrates poor handling skills. Includes inappropriate pilot action, unsuitable use of helicopter systems/controls, etc. This ESD applies to all flight phases except takeoff.
Loss of lift	US-R17b1	Loss of lift occurs. Loss of lift includes a low rotor rpm/blade stall event, vortex ring state (or settling with power).
Pilot does not maintain or recover control	US-R17c1	The pilot does not maintain or recover control after a loss of lift.
Low G condition due to inappropriate handling	US-R17c2	A low G condition occurs because of inappropriate helicopter handling. Note: "In a low G (weightless) flight condition, improper corrective action could lead to the main rotor hub contacting the rotor mast. The result could be a severely damaged rotor mast, or the main rotor system could separate from the helicopter" [17].
Collision with the ground	US-R17d1	Helicopter collision with ground; this includes hard landings with damage.
Helicopter safe landing	US-R17d2	Helicopter continues flight and lands safely.
Pilot does not maintain or recover control	US-R17d3	The pilot does not maintain or recover control after a low G condition because of inappropriate helicopter handling.
Pilot does not maintain or recover control	US-R17d4	The pilot does not maintain or recover control after inappropriate helicopter handling without loss of lift or a low G condition. This includes cases in which the pilot forgets to extract the landing gear, resulting in damage.
Collision with the ground	US-R17e1	Helicopter collision with ground; the rotor system may have separated because of mast bumping. This includes hard landings with damage.
Helicopter continues flight	US-R17e2	Helicopter continues flight, possibly with damage due to mast bumping.
Collision with the ground	US-R17e3	Helicopter collision with ground; this includes hard landings with damage.
Helicopter continues flight	US-R17e4	Helicopter continues flight.
FT—Initiating Event—US-R17a1		
Pilot error in handling of flight controls/throttle	US-R17a11	Pilot does not display appropriate competency or handling skills, handling and operation error of flight controls/throttle. This includes the pilot's inappropriate use of the autopilot.
Pilot decision-making or judgment error	US-R17a12	Pilot does not display appropriate judgment and decision-making regarding the flight, a maneuver, flight envelope, etc.

Table 63. Definitions of ESD US-R17—Pilot Judgment, Decision, or Action Error (Continued)

Event	Code	Definition
FT—Pivotal Event—US-R17b1		
Loss of lift due to vortex ring state	US-R17b11	Loss of lift due to vortex ring state.
Loss of lift due to low rotor rpm/ (retreating) blade stall event	US-R17b12	There is a loss of lift due to low rotor rpm or a blade stall event. This could be a retreating blade stall event.
FT—Pivotal Event—US-R17c2		
Not further detailed.		
FT—Pivotal Event—US-R17c1/d3/d4		
Pilot does not maintain and recover control because insufficient time/space is available	US-R17c11 & US-R17d31 & US-R17d41	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R17c12 & US-R17d32 & US-R17d42	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R17c13 & US-R17d33 & US-R17d43	Successful recovery not achieved because of pilot error.

5.17.2 Quantification.

5.17.2.1 The IE.

The IE "pilot judgment, decision, or action error" (US-R17a1) is quantified using the NTSB and Concern Network databases. For HEMS, nine occurrences were found in the dataset (six in NTSB and three in the Concern Network database). Five occurrences were related to "pilot error in handling of flight controls and/or throttle" (US-R17a11), and four were cases of "pilot decision making or judgment error" (US-R17a12).

For tour operations, two occurrences were found in the NTSB dataset and none in the ASRS dataset. The two occurrences were related to "pilot error in handling of flight controls and/or throttle" (US-R17a11). The number of occurrences found in the databases and the associated probabilities of the events are given in table 64.

Table 64. Occurrences and Probability of US-R17a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R17a1			$3.58 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R17a11	5 (n)	2 (n)	$1.99 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R17a12	4 (a,n)	0	$1.59 \cdot 10^{-6}$	Unknown	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.17.2.2 Pivotal Event(s).

The base events of the five pivotal events were quantified using occurrences found in both the NTSB and Concern Network databases for HEMS operations. Five cases were found of a loss of lift due to a "low rotor rpm/(retreating) blade stall event" (US-R17b12), followed by a loss of control. In two of these occurrences, the loss of control was because "pilot does not maintain and recover control because insufficient time and/or space is available" (US-R17c11) and in three cases because "successful recovery not achieved because of pilot error" (US-R17c13). Three occurrence were found in which the IE resulted in "successful recovery not achieved because of pilot error" (US-R17d43) without a loss of lift or low G condition occurring.

For tour operations, the two occurrences found in the NTSB dataset were used to quantify the pivotal events' base events. Two occurrences were found in which the IE resulted in loss of control: in one case because of "insufficient time/space available" for recovery (US-R17d43) and in another case of "loss/degradation of flight controls/power supply" (US-R17d42). The results are summarized in table 65.

Table 65. Occurrences and Probabilities of the Pivotal Events of ESD US-R17

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R17b1			$5.56 \cdot 10^{-1}$	Unknown	US-R17a1
			$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R17b11	0	0	Unknown	Unknown	Flight hour
US-R17b12	5 (n)	0	$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R17c2	0	0	Unknown	Unknown	US-R17a1/nb1
US-R17c1			1	Unknown	US-R17a1/b1
			$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R17c11	2 (n)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R17c12	0	0	Unknown	Unknown	Flight hour
US-R17c13	3 (n)	0	$1.19 \cdot 10^{-6}$	Unknown	Flight hour
US-R17d3			Unknown	Unknown	US-R17a1/nb1/c2
			Unknown	Unknown	US-R17a1/nb1/c2
US-R17d31	0	0	Unknown	Unknown	Flight hour
US-R17d32	0	0	Unknown	Unknown	Flight hour
US-R17d33	0	0	Unknown	Unknown	Flight hour

Table 65. Occurrences and Probabilities of the Pivotal Events of ESD US-R17 (Continued)

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R17d4			$7.50 \cdot 10^{-1}$	1	US-R17a1/nb1/nc2
			$1.19 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R17d41	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R17d42	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R17d43	3 (c,n)	0	$1.19 \cdot 10^{-6}$	Unknown	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database					

5.17.2.3 End States.

The end states are quantified using the quantification of the IE and the pivotal events. The results are given in table 66.

Table 66. Probabilities of End States of ESD US-R17

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R17d1			$1.99 \cdot 10^{-6}$	Unknown	Flight hour
US-R17d2			Unknown	Unknown	Flight hour
US-R17e1			Unknown	Unknown	Flight hour
US-R17e2			Unknown	Unknown	Flight hour
US-R17e3			$1.19 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R17e4			$3.97 \cdot 10^{-7}$	Unknown	Flight hour

5.18 US-R18: ESD AND FT DIAGRAMS.

Figures 67 through 70 show the ESD and FT diagrams of US-R18, Structural Failure in Flight.

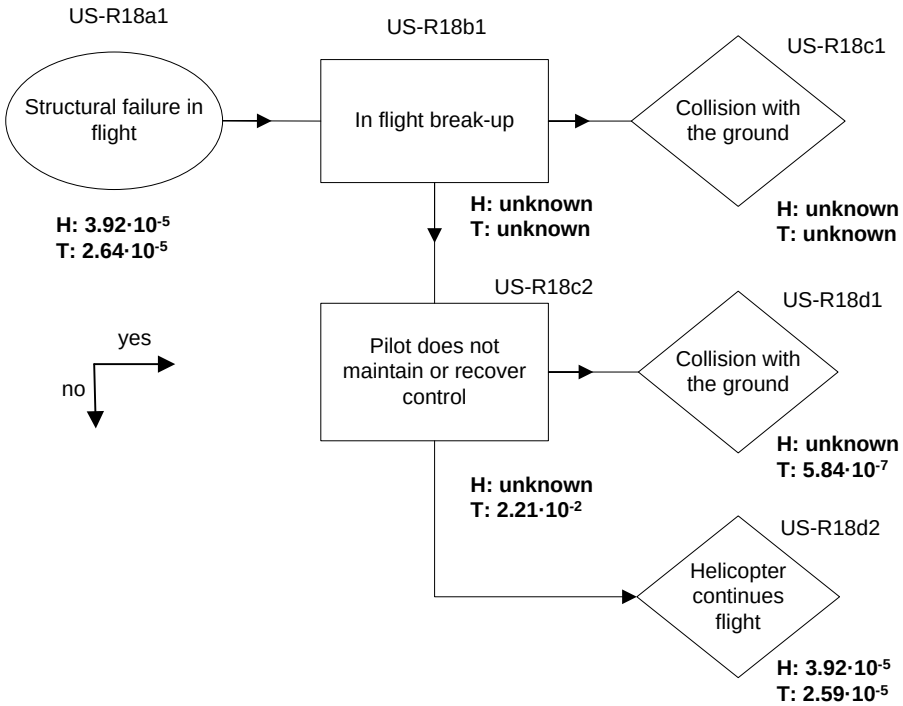


Figure 67. The ESD US-R18—Structural Failure in Flight

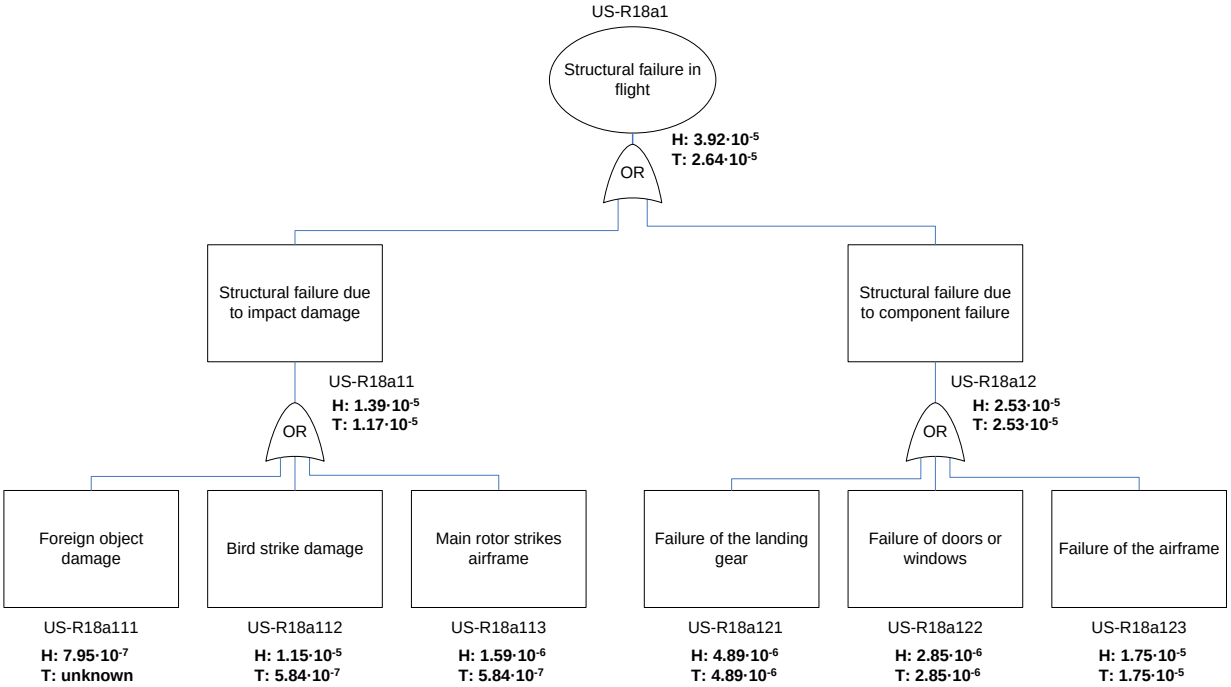


Figure 68. The FT US-R18a1—Structural Failure in Flight

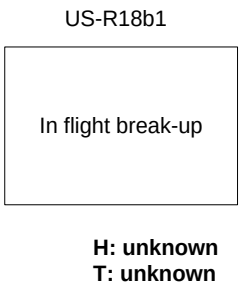


Figure 69. The FT US-R18b1—In-Flight Breakup

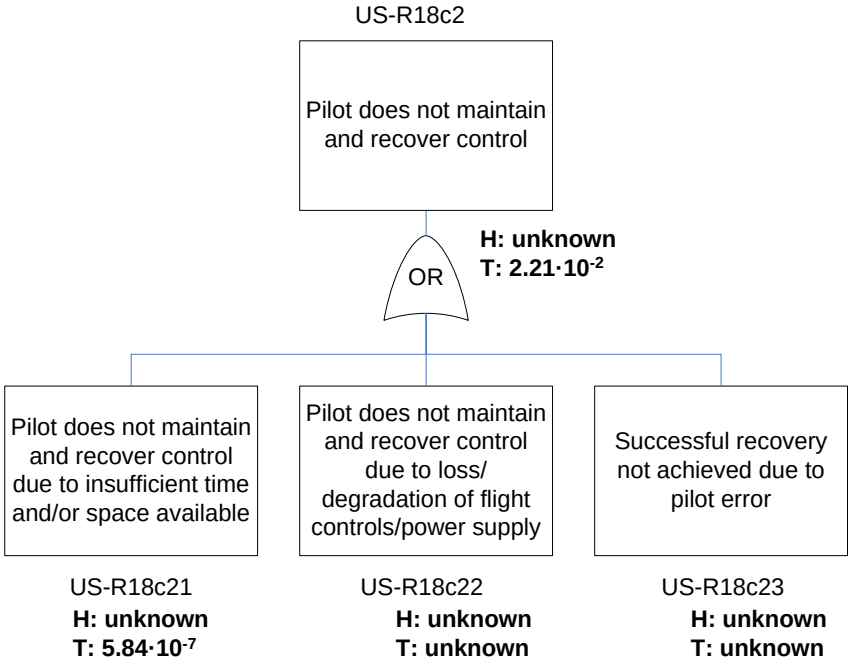


Figure 70. The FT US-R18c2—Pilot Does Not Maintain and Recover Control

5.18.1 Definitions.

Table 67 shows the definitions of US-R18, ESD and FT events.

Table 67. Definitions of ESD US-R18—Structural Failure in Flight

Event	Code	Definition
Structural failure in flight	US-R18a1	Structural failure in flight due to impact damage or component failure (fatigue or overload failure). Causes for the latter include flying into adverse weather conditions, component failure (e.g. due to maintenance, design, manufacturing etc.), pilot error. The following systems are included: ATA 3200 landing gear; ATA 5200 doors; ATA 5300 fuselage (airframe); ATA 5600 windows. The event includes separation of doors, windows, or airframe parts. Cargo hook overload is excluded. Failure or loss of parts of the tail rotor blades is excluded and covered by ESD US-R13. Failure or loss of parts of the main rotor blades is excluded and covered by ESD US-R14.
Inflight breakup	US-R18b1	Structural failure is so severe that the helicopter breaks up in flight.
Collision with the ground	US-R18c1	The helicopter hits the ground after an inflight breakup.
Pilot does not maintain or recover control	US-R18c2	The pilot is unable to maintain or recover control after a structural failure in flight.
Collision with the ground	US-R18d1	Helicopter collision with ground after the pilot loses control.
Helicopter continues flight	US-R18d2	The pilot is able to continue flight with a structural failure. There may be injuries due to bird strike or foreign object damage, without incapacitation due to the injuries.
FT—Initiating Event—US-R18a1		
Structural failure due to impact damage	US-R18a11	Structural failure due to an external impact.
Foreign object damage	US-R18a111	Structural failure due to the impact of a foreign object.
Bird strike damage	US-R18a112	Structural failure due to the impact of a bird.
Main rotor strikes airframe	US-R18a113	Structural failure due to the main rotor impacting the airframe.
Structural failure due to component failure	US-R18a12	Structural failure due to a component failure.
Failure of the landing gear	US-R18a121	Structural failure in flight of: ATA 3200 landing gear.
Failure of doors or windows	US-R18a122	Structural failure in flight of: ATA 5200 doors; ATA 5600 windows. Includes separation of doors or windows.
Failure of the airframe	US-R18a123	Structural failure in flight of: ATA 5300 fuselage; ATA 5400 nacelles/pylons; ATA 5500 stabilizers; ATA 5700 wings. Includes separation of airframe parts.
FT—Pivotal Event—US-R18b1		
Inflight breakup is not further specified because it is mostly dependent on the severity of the structural failure (i.e., the initiating event).		

Table 67. Definitions of ESD US-R18—Structural Failure in Flight (Continued)

Event	Code	Definition
FT—Pivotal Event—US-R18c2		
Pilot does not maintain and recover control because insufficient time/space is available	US-R18c21	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R18c22	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R18c23	Successful recovery not achieved because of pilot error.

5.18.2 Quantification.

5.18.2.1 The IE.

The IE "structural failure in flight" (US-R18a1) is quantified using the NTSB, SDR, ASRS, and Concern Network datasets. The base events of "structural failure due to impact damage" (US-R18a11) were quantified with occurrences found in the NTSB, Concern Network, and ASRS databases for HEMS. Of the 35 occurrences found in these databases, two were related to "foreign object damage" (US-R18a111), 29 were related to "bird strike damage" (US-R18a112), and four were related to "main rotor strikes airframe" (US-R18a113).

For tour operations, two occurrences were found in the NTSB dataset for "structural failure due to impact damage," one was due to "bird strike damage," and one was related to "main rotor strikes airframe."

The base events of "structural failure due to component failure" (US-R18a12) were quantified with SDR data for both HEMS and tour operations. In the SDR dataset, 96 events were found for "failure of the landing gear" (US-R18a121), 56 events for "failure of doors or windows" (US-R18a122), and 344 events for "failure of the airframe" (US-R18a123).

The number of occurrences found in the databases and the associated probabilities of the events are given in table 68.

Table 68. Occurrences and Probability of US-R18a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R18a1			$3.92 \cdot 10^{-5}$	$2.64 \cdot 10^{-5}$	Flight hour
US-R18a11			$1.39 \cdot 10^{-5}$	$1.17 \cdot 10^{-6}$	Flight hour
US-R18a111	2 (c)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R18a112	29 (a, c, n)	1 (n)	$1.15 \cdot 10^{-5}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R18a113	4 (a, c)	1 (n)	$1.59 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R18a12			$2.53 \cdot 10^{-5}$	$2.53 \cdot 10^{-5}$	Flight hour
US-R18a121	96 (s)	96 (s)	$4.89 \cdot 10^{-6}$	$4.89 \cdot 10^{-6}$	Flight hour
US-R18a122	56 (s)	56 (s)	$2.85 \cdot 10^{-6}$	$2.85 \cdot 10^{-6}$	Flight hour
US-R18a123	344 (s)	344 (s)	$1.75 \cdot 10^{-5}$	$1.75 \cdot 10^{-5}$	Flight hour
(a) = ASRS database; (c) = Concern Network database; (n) = NTSB database; (s) = SDR database					

5.18.3 Pivotal Event(s).

An FT has not been constructed for the pivotal event “in flight breakup” (US-R18b1). No occurrences have been found for that pivotal event. Only one occurrence has been found for tour operations for the pivotal event “pilot does not maintain or recover control” (US-R18c2). The results are summarized in table 69.

Table 69. Occurrences and Probabilities of the Pivotal Events of ESD US-R18

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R18b1	0	0	Unknown	Unknown	Flight hour
US-R18c2			Unknown	$2.21 \cdot 10^{-2}$	US-R18a1
			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R18c21	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R18c22	0	0	Unknown	Unknown	Flight hour
US-R18c23	0	0	Unknown	Unknown	Flight hour
(n) = NTSB database					

5.18.4 End States.

The three end states are quantified using the quantification of the IE and the pivotal events. The results are given in table 70.

Table 70. Probabilities of End States of ESD US-R18

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R18c1			Unknown	Unknown	Flight hour
US-R18d1			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R18d2			$3.92 \cdot 10^{-5}$	$2.59 \cdot 10^{-5}$	Flight hour

5.19 US-R20: ESD AND FT DIAGRAMS.

Figures 71 through 75 show the ESD and FT diagrams of US-R70, improper approach/flare by pilot.

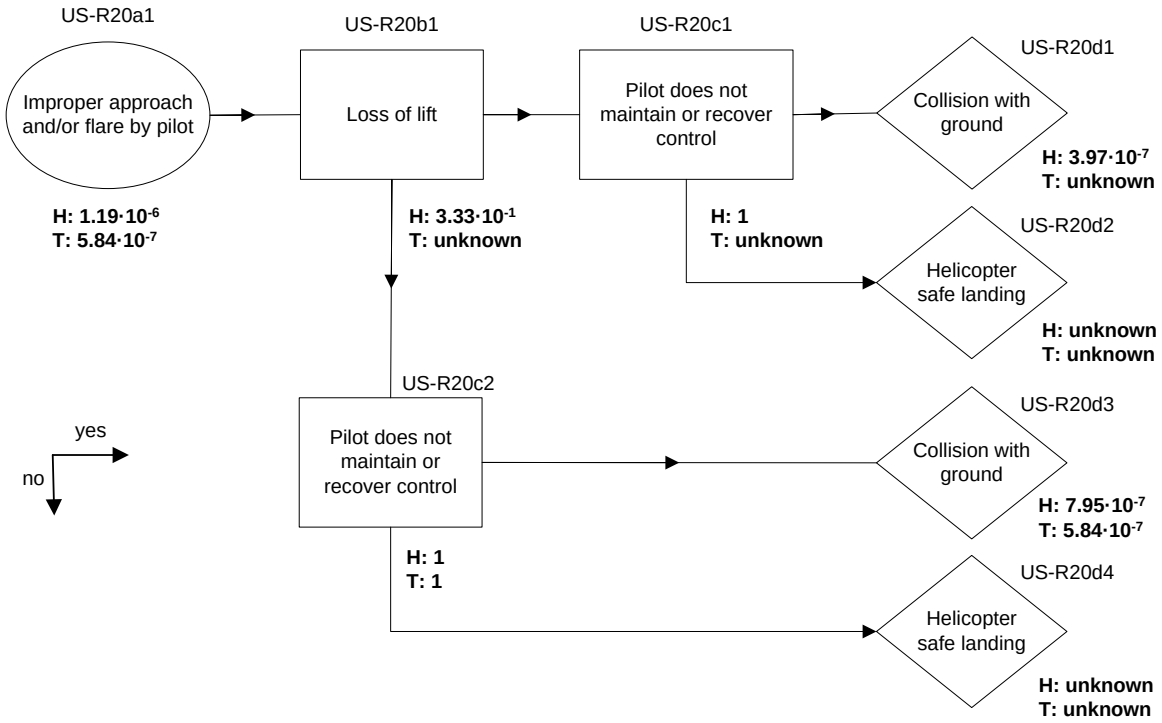


Figure 71. The ESD US-R20—Improper Approach/Flare by Pilot

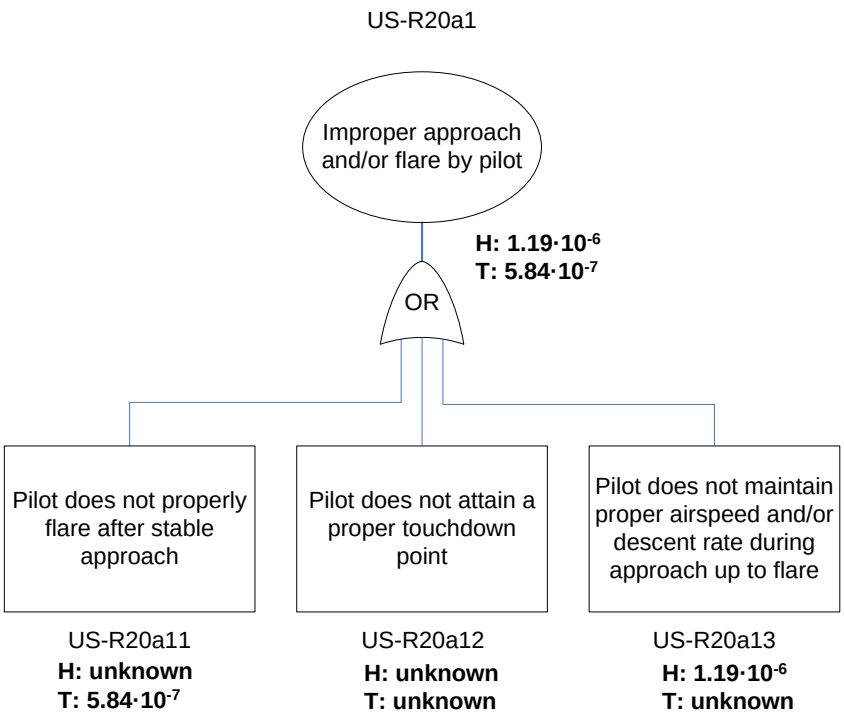


Figure 72. The FT US-R20a1—Improper Approach/Flare by Pilot

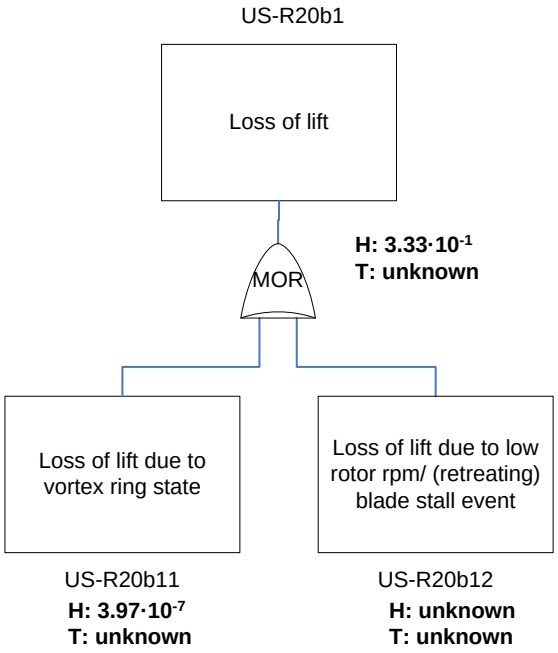


Figure 73. The FT US-R20b1—Loss of Lift

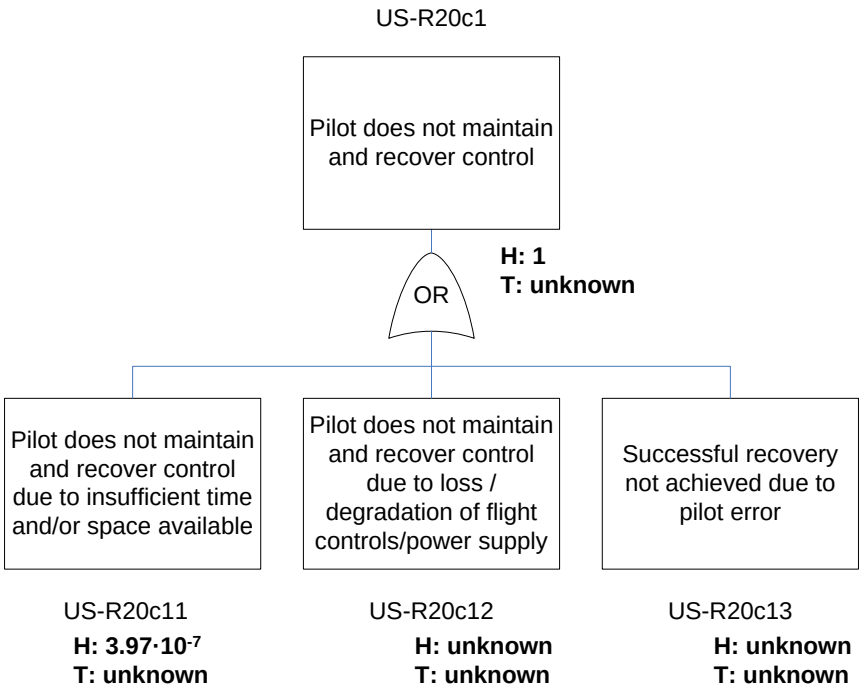


Figure 74. The FT US-R20c1/c2—Pilot Does Not Maintain and Recover Control

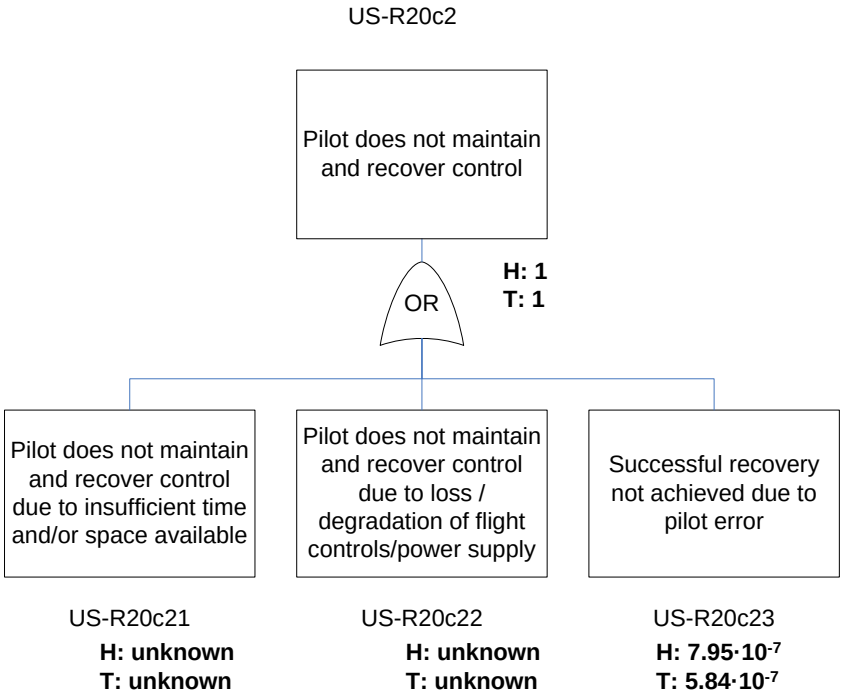


Figure 75. The FT US-R20c2—Pilot Does Not Maintain and Recover Control

5.19.1 Definitions.

Table 71 shows the definitions of US-R10, ESD and FT Events.

Table 71. Definitions of ESD US-R20—Improper Approach/Flare by Pilot

Event	Code	Definition
Improper approach/flare by pilot	US-R20a1	The pilot does not fly a proper approach or does not execute a proper flare.
Loss of lift	US-R20b1	Loss of lift occurs. Loss of lift includes a low rotor rpm/blade stall event and a vortex ring state (settling with power).
Pilot does not maintain or recover control	US-R20c1	The pilot does not maintain or recover control after a loss of lift.
Pilot does not maintain or recover control	US-R20c2	The pilot does not maintain or recover control after an improper approach/flare without a loss of lift.
Collision with the ground	US-R20d1	Helicopter collision with ground; this includes hard landings with damage.
Helicopter safe landing	US-R20d2	Helicopter continues flights and lands safely.
Collision with the ground	US-R20d3	Helicopter collision with the ground; the rotor system may have separated. This includes dynamic rollover, tail strikes, and hard landings with damage.
Helicopter safe landing	US-R20d4	Helicopter continues flights and lands safely.
FT—Initiating Event—US-R20a1		
Pilot does not properly flare after stable approach	US-R20a11	The pilot does not properly flare after a normal and stable approach.
Pilot does not attain a proper touchdown point	US-R20a12	Pilot does not attain a proper touchdown point, resulting in an undershoot or overshoot.
Pilot fails to maintain proper airspeed/descent rate during approach up to flare	US-R20a13	Pilot fails to maintain proper airspeed/descent rate during approach up to the flare.
FT—Pivotal Event—US-R20b1		
Loss of lift because of vortex ring state	US-R20b11	There is a loss of lift because of a vortex ring state.
Loss of lift due to low rotor rpm/ (retreating) blade stall event	US-R20b12	There is a loss of lift due to low rotor rpm or a blade stall event. This could be a retreating blade stall event.
FT—Pivotal Event—US-R20c1/c2		
Pilot does not maintain and recover control because of insufficient time/space available	US-R20c11 & US-R20c21	Pilot does not maintain and recover control because insufficient time/space is available.
Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply	US-R20c12 & US-R20c22	Pilot does not maintain and recover control because of loss/degradation of flight controls/power supply.
Successful recovery not achieved because of pilot error	US-R20c13 & US-R20c24	Successful recovery not achieved because of pilot error.

5.19.2 Quantification.

5.19.2.1 The IE.

The IE, "improper approach/flare by pilot" (US-R20a1), is quantified using the NTSB and Concern Network data. In total, only three occurrences for HEMS operations were found in the NTSB dataset, one of which was also covered by the Concern Network dataset. One occurrence for tour operations was found in the NTSB dataset. No occurrences of this event were found in the ASRS database. The associated probabilities of the events are given in table 72.

Table 72. Occurrences and Probability of US-R20a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R20a1			$1.16 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R20a11	0	1 (n)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R20a12	0	0	Unknown	Unknown	Flight hour
US-R20a13	3 (c,n)	0	$1.16 \cdot 10^{-6}$	Unknown	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.19.2.2 Pivotal Event(s).

The pivotal events are quantified using the occurrences found in the NTSB and Concern Network databases. For HEMS, one occurrence was found in the NTSB dataset that was related to "loss of lift due to vortex ring state" (US-R20b11), followed by a loss of control "because insufficient time/space is available for recovery" (US-R20c11). Two occurrences of the event "successful recovery not achieved because of pilot error" after an improper approach/flare by the pilot (US-R20c23) were found for HEMS (two occurrences in the NTSB dataset, one of which was also present in the Concern Network data). For tour operations, one occurrence was found in the NTSB dataset related to "successful recovery not achieved because of pilot error" (US-R20c23). The results are summarized in table 73.

Table 73. Occurrences and Probabilities of the Pivotal Events of ESD US-R20

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R20b1			$3.33 \cdot 10^{-1}$	Unknown	US-R20a1
			$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R20b11	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R20b12	0	0	Unknown	Unknown	Flight hour
US-R20c1			1	Unknown	US-R20a1/b1
				Unknown	Flight hour
US-R20c11	1 (n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R20c12	0	0	Unknown	Unknown	Flight hour
US-R20c13	0	0	Unknown	Unknown	Flight hour
US-R20c2			1	1	US-R20a1/nb1
			$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R20c21	0	0	Unknown	Unknown	Flight hour
US-R20c22	0	0	Unknown	Unknown	Flight hour
US-R20c23	2 (c,n)	1 (n)	$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.19.2.3 End States.

The four end states are quantified using the quantification of the IE and the pivotal events. The results are given in table 74.

Table 74. Probabilities of End States of ESD US-R20

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R20d1			$3.97 \cdot 10^{-7}$	Unknown	Flight hour
US-R20d2			Unknown	Unknown	Flight hour
US-R20d3			$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R20d4			Unknown	Unknown	Flight hour

5.20 US-R21: ESD AND FT DIAGRAMS.

Figures 76 through 78 show the ESD and FT diagrams of US-R21, Presence of Person Near Helicopter With Turning Rotors.

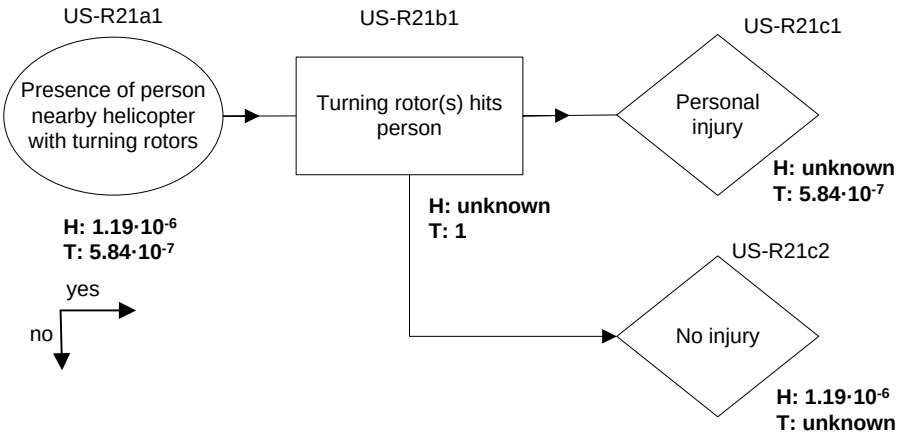


Figure 76. The ESD US-R21—Presence of Person Near Helicopter That Has Turning Rotors

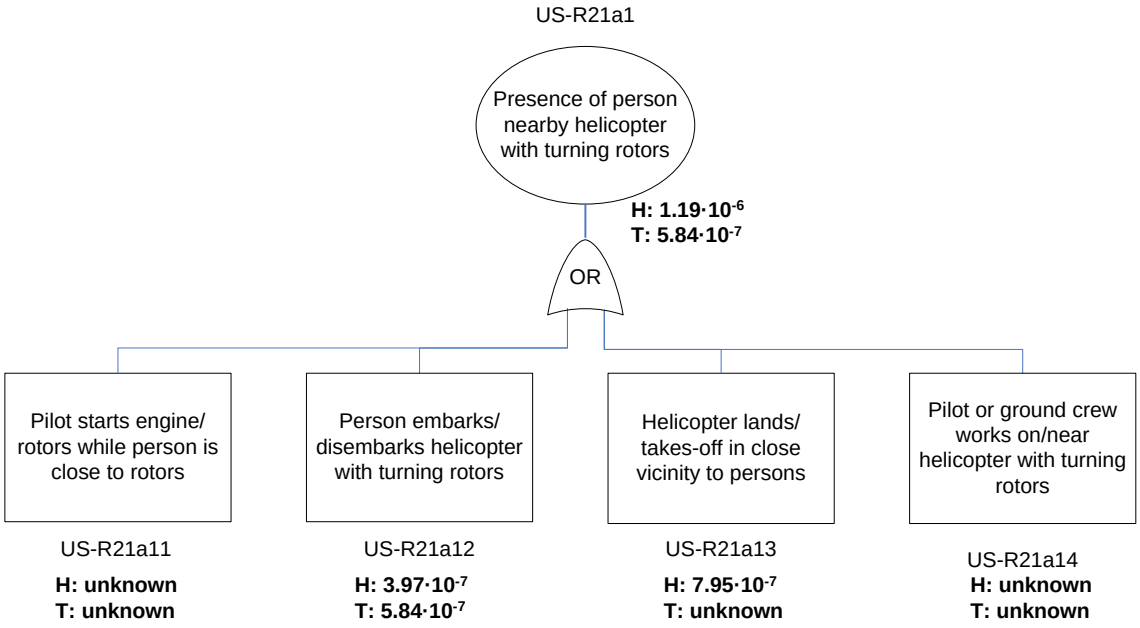


Figure 77. The FT US-R21a1—Presence of Person Near Helicopter That Has Turning Rotors

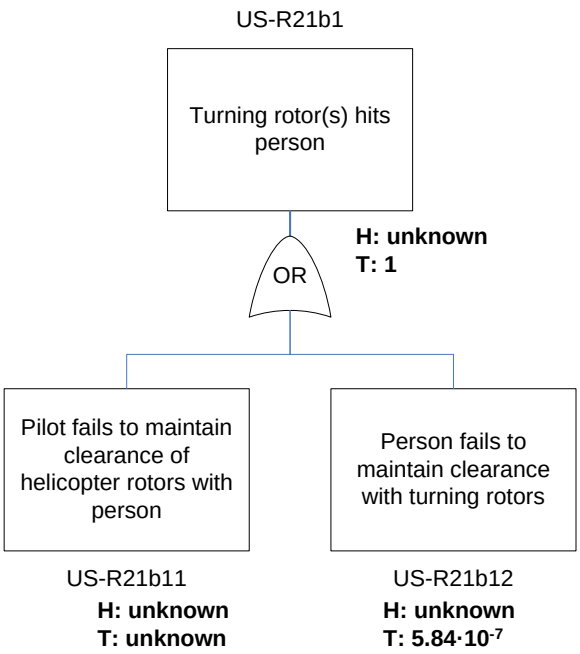


Figure 78. The FT US-R21b1—Turning Rotor Hits Person

5.20.1 Definitions.

Table 75 shows the definitions of US-R21, ESD and FT Events.

Table 75. Definitions of ESD US-R21—Presence of Person Near Helicopter With Turning Rotors

Event	Code	Definition
Presence of person near helicopter that has turning rotors	US-R21a1	A person is close to the helicopter while it is standing, in takeoff or landing, with main/tail rotors turning. This includes the case of a person working or servicing the helicopter (pilot, ground crew) as well as passengers boarding/deplaning or the presence of a person near the helicopter.
Turning rotor hits person	US-R21b1	Person fails to maintain clearance with the helicopter rotors and is hit by one or more rotors.
Personal injury	US-R21c1	Person is injured by the rotors. This includes the case of a fatal injury.
No injury	US-R21c2	Person is not hit by turning rotors and has no injuries.
FT—Initiating Event—US-R20a1		
Pilot starts engine/rotors while person is nearby	US-R21a11	Pilot starts the engine/rotors while a person is close to the rotors (e.g., the pilot does not check that the area is clear before starting the engine).

Table 75. Definitions of ESD US-R21—Presence of Person Near Helicopter With Turning Rotors (Continued)

Event	Code	Definition
Person embarks/disembarks helicopter with turning rotors	US-R21a12	Person embarks/disembarks the helicopter while rotors are turning. The person may misunderstand or not follow instructions; a person embarks or disembarks the helicopter with turning rotors without instruction, clearance, or guidance; or a person intentionally embarks/disembarks the helicopter with turning rotors.
Helicopter lands/takes off in close proximity to persons	US-R21a13	Pilot lands/takes off close to a person who is dangerously close to the turning rotors.
Pilot or ground crew works on/near helicopter with turning rotors	US-R21a14	Pilot or ground crew works on/near the helicopter with turning rotors (e.g., servicing the helicopter).
FT—Pivotal Event—US-R20b1		
Pilot fails to maintain clearance of helicopter rotors with person	US-R21b11	Pilot moves the helicopter and a person is hit by the turning rotors.
Person fails to maintain clearance with turning rotors	US-R21b12	Person walks into the turning rotors because of a human error, loss of situational awareness, not adhering to procedures, not following boarding or deplaning instructions, visibility conditions, visibility of rotor disc, etc.

5.20.2 Quantification.

5.20.2.1 The IE.

The IE, "presence of person near helicopter with turning rotors" (US-R21a1), is quantified using the ASRS and Concern Network databases. Three occurrences for HEMS operations were found in the Concern Network database and one occurrence for tour operations was present in the ASRS database. No occurrences of this event were found in the NTSB dataset. The associated probabilities of the events are given in table 76.

Table 76. Occurrences and Probability of US-R21a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R21a1			$1.16 \cdot 10^{-6}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R21a11	0	0	Unknown	Unknown	Flight hour
US-R21a12	1 (c)	1 (a)	$3.97 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R21a13	2 (c)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R21a14	0	0	Unknown	Unknown	Flight hour
(a) = ASRS database; (c) = Concern Network database					

5.20.2.2 Pivotal Event(s).

Only one occurrence was found of a personal injury due to contact with the rotor, “turning rotor hits person” (US-R21b1). This occurrence was found in the ASRS dataset and related to tour operations. This result is given in table 77.

Table 77. Occurrences and Probabilities of the Pivotal Events of ESD US-R21

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R20b1			Unknown	1	US-R21a1
			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R20b11	0	0	Unknown	Unknown	Flight hour
US-R20b12	0	1 (a)	Unknown	$5.84 \cdot 10^{-7}$	Flight hour
(a) = ASRS database					

5.20.2.3 End States.

The end states are quantified using the quantification of the initial event and the pivotal events. The results are given in table 78.

Table 78. Probabilities of End States of ESD US-R21

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R21c1			Unknown	$5.84 \cdot 10^{-7}$	Flight hour
US-R21c2			$1.16 \cdot 10^{-6}$	Unknown	Flight hour

5.21 US-R23: ESD AND FT DIAGRAMS.

The ESD and FT diagrams of US-R23, Helicopter Enters Ground Resonance, are shown in figures 79 through 81.

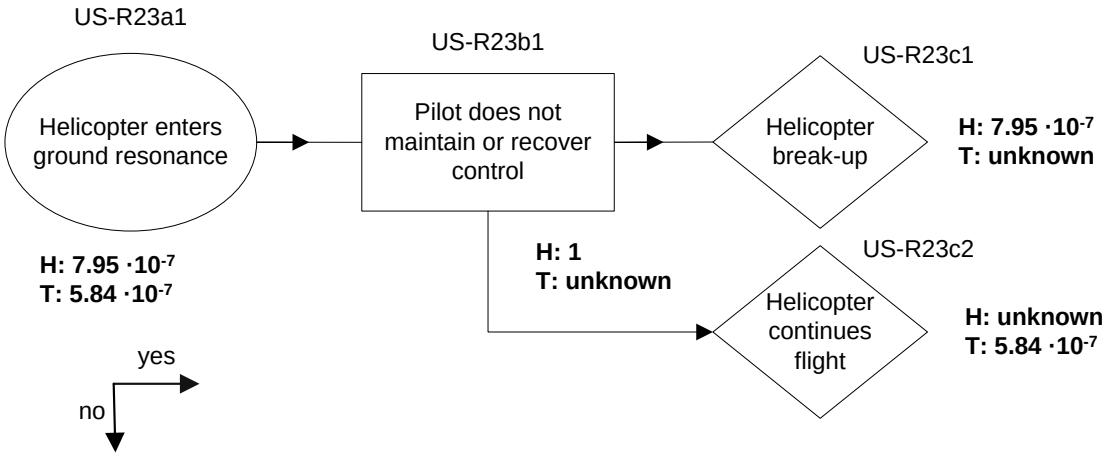


Figure 79. The ESD US-R23—Helicopter Enters Ground Resonance

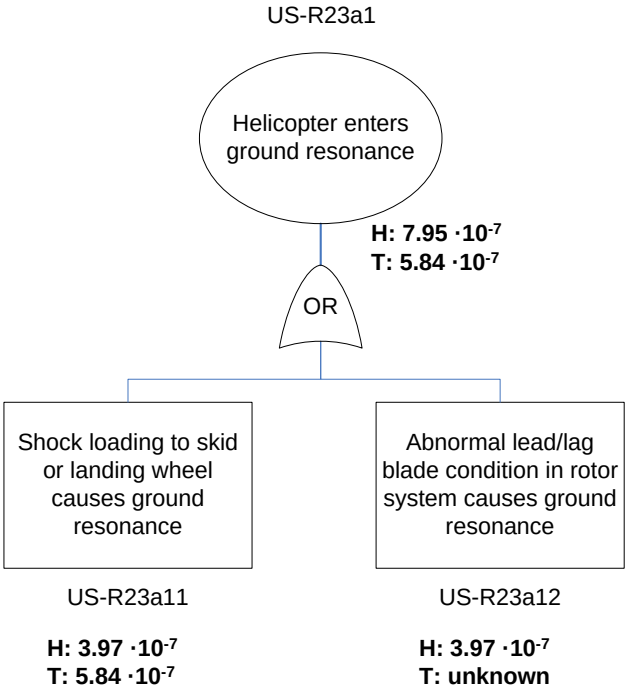


Figure 80. The FT US-R23a1—Helicopter Enters Ground Resonance

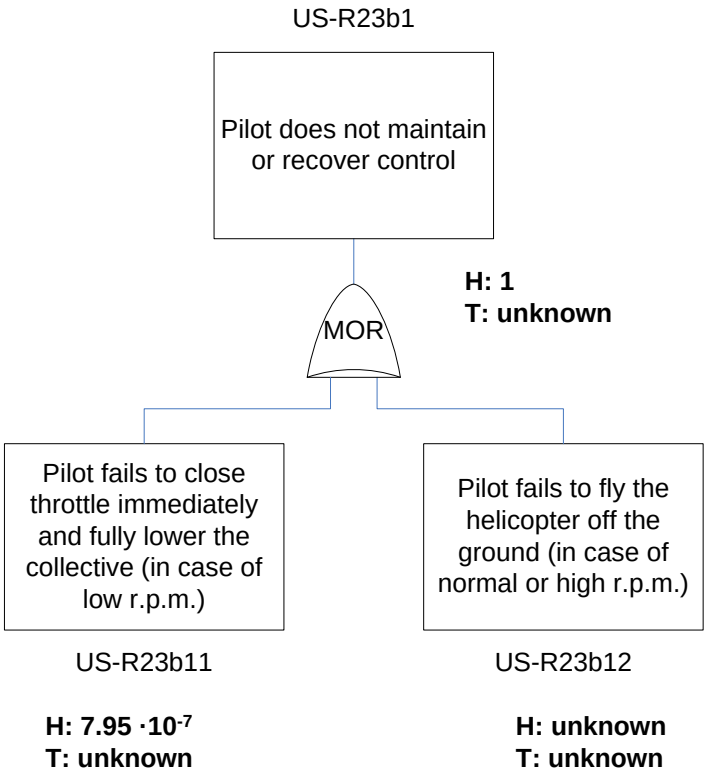


Figure 81. The FT US-R23b1—Pilot Does Not Maintain or Recover Control

5.21.1 Definitions.

Table 79 shows the definition of US-R23, ESD and FT Events.

Table 79. Definitions of ESD US-R23—Helicopter Enters Ground Resonance

Event	Code	Definition
Helicopter enters ground resonance	US-R23a1	The helicopter enters ground resonance. Ground resonance is an aerodynamic phenomenon associated with fully articulated rotor systems. It develops when the rotor blades move out of phase with each other and cause the rotor disc to become unbalanced. Skid-type landing gear is not as prone to ground resonance as wheel-type gear [17].
Pilot does not maintain or recover control	US-R23b1	The pilot does not maintain or recover control.
Helicopter breakup	US-R23c1	The helicopter breaks up on the ground; structural failure of rotor and airframe.
Helicopter continues flight	US-R23c2	The pilot is able to continue flight.

Table 79. Definitions of ESD US-R23—Helicopter Enters Ground Resonance (Continued)

Event	Code	Definition
FT—Initiating Event—US-R23a1		
Shock loading to skid or landing wheel causes ground resonance	US-R23a11	Shock transmitted to the main rotor system (because of, e.g., hard landing, touchdown with pitching or rolling motion, or taxiing on rough surface) leads to ground resonance. Failure of landing gear dampers or oleos with uneven or low pressure may contribute to ground resonance by not providing even damping and could be factors deeper in this FT branch.
Abnormal lead/lag blade condition in rotor system causes ground resonance	US-R23a12	The abnormal lead/lag condition is related to the rotor system condition (i.e., includes unbalanced blades, incorrect tracking, or faulty lead-lag dampers).
FT—Pivotal Event—US-R23b1		
Pilot fails to close throttle immediately and fully lower the collective (in case of low rpm)	US-R23b11	Pilot fails to close throttle immediately and fully lower the collective (in case of low rpm).
Pilot fails to fly the helicopter off the ground (in case of normal or high rpm)	US-R23b12	Pilot fails to fly the helicopter off the ground (in case of normal or high rpm).

5.21.2 Quantification.

5.21.2.1 The IE.

The IE is quantified using the NTSB, the Concern Network, and the ASRS databases. Two occurrences were found in the NTSB dataset and two in the Concern Network dataset for HEMS, which are the same events. For tour operations, one occurrence was found in the NTSB dataset. The following table shows the distribution of occurrences over the FT events for HEMS and tour operations and the corresponding probability per flight hour. The quantification of US-R23a1 is shown in table 80.

Table 80. Occurrences and Probabilities of FT Events of US-R23a1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R23a1			$7.95 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R23a11	1 (c,n)	1 (n)	$3.97 \cdot 10^{-7}$	$5.84 \cdot 10^{-7}$	Flight hour
US-R23a12	1 (c,n)	0	$3.97 \cdot 10^{-7}$	Unknown	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.21.2.2 Pivotal Event(s).

The pivotal event “pilot does not maintain or recover control” (US-R23b1) can be quantified by using the occurrences of a helicopter breakup/disintegration after ground resonance started. The data sample contains two occurrences for HEMS operations (both found in the NTSB and

Concern Network datasets) and one for tour operations. The single occurrence of ground resonance in tour operations resulted in a safe landing and, therefore, is not applicable to this pivotal event. Table 81 shows the distribution of occurrences over the FT base events for HEMS and tour operations, and the corresponding probability per flight hour.

Table 81. Occurrences and Probabilities of FT Events of US-R23b1

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R23b1			1	Unknown	US-R23a1
			$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R23b11	2 (c,n)	0	$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R23b12	0	0	Unknown	Unknown	Flight hour
(c) = Concern Network database; (n) = NTSB database					

5.21.2.3 End States.

The end states of the ESD are quantified using the quantification of the IE and the pivotal event. The results are given in table 82.

Table 82. Occurrences and Probabilities of End States of US-R23

Event	Occurrences		Probability		Per
	HEMS	Tour	HEMS	Tour	
US-R23c1			$7.95 \cdot 10^{-7}$	Unknown	Flight hour
US-R23c2			Unknown	$5.84 \cdot 10^{-7}$	Flight hour

6. MAPPING OF FUNCTIONS TO THE ROTORCRAFT CAUSAL MODEL.

6.1 BACKGROUND ON THE FUNCTIONAL MODEL.

A generic functional model of Part 135 certificate holders was developed by the FAA and partners in 2009 [18]. The functional model identifies the functions that should be performed by Part 135 certificate holders. It describes a hierarchy of functions or activities and is not based on cause-effect relationships. The functions basically describe what should be done for a system to function properly. The Part 135 certificate holder functional model also applies to HEMS and tour operations. In a separate effort, the FAA reviewed the Part 135 certificate holder functional model to identify critical functions applicable to HEMS and tour operations. This review resulted in a subset of 51 functions from the complete Part 135 functional model.

6.2 OBJECTIVE OF THE MAPPING.

The failure of functions or the incorrect performance of a function could impact the safety of the Part 135 certificate holder's operation. Hence, a relationship can be defined between the

functional model and the rotorcraft causal model. The set of 51 critical functions for HEMS and air tour operations was mapped to the rotorcraft causal model. The objective of the mapping of functions to the rotorcraft causal model is to prioritize functions based on the relative contribution of the function to the occurrence of an IE or the relative contribution of a function-to-accident probability.

6.3 APPROACH.

The research team assessed each function in the set of 51 critical functions for HEMS and tour operations to determine if the function could impact or has an impact on the initiating event or pivotal events of each ESD. If so, the function was mapped to (or assigned to) the ESD. Figure 82 shows the concept of the mapping of functions (numbered) to the ESD initiating and pivotal events. The mapping is documented as in table 83, where *x* indicates that the function is mapped to the corresponding ESD.

Figure 83 shows the concept of the mapping of functions to the base events of the ESD. In figure 83, the base events of the IE are D and the base events of the pivotal events are E, K, and L (pivotal event 1) and Q, R, and S (pivotal event 3). Mapping a function to a base event indicates that the function has or could have an impact on the base event.

The current study mapped the functions to the base events of ESD R-14 (loss of power) to illustrate the process. The mapping of ESD R-14 is also used to determine the feasibility and to compare the outcomes of a mapping of a function to the base events and the mapping of a function to the ESD initiating and pivotal events.

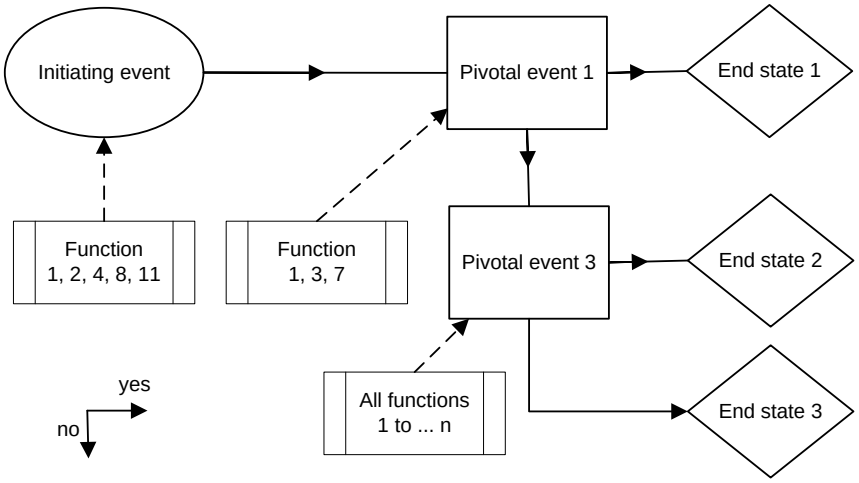


Figure 82. Example of Mapping of Functions to the ESD Initiating and Pivotal Events

Table 83. Sample Documentation of the Mapping of Functions to ESDs

			ESD number												
Code	Function	Definition	2	3	5	6	7	8	9	10	11	12	13	14	etc
A.X (e.g. A.1)	…	…	x	x	x	x	x	x	x	x	x	x	x	x	x
A.X.y (e.g. A.1.1)	…	…		x		x								x	
A.X.y.z (e.g. A.1.1.1)	…	…	x	x	x									x	
Etc.															

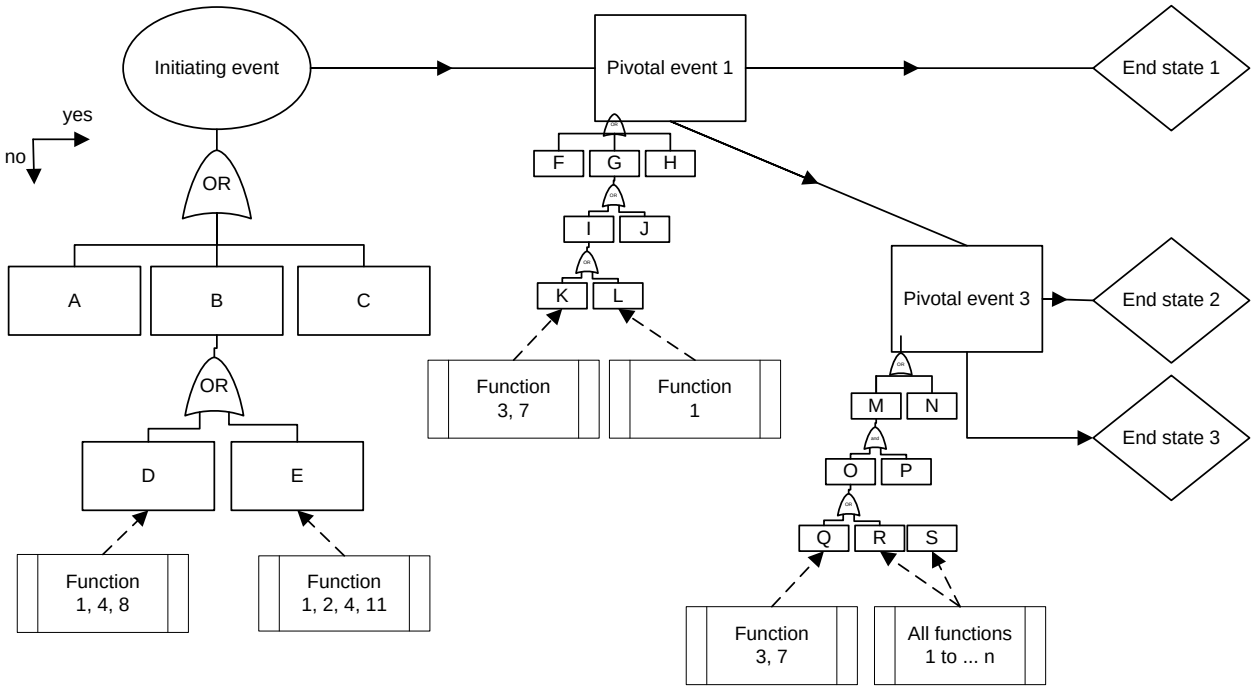


Figure 83. Example of Mapping of Functions to the ESD Base Events

6.4 WEIGHT FACTOR DEFINITION.

The functions can be weighted and prioritized based on the three weight factors:

1. The (cumulative) probability of the IEs of the ESDs to which the functions are mapped, which is a measure of the importance of the functions in relation to the occurrence of the IEs.

2. The (cumulative) probability of the unsafe end states of the ESDs to which the functions are mapped, which is a measure of the importance of the functions in relation to the

accident probability. The unsafe end states represent a negative outcome that could be classified, for instance, as an accident, incident, injury, or damage.

3. The (cumulative) conditional probability of the IEs leading to accident end states in the ESDs to which the functions are mapped. This is a measure of a function's importance in a contribution to accident probability.

The following example explains these three factors. The function "A1.3.2.5 performs load/fuel planning" is related to the causal model ESD R-3 (attempted flight with weight and/or CG outside limits) and ESD R-14 (loss of power). The IE probability and the cumulative accident probability of ESD R-3 and R-14 are shown table 84. The probabilities for HEMS and tour operations are aggregated.

The weight factor (1) that is based on the IE probability is the sum of the IE probabilities of both ESDs. The resulting weight factor for the function "A1.3.2.5 Perform Load/Fuel Planning" becomes $1.08 \cdot 10^{-4}$. The weight factor (2) that is based on cumulative accident probability is the sum of the accident end states probabilities of both ESDs. The ESD R-3 has one end state, "collision with ground." The ESD R-14 has three end states, "collision with ground." The cumulative accident probability of ESD R-14 is the sum of probabilities of those three end states, "collision with ground." The resulting weight factor (2) for the function "A1.3.2.5 Perform Load/Fuel Planning" becomes $1.16 \cdot 10^{-5}$ (see table 84). The weight factor (3) is the conditional probability that these two IEs lead to an accident end state, which is $1.16 \cdot 10^{-5}$ divided by $1.08 \cdot 10^{-4} = 0.11$.

Table 84. Example of Weight Factor Definition for HEMS and Tour Operations

ESD	Initiating Event Probability (per flight hr)	Cumulative Accident Probability (per flight hr)	Conditional Accident Probability
R-3	$1.17 \cdot 10^{-6}$	$1.17 \cdot 10^{-6}$	
R-14	$1.07 \cdot 10^{-4}$	$1.04 \cdot 10^{-5}$	
Weight factor (sum)	$1.08 \cdot 10^{-4}$	$1.16 \cdot 10^{-5}$	0.11

6.5 RESULT OF MAPPING FUNCTIONS TO SCENARIOS.

Appendix E shows the result of the ranking of functions. The functions are sorted first by the cumulative IE probability (weight factor 1), then by the cumulative accident probability (weight factor 2), and then by the number of matching ESDs. The ranking based on conditional accident probability (weight factor 3) was not done because the quantification of events in a few ESDs is based on a small data sample, leading to relatively high conditional probabilities that are not representative for prioritization.

This approach helps the analyst to assess the importance of functions in relation to the IE occurrence and accident probability, and to prioritize functions accordingly. The added value of this approach is that the ranking of functions is data driven; the weight factor for the ranking is

based on a structured and integrated analysis of accidents, incidents, and occurrences from various data sources.

The mapping effort in the current study shows that it is technically feasible to use the causal model as a prioritization tool for the Part 135 certificate holder functions. The current maturity level of the rotorcraft causal model and functional model is a limitation in the mapping. Adding more detail to the FTs could provide better hooks for the functional model mapping. Similarly, more detail of the functional model through the definition of specific (safety critical) tasks and activities would enable a more accurate mapping of functions to ESD events. Conversely, quantification of more-detailed events in the FTs will be complicated or impossible. If some base events of the causal model cannot be quantified, then the weight factors for these base events cannot be determined. Another limitation is that some base events may not have yet led to an accident, so defining a probability of accident as a result of a particular base event could be difficult or impossible.

7. DISCUSSION.

7.1 MODEL COVERAGE AND COMPLETENESS.

The rotorcraft causal model consists of 19 generic accident scenarios (ESDs) with underlying FTs defining the causal factors that contribute to the accident scenarios. This causal model represents most accident scenarios of HEMS and tour operations. All rotorcraft accidents with HEMS and tour operators in the 2005 to 2010 timeframe could be associated with one of the 19 scenarios. Because of the generic nature of the qualitative model, the current set of scenarios is also applicable to other types of helicopter operations (e.g., passenger transport flights, general aviation, etc.). When the scope of the model is expanded to include other types of operations, a review of accident scenarios is required to assess the need to develop additional scenarios.

In this study, it was decided that FTs would be developed to a level of detail at which it was still possible to quantify the events with data and the cause-effect mechanisms could be understood and modeled. As a result, most FTs are two or three layers deep. There is a need to consider more detailed factors, such as maintenance, operational, and human factors issues; pilot level of experience; level of training; etc. Data on such factors in incidents and occurrences are generally not available in the datasets used in this study. This implies that other data sources need to be used to complement the currently used datasets and that data reporting and collection need to be redesigned to capture required information to populate the models (see section 8).

The FAA and model developers need to balance the development of a qualitative FT with more detail against the availability of data for quantification. The quantification can be done with actual data or expert judgment. A detailed, qualitative FT may still have value to understand cause-effect relationships or to qualitatively assess hazards. Conversely, if more detailed FT events cannot be quantified because of a lack of data, such a level of detail is not useful for a quantitative risk assessment.

7.2 DATA QUALITY.

7.2.1 Coverage and Completeness of Different Data Sources Used in This Study.

7.2.1.1 The NTSB Data.

For accident and serious incident data, the NTSB database was used. This resulted in a dataset with good quality information (i.e., details of the sequence of events, the causal factors, and attention to different aspects of the accident). This information is useful for developing accident scenarios. Information on incidents is generally of low quality and depth. It is often difficult to draw conclusions on the sequence of events or causes of an accident in which the pilot was fatally injured. Helicopters are rarely equipped with flight data recorders or cockpit voice recorders, which represent additional challenges to incident and accident investigations, thus impacting the overall available accident and incident data.

7.2.1.2 Concern Network.

This voluntary reporting system was helpful in quantifying the IEs. The reported occurrences contain, in general, a short description of the sequence of events, but lack the details of the causal factors. Therefore, the reports have limited value for the development of IE FTs. The dataset was limited to HEMS operations. The level of underreporting is uncertain.

7.2.1.3 The ASRS.

The ASRS dataset was less useful than the Concern Network dataset because the number of applicable reports was small and the reports mostly contain information on the sequence of events with little or no details on the causal factors. The dataset also includes reports with general remarks about specific unsafe conditions from the viewpoint of the reporter. Such reports are not useful for model development and quantification because they consider, for example, specific circumstances, locations, ATC centers, routes, and type of helicopter, whereas the causal model is generic. The dataset that is available through the Internet does not contain information about the operation type.

7.2.1.4 The SDR.

The SDR dataset is useful to estimate system failure probability. A drawback is that the type of operation is unknown and the narrative contains little operational information. The SDR dataset uses ATA codes and modifiers to classify system failures, which requires interpretation by the research team to match the SDR occurrences with system failure events in FTs.

7.2.2 Data Quality and Quantification.

Good quality data on accidents are available for HEMS and tour operations from the NTSB. Therefore, the probability estimates of the end states representing an accident or serious incident outcome (e.g., collision with ground) are considered to be representative and reliable.

The initiating and pivotal events probabilities and the FT events probabilities should be considered as rough order-of-magnitude estimates. A significant limitation in the quantification was the limited amount of information, in particular a lack of details on causes, contributing factors or circumstances, in the analyzed occurrence data. The data to quantify these events are based on voluntary reports with expected underreporting and reporting bias (some occurrences more likely to be reported than others). For HEMS, the dataset is of better quality and contains more information, as provided by the Concern Network. For tour operations, occurrence data are scarce and the only source that can be used is ASRS. It is time-consuming to analyze the occurrence data because the analyst has to read the narrative to understand the event and to classify the event by accident scenario and model event.

7.3 USE OF THE CURRENT MODEL.

Section 2 explained the general application areas of a causal model. In this section, the potential use of the current rotorcraft causal model in the short term is addressed.

7.3.1 The Qualitative Model Supports Safety Analysis.

The qualitative model (i.e., the ESD and FT diagrams) can be used by a team of safety analysts and operational SMEs for safety assessment and risk mitigation. The model visualizes accident scenarios, hazards, and safety barriers; this is a starting point to gain a further understanding of accident and incident scenarios. The model will enhance the understanding of the safety issues and cause-effect relationships. The model provides a basis for safety assessment and mitigation based on integrated data analysis and knowledge.

7.3.2 Assessment of Changes to the Aviation Systems.

The impact of changes to the current aviation system, such as operational improvements under NextGen, can be qualitatively evaluated with the model. The model provides a framework that can be used to identify, in a structured manner, where and how changes impact accident scenarios and, thus, influence accident risk.

The quantitative model enables the calculation of the change in accident probability as a result of a change in the probability of a model element through the quantified cause-effect structure. If the effect of a change on a model element can be quantified, then the effect of this change on accident probability can be assessed.

7.3.3 Quantified Model.

The quantification effort has resulted in three positive results:

1. The model can be used as a classification system to aggregate data from various repositories. The available accident, incident, and occurrence data were mapped on the accident scenarios and FTs, supporting a systematic data analysis.

2. The quantification effort made maximum use of existing data by integrating different datasets. This approach provides an integrated review of accident, incident, and

occurrence data. Most safety analyses consider a single data source by itself and do not integrate and analyze data from various sources in a structured manner. The added value of a causal model lies in the capability to correlate data in different areas and from different sources, to improve the aggregate understanding of the safety performance.

3. The quantified model supports the prioritization of accident scenarios and determination of the relative importance of hazards (i.e., model events) to the accident probability.

7.4 RESULTS OF BASIC ANALYSES.

Tables 85 through 88 show the ranking of accident scenarios for both HEMS and tour operations based on the estimated frequency of occurrence of the IEs (tables 85 and 87) and the cumulative probability of accident end states (tables 86 and 88). The estimation of the IE probability was based on a combination of accident, incident, and occurrence data, and in a handful of cases that included expert judgment as well. The quantification of the end states was done using the NTSB dataset. A scenario may have more than one end state that is related to a negative outcome (e.g., a collision with the ground or helicopter breakup, fatality, injury, or damage). The probabilities of the accident end states were aggregated per scenario for tables 86 and 88.

The added value of this approach of ranking (compared to a straightforward collection of accidents/incidents and ranking them in order of occurrence) is that this approach takes into account different types of data, data sources, and the corresponding exposure (flight hours).

Table 85. Ranking of Accident Scenarios Based on Frequency of Occurrence of the IE for HEMS Operations

Rank	Estimated Initiating Event Probability	HEMS Operations Accident Scenario (initiating event)
1	5.35E-05	R14: Loss of power
2	3.92E-05	R18: Structural failure in flight
3	2.37E-05	R13: Flight-control system failure
4	1.41E-05	R10: Deviation from safe flight path towards obstacle
5	1.19E-05	R16: Aircraft are positioned on collision course in flight
6	1.01E-05	R7: Fire onboard helicopter
7	6.75E-06	R9: Loss of visual reference in degraded visual environment
8	5.35E-06	R12: Flight instrument failure
9	4.92E-06	R8: Loss of situational awareness in degraded visual environment
10	3.58E-06	R17: Pilot judgment, decision, or action error
11	2.78E-06	R2: Helicopter handling by pilot inappropriate or handling impaired during takeoff
12	2.38E-06	R15: Helicopter enters adverse weather
13	1.59E-06	R6: Loss of tail rotor effectiveness

Table 85. Ranking of Accident Scenarios Based on Frequency of Occurrence of the IE for HEMS Operations (Continued)

Rank	Estimated Initiating Event Probability	HEMS Operations Accident Scenario (initiating event)
14	1.19E-06	R20: Improper approach/flare by pilot
	1.19E-06	R11: Pilot incapacitation
	1.19E-06	R21: Presence of person near helicopter with turning rotors
17	7.95E-07	R23: Helicopter enters ground resonance
---	Unknown	R3: Attempted flight with weight/CG outside limits
	Unknown	R5: Conflict on taxiway or runway area

Table 86. Ranking of Accident Scenarios Based on Cumulative Frequency of Occurrence of Accident End States per Scenario for HEMS Operations

Rank	Estimated Accident Probability	HEMS Operations: Accident Scenario (initiating event)
1	1.01E-05	R7: Fire onboard helicopter
2	6.36E-06	R14: Loss of power
3	4.26E-06	R8: Loss of situational awareness in degraded visual environment
4	3.18E-06	R17: Pilot judgment, decision, or action error
5	2.38E-06	R13: Flight control system failure
6	1.99E-06	R9: Loss of visual reference in degraded visual environment
7	1.59E-06	R6: Loss of tail-rotor effectiveness
8	1.19E-06	R20: Improper approach/flare by pilot
	1.19E-06	R10: Deviation from safe flight path towards obstacle
10	7.95E-07	R23: Helicopter enters ground resonance
	7.95E-07	R16: Aircraft are positioned on collision course in flight
	7.95E-07	R2: Helicopter handling by pilot inappropriate or handling impaired during takeoff
13	3.97E-07	R11: Pilot incapacitation
	3.97E-07	R15: Helicopter enters adverse weather
---	Unknown	R3: Attempted flight with weight/CG outside limits
	Unknown	R5: Conflict on taxiway or runway area
	Unknown	R12: Flight instrument failure
	Unknown	R18: Structural failure in flight
	Unknown	R21: Presence of person near helicopter with turning rotors

Table 87. Ranking of Accident Scenarios Based on Frequency of Occurrence of IE for Air Tour Operations

Rank	Estimated Initiating Event Probability	Tour Operations: Accident Scenario (initiating event)
1	5.32E-05	R14: Loss of power
2	2.64E-05	R18: Structural failure in flight
3	2.37E-05	R13: Flight control system failure
4	5.35E-06	R12: Flight instrument failure
5	3.72E-06	R7: Fire on board helicopter
6	3.07E-06	R10: Deviation from safe flight path towards obstacle
7	2.34E-06	R16: Aircraft are positioned on collision course in flight
8	1.17E-06	R6: Loss of tail rotor effectiveness
	1.17E-06	R17: Pilot judgment, decision, or action error
	1.17E-06	R3: Attempted flight with weight and/or cg outside limits
11	7.37E-07	R8: Loss of situational awareness in degraded visual environment
12	5.84E-07	R9: Loss of visual reference in degraded visual environment
	5.84E-07	R2: Helicopter handling by pilot inappropriate or handling impaired during takeoff
	5.84E-07	R15: Helicopter enters adverse weather
	5.84E-07	R20: Improper approach/flare by pilot
	5.84E-07	R21: Presence of person near helicopter that has turning rotors
	5.84E-07	R23: Helicopter enters ground resonance
---	Unknown	R5: Conflict on taxiway or runway area
	Unknown	R11: Pilot incapacitation

Table 88. Ranking of Accident Scenarios Based on Cumulative Frequency of Occurrence of Accident End States per Scenario for Air Tour Operations

Rank	Estimated Accident Probability	Tour Operations: Accident Scenario (initiating event)
1	4.09E-06	R14: Loss of power
2	1.99E-06	R13: Flight control system failure
3	1.75E-06	R10: Deviation from safe flight path towards obstacle
4	1.17E-06	R16: Aircraft are positioned on collision course in flight
	1.17E-06	R3: Attempted flight with weight/CG outside limits
	1.17E-06	R6: Loss of tail-rotor effectiveness
	1.17E-06	R17: Pilot judgment, decision, or action error
8	6.62E-07	R8: Loss of situational awareness in degraded visual environment
9	5.84E-07	R2: Helicopter handling by pilot inappropriate or handling impaired during takeoff
	5.84E-07	R15: Helicopter enters adverse weather
	5.84E-07	R18: Structural failure in flight
	5.84E-07	R20: Improper approach/flare by pilot
	5.84E-07	R21: Presence of person near helicopter that has turning rotors
---	Unknown	R5: Conflict on taxiway or runway area
	Unknown	R7: Fire onboard helicopter
	Unknown	R9: Loss of visual reference in degraded visual environment
	Unknown	R11: Pilot incapacitation
	Unknown	R12: Flight instrument failure
	Unknown	R23: Helicopter enters ground resonance

7.5 MAPPING OF FUNCTIONS TO THE ROTORCRAFT CAUSAL MODEL.

Section 6 explained the mapping of Part 135 certificate holder critical functions to the rotorcraft causal model. The three following issues should be taken into consideration:

1. If a single function is mapped to multiple ESDs, it does not mean that this function has the same impact on every scenario. For example, the function “A4 Perform Personnel Training” could be mapped to all ESDs. If a certificate holder would improve its autorotation training as part of this function, the improved training would impact the ESD related to engine failure only, because that is the ESD for which autorotation plays a role. Other ESDs with a relation to the function “A4 perform personnel training” will not be affected by autorotation training. For instance, the ESD related to attempted takeoff with weight and balance outside limits will not be affected by autorotation training.

With the current level of detail in the Part 135 certificate holder functional model, it is difficult to assess the impact of the functions or a change of the functions. If the user needs to assess the impact of specific or safety-critical activities, the functions need to be developed into more detail, defining those specific activities. Subsequently, these detailed functions need to be mapped to rotorcraft causal model base events, not ESDs.

2. Mapping functions to ESDs leads to an overestimation of the weight of a function. The preferred mapping is: (sub)functions to base events of the ESDs. For example, the function "A.1.3.2.7 assign crew members" is related to every ESD. This function schedules and assigns crew members to perform specific flight tasks. Some examples include flight and duty time; crew member qualifications; and special requirements for medical staff. This function may have an effect on flight crew fatigue or flight crew skills, for example, which, in turn, may impact the probability of a pilot handling error or a pilot decision-making and judgment error. In the current mapping, this function was allocated to every ESD because all ESDs include one or both errors as part of the IE FT or the pivotal event FT.

   When mapping this function to the ESD, the IE probability is used as weight factor for this function, whereas it would be more appropriate to use as weight factor the probability of occurrence of only the base event(s) affected by this function. For example, consider the FT of the IE "engine malfunction or loss of power" (see figure 46). The function "assign crew members" may affect events R14a112, R14a13212, R14a13213, and R14a1322. The cumulative probability of occurrence of the four base events is $3.93 \cdot 10^{-6}$ per flight hour for HEMS and tour operations combined (see table 52). This weight factor is better than using the IE probability of ESD R-14: $1.07 \cdot 10^{-4}$ per flight hour for HEMS and tour operations combined.

   To be able to determine the associated accident probability and conditional probability of a base event leading to an accident end state, it is required that the number (or rate) of accidents caused by this particular base event be determined. The conditional probability of a set of base events leading to an accident end state can be estimated by dividing the probability of an accident caused by this set of base events by the probability of occurrences of the set of base events. In the current study, the NTSB dataset shows the number of accidents as a result of a particular base event. In the NTSB dataset, 28 accidents for ESD R-14 were found, which included one with an unknown cause. For each of the 27 accidents, the applicable base event has been determined. This can be used to estimate an accident rate per base event (see table 89). The occurrence rate for each base event was estimated based on historical data as well. These two results make it possible to estimate the conditional probability that the set of base events will result in an accident. The cumulative probabilities for the four events R14a112, R14a13212, R14a13213, and R14a1322 affected by the function "assign crew members" are aggregated for HEMS and tour operations.

   The accident rate associated with this set of base events is $1.42 \cdot 10^{-6}$ per flight hour. The occurrence rate of this set of base events is $3.93 \cdot 10^{-6}$ per flight hour. Hence, the

conditional probability for this set of base events leading to an accident is 0.361. These three weight factors can be used to rank the function.

Table 89. Example of Event Probabilities for Weight Factor Calculation (per flight hour)

Base Event Name	Base Event Code	Accidents (NTSB)	Accident Rate by Base Event	Occurrence Rate by Base Event
Pilot error in operation of engine controls	US-R14a112	3	$7.09 \cdot 10^{-7}$	$1.19 \cdot 10^{-6}$
Pilot selects wrong fuel tank, resulting in insufficient fuel	US-R14a13212	0	0	0
Pre-flight or in-flight planning error resulting in insufficient fuel	US-R14a13213	3	$7.09 \cdot 10^{-7}$	$2.73 \cdot 10^{-6}$
Pilot does not detect rotorcraft running out of fuel	US-R14a1322	3 (*)	N/A	N/A
Cumulative probability of base events			$1.42 \cdot 10^{-6}$	$3.93 \cdot 10^{-6}$
Conditional probability of base events resulting in an accident			0.361	
(*) this event occurred in NTSB data by definition when US-R14a13212 and US-R14a13213 occurred.				

3. Mapping functions to the base events of the ESDs provides a more representative ranking. The set of 51 Part 135 certificate-holder functions was mapped to the base events of the initiating and pivotal event FTs of ESD R-14 (loss of power) for illustration purposes. The mapping of functions to base events adds value compared to the mapping of functions to ESDs because it shows the analyst which base events in the causal model are affected by a particular function and it explains where or how a function enters an accident scenario. However, because the current functions are generic, the mapping of a function with a base event provides little insight into how, why, or when that particular function influences that base event. A practical problem is that, for each function, it requires much effort to describe and explain the reason for mapping (or not mapping) a function to a particular base event.

8. RECOMMENDATIONS.

8.1 EXPANDING THE MODEL SCOPE AND DEPTH.

The current model was developed for HEMS and tour operations. It is recommended that the scope of the model be expanded and that the ESDs and FTs be further developed to include other types of operations.

The FTs may be further decomposed, which would provide more insight into specific causal factors and would also help integrate the functional model with the causal model elements. The FAA and model developers need to balance the development of a qualitative FT with more details against the availability of data for model quantification. It is recommended that all available data, such as different data sources, different types of data, level of detail, and scope of data be considered before FT development starts. A proper definition and selection of base events during FT development is an important factor for successful quantification.

Review of the current set of FTs in light of available data is recommended to identify areas for improvement. The research team believes the quantification of the FTs can be improved, not only by considering other approaches in the quantification process itself, but also by improving the FT diagrams (definition of events and structure).

8.2 QUANTIFICATION.

For many FT events in the current rotorcraft causal model, data is limited or absent in the datasets used. To improve the quantification of these events, the following actions can be taken:

- Using expert judgment to estimate event probability.
- Expanding the timeframe of the datasets so that more data become available.
- Using a combination of HEMS and tour operations data for the entire model, no longer making a distinction between HEMS and tour operations. A second option is estimating an event probability based on a combination of HEMS and tour operations data for those events that are not dependent on the type of operation.
- Using other data sources for the quantification of certain FT events; other data sources may be available. The current quantification is based on accident, incident, and occurrence data only. For example, weather data, operational data, and equipage data could be used to support quantification of related events.
- Using operator data and expertise to quantify model elements. For example, HEMS and tour operators could be approached with a request to participate in a voluntary reporting campaign, a dedicated data-collection campaign, or for expert judgment elicitation in support of model development and quantification.

It is proposed that the model quantification be expanded to cover all helicopter operations in the U.S. (training, external load, oil rig transport, etc.). Expanding the scope so that the model can be populated with more data could produce interesting results applicable to all helicopter operations. Further quantification could show gaps in the model, the filling of which would be worthwhile as well. The current causal model should first be reviewed to evaluate its completeness and the coverage of all types of operations. Additional ESDs and FTs may need to be developed for other types of rotorcraft operations before the quantification scope can be expanded.

8.3 IMPROVE DATA COLLECTION.

The main reason to report incidents and occurrences is to be able to use the acquired knowledge to prevent accidents and serious incidents. Therefore, it is necessary to determine causal relationships between incidents and accidents. Hence, the type of information collected for an incident should be similar to that collected for an accident.

Data on operational and causal factors in incidents and occurrences were generally not available in the datasets used in this study. Data of good quality are required, especially for the causal model base events. Once the base events can be reliably quantified, the rest of the model can be quantified bottom-up with the FT logic. The quantified model is useful for identifying the data needed. The FAA needs to adopt the model as a formal analytical tool and then drive data collection. It is recommended that data-collection programs and reporting forms consider the model elements (e.g., FT base events) as reportable events to enable population of the model with occurrence data. Because many organizations are collecting data, feedback from the causal model to the source collectors (e.g., about the required data and gaps in the current data collection) could result in better data collection and better quality data, while also improving the model.

It is recommended that the Concern Network encourage EMS professionals to report occurrences in more detail and provide a reporting form that allows them to report on relevant operational circumstances and causal factors. The reporting form should use the causal model elements as reporting fields to support the further development and quantification of the current model.

8.4 FURTHER DEVELOPMENT OF PART 135 CERTIFICATE HOLDER FUNCTION MODEL.

The functions in the Part 135 certificate holder functional model should be developed in more detail, specifying safety-critical tasks or activities, to provide sufficient granularity and to enable the analyst to assess the impact of specific functions or specific changes to functions on events in the rotorcraft causal model ESDs.

8.5 MAPPING OF FUNCTIONS TO BASE EVENTS OF THE CAUSAL MODEL.

The mapping of Part 135 certificate holder functions to the base events of the rotorcraft causal model is recommended. This approach provides added value compared to the mapping of functions to ESDs only because it shows the analyst where or how functions possibly impact accident scenarios. The functional model should be developed in more detail, possibly in conjunction with further development of the rotorcraft causal model FTs, before a mapping at the base event level can be undertaken.

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APPENDIX A—DEFINITIONS

A.1. DEFINITIONS.

This appendix provides the ICAO and NTSB definitions of accident, as well as definitions for other flight operation terms.

A.1.1 International Civil Aviation Organization Definition of Accident.

In this study, the International Civil Aviation Organization (ICAO) definition of an accident is used, which is summarized as follows:

Accident: An occurrence associated with the operation of an aircraft, which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, and:

- A person is fatally or seriously injured as a result of:
  - being in the aircraft, or
  - direct contact with any part of the aircraft, including parts that have become detached from the aircraft, or
  - direct exposure to jet blast,
  - (except when the injuries are from natural causes; self-inflicted or inflicted by other persons; or when the injuries are to stowaways hiding outside the areas normally available to the passengers and crew); or
- The aircraft sustains damage or structural failure, which:
  - adversely affects the structural strength, performance, or flight characteristics of the aircraft, and
  - would normally require major repair or replacement of the affected component (except for engine failure or damage when the damage is limited to the engine, its cowlings, or its accessories; or for damage limited to propellers, wing tips, antennas, tires, brakes, fairings, or small dents or puncture holes in the aircraft skin); or
- The aircraft is missing or is completely inaccessible.

A.1.2 National Transportation Safety Board Definition of Accident.

There are some minor differences in the definitions adopted by ICAO and those used by the National Transportation Safety Board (NTSB). The definitions used by the NTSB are defined in

49 Code of Federal Regulations Part 830 (Notification and Reporting of Aircraft Accidents or Incidents and Overdue Aircraft, and Preservation of Aircraft Wreckage, Mail, Cargo, and Records). The NTSB defines accident, serious injury, and substantial damage as follows:

- Aircraft accident means an occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage.

- Serious injury means any injury that: (1) Requires hospitalization for more than 48 hours, commencing within 7 days of the date the injury was received; (2) results in a fracture of any bone (except simple fractures of fingers, toes, or nose); (3) causes severe hemorrhages, nerve, muscle, or tendon damage; (4) involves any internal organ; or (5) involves second- or third-degree burns, or any burns affecting more than 5 percent of the body surface.

- Substantial damage means damage or failure that adversely affects the structural strength, performance, or flight characteristics of the aircraft, and which would normally require major repair or replacement of the affected component. Engine failure or damage limited to an engine if only one engine fails or is damaged, bent fairings or cowling, dented skin, small punctured holes in the skin or fabric, ground damage to rotor or propeller blades, and damage to landing gear, wheels, tires, flaps, engine accessories, brakes, or wingtips is not considered substantial damage for the purpose of this part.

The definition of accident used by NTSB is generally consistent with the ICAO definition of an accident, although ICAO does use and define the term "substantial damage." The ICAO includes under serious injury "verified exposure to infectious substances or injurious radiation," whereas NTSB does not. These differences do not affect the outcome of this research study.

A.1.3 Hover.

"During hovering flight, a helicopter maintains a constant position over a selected point, usually a few feet above the ground. For a helicopter to hover, the lift and thrust produced by the rotor system act straight up and must equal the weight and drag, which act straight down" [A-1].

A.1.4 Autorotation.

"Autorotation is the state of flight where the main rotor system is being turned by the action of relative wind rather than engine power. It is the means by which a helicopter can be landed safely in the event of an engine failure. In this case, you are using altitude as potential energy and converting it to kinetic energy during the descent and touchdown. All helicopters must have this capability in order to be certified" [A-1].

Ground Resonance.

"Ground resonance is an aerodynamic phenomenon associated with fully articulated rotor systems. It develops when the rotor blades move out of phase with each other and cause the rotor disc to become unbalanced. This condition can cause a helicopter to self-destruct in a matter of seconds. However, for this condition to occur, the helicopter must be in contact with the ground" [A-1].

"For ground resonance to occur, there must be some abnormal lead/lag blade condition that would dynamically unbalance the rotor. This condition may be present in the rotor head in the form of unbalanced blades, incorrect tracking or faulty lead-lag dampers, or may be the result of a hard landing, which can cause a shock to be transmitted to the main rotor system, forcing the blades out of phase. In either case, an unbalanced rotor system causes an unusual vibration that is further aggravated when ground contact, and especially light contact, is made. This can be during lift-off when the helicopter is light on its skids or during landing. In order to reduce the chance of ground resonance, helicopters with fully articulated rotor systems usually have landing gear dampers or oleos to dampen vibrations when on the ground. However, oleos with uneven or low pressures may contribute to ground resonance by not providing even damping" [A-2].

A.1.6 Hazard.

A hazard is an event or a condition that can lead to an unsafe and unwanted outcome or that can hamper the resolution (mitigation) of an unsafe situation.

A.1.7 Risk.

The risk of an event is the combination of the severity level of the event and the likelihood of that severity level.

A.2. REFERENCES.

A-1. Rotorcraft Flying Handbook, FAA, FAA-H-8083-21, 2000.

A-2. Agave, C. and Li, H., Part 135 Certificate Holder Functional Model, FAA AJP-6350, William J. Hughes Technical Center, January 30, 2009.

APPENDIX B—DEFINITION OF FLIGHT PHASES

In this study, the definition of flight phases is presented in table B-1. For the model development, the following flight phases will be considered:

- Standing
- Taxi
- Takeoff
- En route (includes climb, cruise, descent, hover)
- Approach and landing (combined into one phase)

For the model, the quantification is not specified according to phase of flight; probabilities of model elements are expressed as "per flight" or "per flight hour."

The term "runway" includes runways, landing strips, waterways, unimproved landing areas, and landing pads, which may include offshore platforms, building roofs, roads, ships, and fields, or other intended landing areas (from CAST/ICAO Common Taxonomy Team definition).

Table B-1. Phase of Flight Definitions Adapted for Helicopter Causal Model (Reprinted from [B-1])

Standing	Prior to pushback or taxi, or after arrival at the gate, ramp, or parking area (helipad, helideck, remote location, etc.), while the helicopter is stationary.
Pushback/towing	Helicopter is moving at the gate, ramp, or parking area, assisted by a tow vehicle.
Taxi	The helicopter is moving on the aerodrome surface under its own power prior to takeoff or after landing, including air taxiing.
Takeoff	From the application of takeoff power through rotation and to an altitude of 35 feet above runway elevation. Land back during rotorcraft operations is considered a rejected takeoff. The takeoff phase for rotorcraft operations can include rearward flight of the helicopter. For rotorcraft operations, takeoff is also subject to the achievement of a positive climb gradient and of an appropriate takeoff safety speed determined with the Helicopter Flight Manual. Including running takeoff, vertical takeoff, and transition from hover to forward flight.
En-route, including initial climb and descent	From the end of the takeoff subphase to the first prescribed power reduction, or until reaching 1000 feet above runway elevation or the VFR pattern, whichever comes first. From completion of initial climb through cruise altitude and completion of control to the IAF [IFR] or to completion of the controlled descent to the VFR pattern or 1000 feet above runway elevation [VFR], whichever comes first. Including emergency descent/autorotation during the en-route phase of flight.

Table B-1. Phase of Flight Definitions Adapted for Helicopter Causal Model (Reprinted from [B-1]) (Continued)

Maneuvering	Aerobatics: Any intentional maneuvering that exceeds 30 degrees of pitch attitude or 60 degrees of bank, or both, or abnormal acceleration (usually associated with air shows and military flight, or with related training flights). Low altitude operations: intentional low-altitude flight not connected with a landing or takeoff, usually in preparation for or during observation work, demonstration, photography work, aerial application, training, sightseeing, ostentatious display, or other similar activity. This also includes hovering not associated with landing or takeoff and handling external loads. Includes practice autorotation.
Approach	From the IAF [IFR] to the beginning of the landing flare or from the point of VFR pattern entry, or 1000 feet above runway elevation, to the beginning of the landing flare [VFR]. Includes transition forward flight to hover.
Landing	From the beginning of the landing flare until helicopter exits the landing runway or comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing. For rotorcraft, includes both vertical and running landings.
Unknown	An event involving a phase of flight of the helicopter that is unknown or not recorded.

IAF = Initial approach fix; IFR = instrument flight rules; VFR = visual flight rules

REFERENCE.

B-1. "Phase of Flight, Definitions and Usage Notes," ICAO CAST, CICCTT (1.1), October 2011.

APPENDIX C—DATA SOURCES

C.1. NTSB DATABASE.

The NTSB aviation accident database [C-1] contains information from 1962 and later about civil aviation accidents and severe incidents within the United States, in its territories and possessions, and in international waters. Generally, a preliminary report is available online within a few days of an accident. Factual information is added when available; when the investigation is completed, the preliminary report is replaced with a final description of the accident or incident and its probable cause.

C.2. CONCERN NETWORK.

According to its website, the CONCERN Network [C-2] was started in 1984 by the National Flight Nurses Association (now, the Air & Surface Transport Nurses Association) as a simple telephone tree; the CoOperative Network Call for Emergency Regional Notification was envisioned as a mechanism to alert the air medical community about situations in which crewmembers had been injured or killed in helicopter or airplane crashes. In the ensuing 20 years, CONCERN has evolved through various incarnations to serve as a means of collecting and distributing information about a variety of air-medical and critical-care ground-transport mishaps.

The purpose of the CONCERN Network is to increase awareness of safety hazards in the medical transport community. Individual air-medical and critical-care transport providers can subscribe to receive bulletins via email. Transport service administrators can submit information about an accident or incident via the Report an Accident/Incident page. Transport crew members can submit anonymous HARP reports via the HARP page.

The Concern Network provides archives with records submitted by personnel (air medical) regarding accidents and incidents in the air-medical and critical-care transport community from 2001 through 2012. The records contain a varying degree of information on the aircraft type, tail number, operator, type of operation, weather, and persons involved. Each record contains a narrative of the incident or occurrence. The reports are anonymous.

C.3. AVIATION SAFETY REPORTING SYSTEM DATABASE.

On the National Aeronautical and Space Administration (NASA) Aviation Safety Reporting System (ASRS) website [C-3], the following explanation is provided on the ASRS program:

> "The ASRS is an important facet of the continuing effort by government, industry, and individuals to maintain and improve aviation safety. The ASRS collects voluntarily submitted aviation safety incident/situation reports from pilots, controllers, and others. The ASRS acts on the information these reports contain. It identifies system deficiencies and issues alerting messages to persons in a position to correct them. It educates through its newsletter 'CALLBACK,' its journal *ASRS Directline*, and through its research studies. Its database is a public repository, which serves the Federal Aviation Administration's (FAA) and NASA's needs and those of other organizations worldwide

that are engaged in research and the promotion of safe flight. The ASRS collects, analyzes, and responds to voluntarily submitted aviation safety incident reports in order to lessen the likelihood of aviation accidents.

The ASRS data are used to:

- Identify deficiencies and discrepancies in the National Airspace System (NAS) so that these can be remedied by appropriate authorities.

- Support policy formulation and planning for, and improvements to, the NAS.

- Strengthen the foundation of aviation human factors safety research. This is particularly important since it is generally conceded that over two-thirds of all aviation accidents and incidents have their roots in human performance errors."

C.4. SERVICE DIFFICULTY REPORT DATABASE.

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

The FAA SDR program has been criticized in the past [C-3]. Some of the criticism is irrelevant for the purpose of this study. However, one of the points of criticism is underreporting, which 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 the FAA. Differences among various airlines' reporting practices would diminish the quality of the data because they would not reflect the actual occurrence of mechanical malfunctions.

The SDR data is not limited to U.S. airlines only; there are some Canadian and Australian carriers that also provide SDR reports.

For more information, refer to http://av-info.faa.gov/dd_sublevel.asp?Folder=\SDRS and http://av-info.faa.gov/sdrx/Query.aspx

C.5 REFERENCES.

C-1. The NTSB Aviation Accident Database. http://www.ntsb.gov/aviationquery/index.aspx (accessed on August 6, 2014)

C-2. The CONCERN Network. http://www.concern-network.org/ (accessed on August 6, 2014)

C-3. Rotorcraft Flying Handbook, FAA, FAA-H-8083-21, 2000.

APPENDIX D—EXPOSURE DATA

Exposure data on rotorcraft flight hours for helicopter emergency medical services (HEMS) and air tour operations were collected through the Federal Aviation Administration (FAA). Tables D-1 and D-2 summarize the number of flight hours for the period 2005-2010.

Table D-1. Exposure Data in Flight Hours for HEMS and Air Tour Rotorcraft Operations

Rotorcraft	Air Medical			Air Tour	
	2005-2010	2005-2010		2005-2010	2005-2010
	Part 91	Part 135		Part 91	Part 135
Piston	2,157	2,189		159,585	41,118
Turbine	283,433	2,229,018		124,413	1,387,086
One Engine	151,977	1,131,220		122,984	1,348,075
Multi-Engines	131,455	1,097,803		1,428	39,009
Total rotorcraft	285,590	2,231,208		283,997	1,428,205
Total rotorcraft 91&135	2,516,798			1,712,202	

In addition, exposure for all rotorcraft operations under Parts 91 and 135 was collected from the FAA website. The FAA conducts a survey to collect information on general aviation and on-demand Part 135 aircraft activity. Based on the data in table 1.4 in "General Aviation and Air Taxi Total Hours Flown by Actual Use by Aircraft Type" for 2005 through 2010, the total number of flight hours for rotorcraft was determined [D-1].

Table D-2. Summary of Total Flight Hours for Rotorcraft Operations Between 2005-2010

Rotorcraft	2010-2005
	Part 91 & 135
Piston	4,488,807
Turbine	15,130,630
One Engine	11,734,541
Multi-Engine	3,396,089
Total Rotorcraft	19,619,437

D.1 REFERENCE.

D-1. General Aviation and Part 135 Activity Surveys, http://www.faa.gov/data_research/aviation_data_statistics/general_aviation/ (accessed on August 6, 2014)

APPENDIX E—RESULTS OF MAPPING FUNCTIONS TO THE ESDs

Table E-1. Functions Ranked by Initiating Event Probability (HEMS and tour operation aggregate probabilities)

Code	Function	Number of Matching ESDs	Initiating Event Probability (weight factor 1)	Cumulative Accident Probability (weight factor 2)	Conditional Probability of Accident (weight factor 3)
A1.1	Manage Certificate Holder Functions	19	3.10E-04	5.15E-05	1.66E-01
A1.3.2	Plan Flight Segments	19	3.10E-04	5.15E-05	1.66E-01
A1.3.2.7	Assign Crewmember(s)	19	3.10E-04	5.15E-05	1.66E-01
A1.5	Develop Certificate Holder Policies & Procedures	19	3.10E-04	5.15E-05	1.66E-01
A1.5.1	Coordinate Certificate Holder Policy & Procedure Development	19	3.10E-04	5.15E-05	1.66E-01
A1.5.3	Develop Operation Policies & Procedures	19	3.10E-04	5.15E-05	1.66E-01
A1.5.4	Develop Training Policies & Procedures	19	3.10E-04	5.15E-05	1.66E-01
A1.5.2.2	Collect & Process Operational Data	19	3.10E-04	5.15E-05	1.66E-01
A1.5.3.3	Develop & Evaluate Operations Policies & Procedures	19	3.10E-04	5.15E-05	1.66E-01
A2	Perform Air Transportation	19	3.10E-04	5.15E-05	1.66E-01
A4	Perform Personnel Training	19	3.10E-04	5.15E-05	1.66E-01
A4.3	Design & Develop Training	19	3.10E-04	5.15E-05	1.66E-01
A4.4	Implement and Record Training	19	3.10E-04	5.15E-05	1.66E-01
A4.5	Evaluate Training	19	3.10E-04	5.15E-05	1.66E-01
A1.3.4	Perform Maintenance Control	12	2.95E-04	4.25E-05	1.44E-01
A1.5.2	Develop Maintenance Policies & Procedures	12	2.95E-04	4.25E-05	1.44E-01
A1.5.2.3	Perform Technical Evaluation	12	2.95E-04	4.25E-05	1.44E-01
A1.5.2.4	Apply Approved Inspection and Maintenance Program	12	2.95E-04	4.25E-05	1.44E-01
A3	Perform Aircraft Maintenance, Inspection and Engineering	12	2.95E-04	4.25E-05	1.44E-01
A3.2	Perform Surveillance of Maintenance	12	2.95E-04	4.25E-05	1.44E-01
A3.2.2	Perform Quality Assurance	12	2.95E-04	4.25E-05	1.44E-01
A3.2.2.2	Monitor Mechanical Performance	12	2.95E-04	4.25E-05	1.44E-01
A3.2.2.3	Perform Maintenance Program Audit/Investigation	12	2.95E-04	4.25E-05	1.44E-01
A3.2.2.4	Analyze Quality Data & Develop Responses	12	2.95E-04	4.25E-05	1.44E-01
A3.2.2.5	Perform QA Administrative Function	12	2.95E-04	4.25E-05	1.44E-01
A3.2.3	Perform Quality Control	12	2.95E-04	4.25E-05	1.44E-01

Table E-1. Functions Ranked by Initiating Event Probability (HEMS and tour operation aggregate probabilities) (Continued)

Code	Function	Number of Matching ESDs	Initiating Event Probability (weight factor 1)	Cumulative Accident Probability (weight factor 2)	Conditional Probability of Accident (weight factor 3)
A3.3	Perform Aircraft Maintenance	12	2.95E-04	4.25E-05	1.44E-01
A3.3.2	Evaluate Aircraft	12	2.95E-04	4.25E-05	1.44E-01
A3.3.3	Perform Scheduled/ Nonscheduled Maintenance	12	2.95E-04	4.25E-05	1.44E-01
A3.4	Obtain Engineering Support	12	2.95E-04	4.25E-05	1.44E-01
A1.3.2.3	Plan Flight Routes	6	1.43E-04	2.40E-05	1.69E-01
A2.5.2.2	Perform Predeparture Ground Operations	9	1.42E-04	1.48E-05	1.04E-01
A2.4.6	Perform Deicing/Anti-Icing Program	3	1.27E-04	1.48E-05	1.16E-01
A2.4	Perform Ground Operations	3	1.11E-04	1.30E-05	1.17E-01
A1.3.2.5	Perform Load/Fuel Planning	2	1.08E-04	1.16E-05	1.08E-01
A2.4.4	Replenish Fuel	1	1.07E-04	1.04E-05	9.79E-02
A2.3	Perform Passenger Services	3	8.12E-05	1.13E-05	1.39E-01
A2.3.4	Perform In-Flight Services	2	7.95E-05	1.07E-05	1.35E-01
A1.3.2.2	Evaluate Weather	5	2.05E-05	1.24E-05	6.06E-01
A2.4.3	Perform Cargo Handling	2	1.50E-05	1.13E-05	7.52E-01
A2.4.3.2	Check/Weigh/Accept Cargo	2	1.50E-05	1.13E-05	7.52E-01
A1.3.2.4	Accept Payload	1	1.17E-06	1.17E-06	1.00E+00
A1.3.3	Dispatch Aircraft	0	0.00E+00	0.00E+00	N/A
A2.5	Perform Aircraft Operations	0	0.00E+00	0.00E+00	N/A
A2.5.2	Perform Departure Operations	0	0.00E+00	0.00E+00	N/A
A2.5.2.3	Perform Takeoff Operations	0	0.00E+00	0.00E+00	N/A
A2.5.3	Perform Enroute Operations	0	0.00E+00	0.00E+00	N/A
	Perform Maneuvering Operations	0	0.00E+00	0.00E+00	N/A
A2.5.4	Perform Arrival Operations	0	0.00E+00	0.00E+00	N/A
A2.5.4.3	Perform Approach Operations	0	0.00E+00	0.00E+00	N/A
A2.5.4.4	Perform Landing Operations	0	0.00E+00	0.00E+00	N/A