An Analysis of the Role of Safety Nets in the National Airspace System

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Abstract

Safe operations of aircraft in the National Airspace System (NAS) may be attributed to many factors, including the application of a variety of safety nets (SNs) as a last line of defense. In preparation for the Next Generation Air Transportation System (NextGen), a review of Aviation Safety Reporting System (ASRS) reports for incidents with positive outcomes was conducted to investigate the importance of current safety nets. The examination of positive outcomes not only shows what went wrong, but also what went right to prevent accidents and "save the day." More than 400 incident reports for 2015 from the voluntary ASRS reporting database were studied in detail to create event sequence diagrams (ESDs), illustrating the effectiveness of SNs. The developed ESDs are considered top-level, representative models and are limited with respect to being reliably quantitative because they are based on only reports from a single year. The ESDs could offer insights into human systems integration research, such as strategically using technologies as SNs without human interface or alleviating human workload with new technologies to provide resilient recovery from off-nominal conditions ensuring flight safety.

Introduction

With years of persistent efforts analyzing accidents and incidents and taking safety measures, the U.S. National Airspace System (NAS) has remained one of the safest in the world, especially for commercial aviation (Dorr, 2017). Safety net (SN) technologies and techniques, combined with other lines of defense such as safety procedural rules, regulations, and redundancies in design, are largely responsible for the historical safety record of the NAS. In the aviation domain, these lines of defense are built into the processes to prevent individual failures. Consequently, a complete failure would only happen if individual breakdowns in all available lines of defense occur, which is analogous to Reason's Swiss Cheese Model (Reason, 1997).

Safety nets are typically the last line of defense for a failure prior to producing an accident. However, in order to maintain or improve the current level of safety, NASA's Aeronautics Research Mission Directorate (ARMD) intends to approach aviation safety concerns more proactively instead of reactively, especially considering the new generation of aircraft fleets in the Next Generation Air Transportation System (NextGen). This approach, which includes examining successful mitigations, will further promote the accident preventative technology development, including safety nets.

With a decrease in the number of accidents over the years, there is an increasing desire to investigate incidents, which are still frequent. The investigation of incidents provides insights on the causal relationships in order to develop next-generation safety technologies to ensure flight safety. Given that incidents and accidents share many of the same causal factors, incidents can be considered as precursors to potential accidents. The Aviation Safety Reporting System (ASRS)

database of voluntary, confidential reports from various sources, including maintenance workers, air traffic controllers, and flight crews, is employed for the collection of the incident reports. In order to utilize these reports to influence safety, one must collect the data and project them in a more meaningful way. Many Event Sequence Diagrams (ESDs) were developed to show the progression of events that occur leading to an outcome. ESDs can be used to show the benefit of safety nets in the NAS that appear in the reports from the ASRS. In addition, the ESDs may assist in identifying safety gaps that currently exist in the NAS for the development of future SNs.

Overview

Positive Taxonomy

In order to aid the use of aviation accident and incident reporting systems, common aviation terminologies and definitions have been established by the Commercial Aviation Safety Team (CAST)/International Civil Aviation Organization (ICAO) Common Taxonomy Team (CICTT), which is composed of several entities ranging from manufacturers to pilots (CAST/ICAO, 2017). The resulting series of common taxonomies help create consistency among reports, allow keyword queries for easier data collection, and improve the quality of information and communication.

In 2011, the CICTT developed a positive taxonomy document that classifies both technical and human factors safety nets (CAST/ICAO, 2013). The positive taxonomy document includes definitions and categories for decisions, external interventions, and soft safety nets that help in avoiding an accident or contribute to limiting the consequences. For instance, a safety net or external intervention will generally lead to a maneuver, from the decision category, in order to return to nominal flight conditions. A safety net is a technology or human/operator action that supports safe operations within the aviation domain by being the last line of defense prior to a failure. Safety nets can be separated into two categories, hard and soft. A hard safety net is equipment-based technology, typically an airborne or ground-based warning system that can detect a problem and potentially suggest a solution to the situation. A hard safety net can be further classified into commercial, military, and general aviation categories. In contrast, soft safety nets represent human-based attributes such as the accurate usage of documentation, communications, or logical problem solving skills.

For this study, commercial aviation hard safety nets were the main focus in conjunction with the soft safety nets and decisions from the CAST/ICAO document (CAST/ICAO, 2013). The development of the positive taxonomy provides a way for the safety nets to be searched in the accident and incident reports in order to show the effectiveness of safety nets in the NAS. The positive taxonomy can also support the classification of incidents, which can aid in finding new accident precursors by placing more emphasis on causal factors instead of just the consequences (Stephens, 2008). In an incident report review, the positive taxonomy can assist in discovering successful safety net intervention, allowing the data collection to not only include the undesirable sequence of events but also the actions to prevent a serious incident or accident. This technique of research offers a proactive prevention of accidents and incidents instead of reactive.

Aviation Safety Reporting System

Figure 1 shows the total and fatal domestic accidents for flights operating under Part 121 and Part 135 for the years of 1986 to 2014 (Evans, 2014)[1]. The reduction in number of accidents over the years suggests that the aviation safety community should focus more on incident reports (Stephens, 2008).
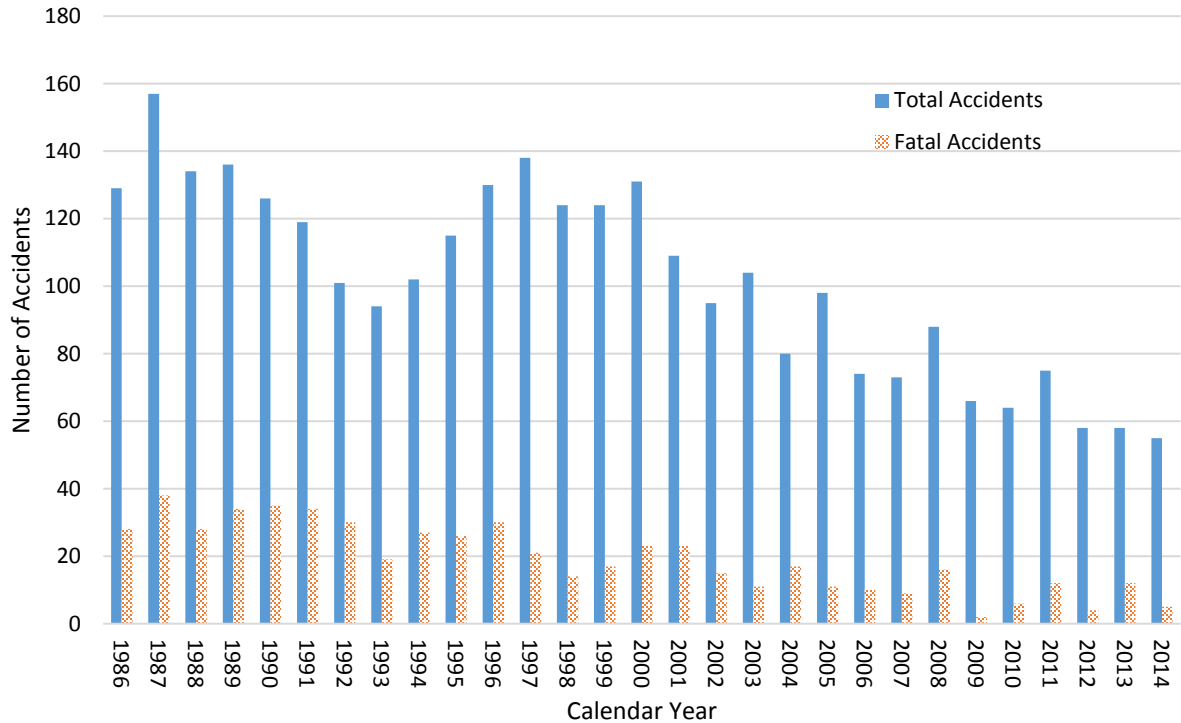

Figure 1 — Part 121 and Part 135 Domestic Accidents, 1986-2014

Given the decrease in total aviation accidents over time, this study relies on a larger sample size of incident reports from the ASRS in order to identify the safety nets encompassed in the NAS. The ASRS is a voluntary reporting system developed by NASA that is accessible by any party involved in an incident, including pilots, passengers, maintenance workers, and air traffic control (ATC), etc., to describe aviation incidents in detail. In this study, general aviation (GA) flights and all flights without a declared Federal Aviation Regulations part in the ASRS report were included in the incident report search since these flights may have been involved in incidents with aircraft flying under Part 121 or Part 135. By the National Transportation Safety Board (NTSB) definition, compared to accidents, the outcomes of incidents are often more desirable partly due to the proper operation of safety nets (Hadley, 2016). The ASRS reports provide information on the role and usage of safety nets in real world operations. For this study, only positive outcome incidents from the ASRS database were investigated to highlight the role of safety nets that avert accidents rather than reviewing accident reports, which identify failures and causal factors that caused accidents.

Although the ASRS reports are written mostly by professionals, the reliability and details of these reports are only as good as the knowledge and recall of the person reporting the information.

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[1] The data was updated by Evans to include dates prior to 2001 and after 2010 for use in this paper.

During an incident, ATC and pilots typically have many tasks. Therefore, they may not be able to recall all information from the event accurately. The reporting system also has multiple points of view, which when collected provide a more comprehensive description of the incident. This description can encompass the events prior to the incident and the resolution that prevented an accident. Typically, accident reports have more details than incident reports since they cover the entire timeline including the crew members' life a few days prior to the flight, the previous trips taken by the aircraft, and a maintenance history. Reporting of incidents is voluntary and it is unlikely that the reporting system captures all the annual incidents in the NAS. However, there are still a significant number of incident reports each year as shown in Figure 2 (Aviation Safety Reporting System, 2016-2017). The frequency of incident reports in a single year allows for a variety of causal factors to be reviewed, compared to the few accidents over many years contributing limited causal factors. More conclusions can be drawn from several instances of what works in the NAS architecture and what does not from the numerous incident reports. For instance, given the very limited occurrence rate of mid-air collision accidents, the investigation of numerous loss-of-separation incidents can potentially shed more light on underlying issues and solutions.
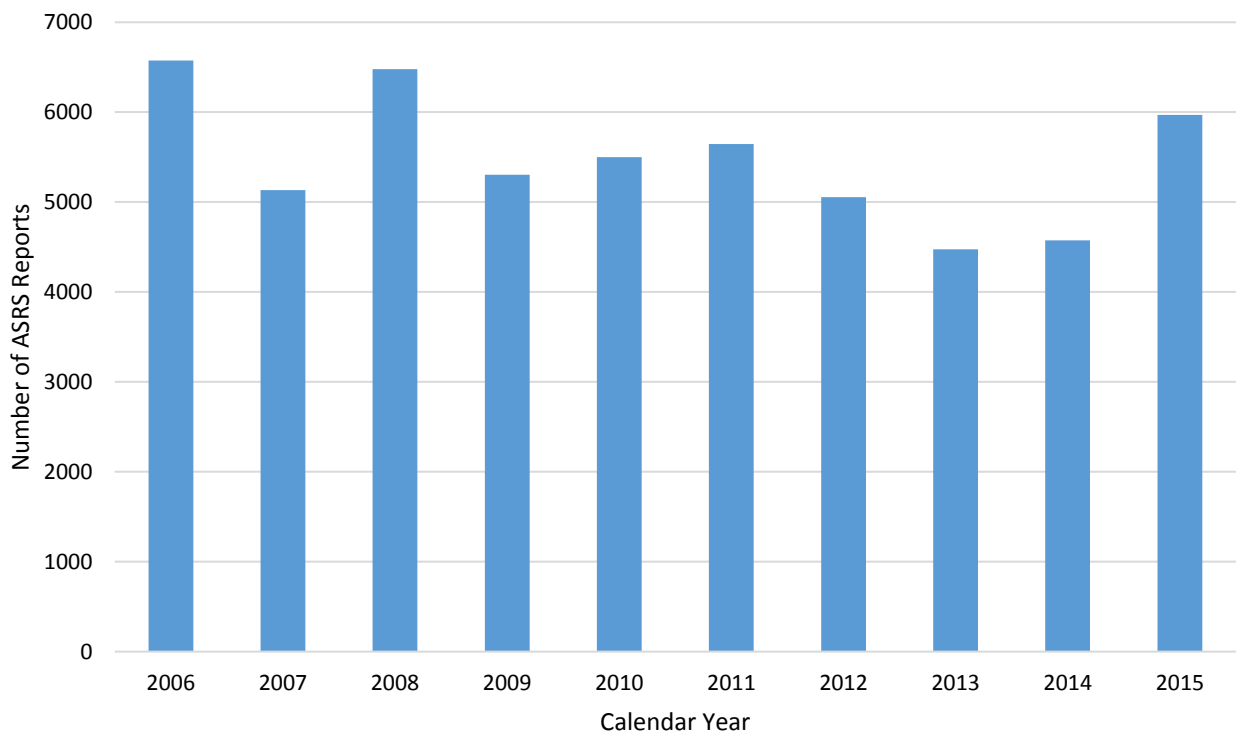

Figure 2 — Number of Incident Reports from the ASRS, 2006-2015

The ASRS reporting system allows the inclusion of search criteria, which helps navigation through the available reports. In this study, the CAST/ICAO's Positive Taxonomy was used to isolate the reports that contained these positive outcomes along with technologies that were used as safety nets. Commercial aviation safety nets were added to the search criteria to further condense the available reports. In order to make sure all reports were captured, both the full name and the acronym of the technology were used in the search criteria. Some of the safety nets that were

searched included: Enhanced Ground Proximity Warning System (EGPWS), Automatic Dependent Surveillance – Broadcast (ADS-B), Traffic Collision Avoidance System (TCAS), Airbus Electronic Centralized Aircraft Monitoring (ECAM), and Boeing Engine Indication and Crew Alerting System (EICAS) (Smith, 2017). The search criteria produced reports that included the safety nets and positive taxonomy and captured a substantial number of the incidents of interest, with the caveat that not all reports follow the taxonomy published by CAST/ICAO. In an effort to reduce the number of incidents to analyze from the vast number available, the search criteria was set to only include reports from the year 2015. This was the most recent available calendar year at the time of study. Because only reports from 2015 were analyzed, the identified SNs within this paper may not be representative of SNs from other years or in the future.

Safety Nets and ESD Representation

To illustrate the effectiveness of SN technologies, the narratives in the ASRS reports were clustered based on technology purpose to create generalized Event Sequence Diagrams (ESDs). ESDs are used to graphically demonstrate the order of events that take place in an incident. Figure 3 depicts a generic ESD. Typically, ESDs are formed using initiating events, key events, and end states. Based on the presence or absence of the key and initiating events, multiple scenarios with various paths and end states can be represented (Roelen, 2008). In this study, incident reports were searched for only positive taxonomy words or phrases; therefore, key events included the use of safety nets and the different end states were all positive outcomes.
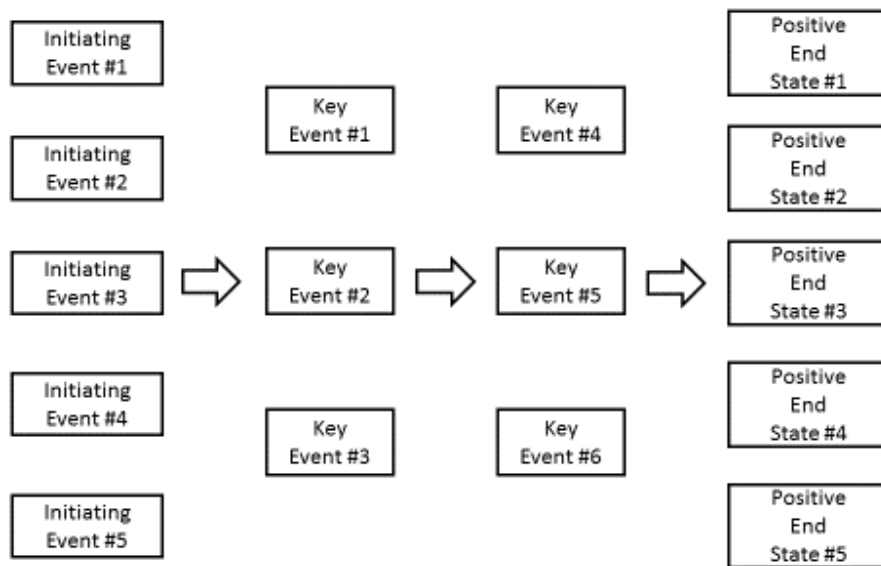

Figure 3 — Generic ESD

The level of detail in the ESDs can vary depending on how descriptive the incident reports are. The number of key events leading to the positive end state can be changed based upon the detail

in the reports. The beginning state of each instance, prior to an initiating event, is assumed to be nominal operations. Similarly, the positive end states represent potentially altered, but still desirable, nominal operations. The graphical use of ESDs facilitates the demonstration of all available paths and scenarios that can occur after an initiating event.

ESDs are often used in the investigation of aviation accidents. Following an official accident investigation, a comprehensive report is published by the NTSB. The report tracks all of the events associated with the accident, leading back to the possible initiating event and the hazards that preceded the accident (Ale, 2009). Although this retrospective investigation process has already been conducted to construct ESDs for major accidents categories (Roelen, 2005), this process has been overlooked for incidents due to the nature of voluntary reporting systems. In addition, the large number of the reports, each report being written by a different entity, and the potential inconsistencies between reports make ESD construction for incidents much more difficult.

Results

The hard safety nets that prevented an accident and led to a positive outcome can be grouped into two categories based upon the initiating events. The first category is Airspace Operations Centric and the second category is Aircraft Operations Centric. The Airspace Operations Centric ESD shown in Figure 4 provides a chronological structure, starting on the left with initiating events or causal factors that lead to undesirable events/conflicts. Next, the anomaly is acknowledged and a solution is provided by the stakeholders (ATC, flight crew, and/or SN), which results in an action that clears the conflict. The Airspace Operations Centric ESD combines all the individual ESDs from safety nets that mitigate operational events including loss of separation, loss of control, runway incursion, etc. Approximately 80% of the reports were related to airspace operational events. The Aircraft Operations Centric ESD, shown in Figure 5, provides causal factors that are recognized by either warning systems or the flight crew. The Quick Reference Handbook (QRH), which contains procedures to resolve abnormal and emergency conditions (*Quick Reference Handbook (QRH)*, 2017), is then referenced. Based on the outcomes of the QRH mandated tasks, the aircraft can either continue to its destination or perform one of the maneuvers listed in red in Figure 5. Although less desirable, alternative maneuvers such as rejecting takeoff or performing an unscheduled landing are still considered positive outcomes since an accident is avoided.
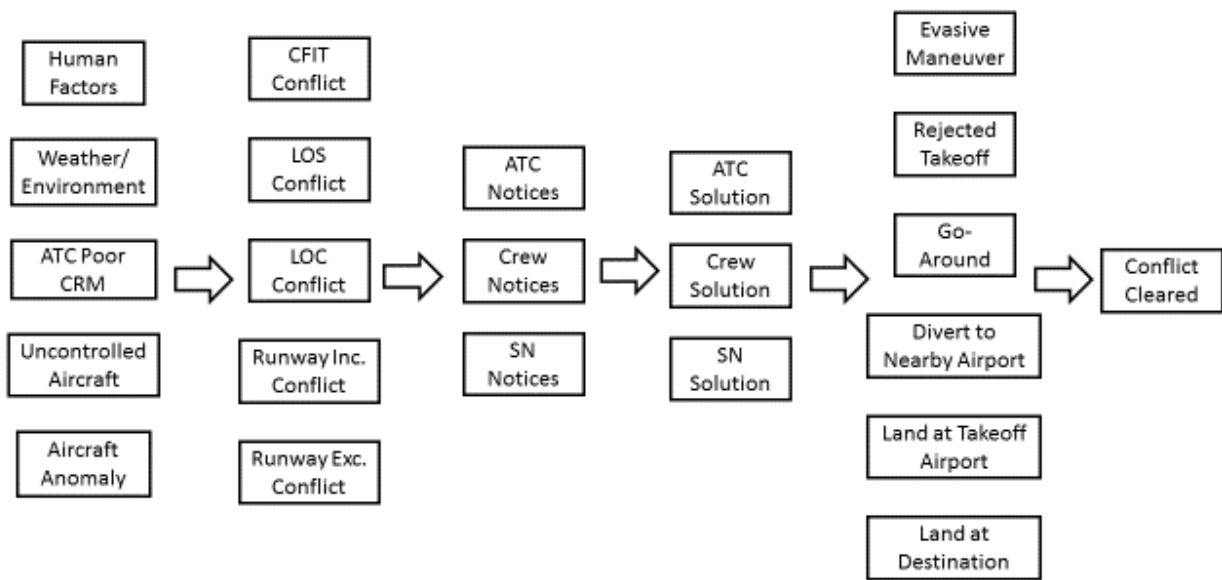
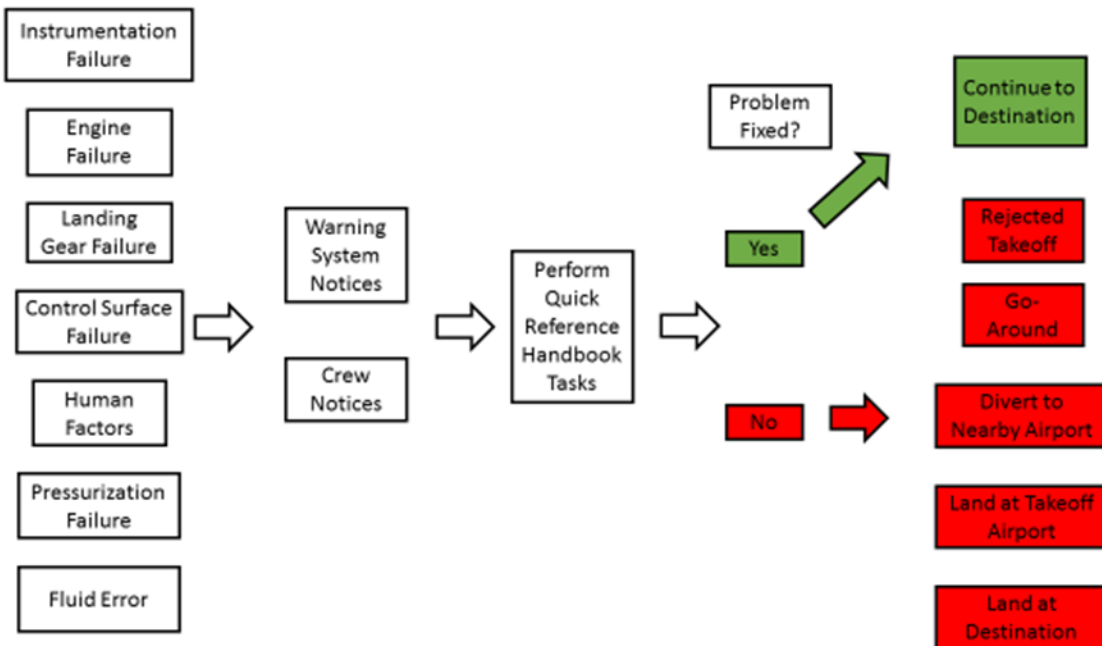**Figure 4 — Airspace Operations Centric ESD**

Figure 5 — Aircraft Operations Centric ESD

The ESDs shown in Figure 4 and Figure 5 were developed using data excerpted from a single year query (Aviation Safety Reporting System, 2016-2017). Using the specified safety nets and positive taxonomy restrictions, the number of reports was reduced from the 5971 reports available for 2015 to 445. Due to the limited sample size, the ESDs are high-level, qualitative representations of the real-world operations. It should also be noted that the majority of the reports are associated with technologies and safety nets that are used on commercial airliners. Among the reviewed reports, there were one general aviation specific technology report, no military reports, 24 reports solely on soft safety nets, and 3 reports that explicitly stated both a hard and soft safety net were employed for the resolution.

Compared to the extensive list of existing SNs (Smith, 2017), it should be noted that only 12 different hard safety nets were found as a last line of defense in the 2015 reported incidents investigated in this study. Those 12 SNs were: TCAS, EGPWS, Airport Surface Detection Equipment Model X (ASDE-X), ADS-B, ECAM, Predictive Wind Shear (PWS), Final Monitor Aid (FMA), EICAS, Minimum Safe Altitude Warning System (MSAW), Terrain Avoidance and Warning System (TAWS), Takeoff Configuration Alerting (TOCA), and Passive Collision Avoidance Systems (PCAS). The 12 hard SNs captured in this review were predominantly used as the last line of defense prior to Mid-Air Collision (MAC), Controlled Flight into Terrain (CFIT), or flight with a System Component Failure (SCF). Two soft SNs, crew resource management (CRM) and ATC ground support, were identified as the last line of defense in 14 of the 24 soft safety net related reports.

In addition to the generalized ESDs, two specific ESDs were developed and are illustrated in Figure 6 and Figure 7. Figure 6 shows the details of the Enhanced Ground Proximity Warning System (EGPWS) ESD, which can be considered as a representative Airspace Operations Centric ESD. The EGPWS ESD lists the causal factors that can lead to a CFIT conflict (e.g., adverse weather, procedural, aircraft anomaly, etc.). The numbers within the arrows in Figure 6 indicate the total number of instances that each causal factor, stakeholder, remedial action, or outcome occurred/contributed for a CFIT conflict-resolution as mentioned in the reviewed reports. However, the sum of the numbers in each column of arrows should not be interpreted as the number of reports associated with the specific technology or action. Not all of the reports explicitly indicate a specific initiating event and/or positive end result. It is also important to note that causal factors or the entities that notice or apply the remedial actions are not mutually exclusive, i.e., more than one causal factor or individual/system can play a role in each CFIT conflict, causing the sums in each column to differ. The EGPWS ESD provides the numerical breakdown of all remedial actions (rejected takeoff, go-around, and evasive maneuver) that are considered to be the positive outcome. Based on the incident reports demonstrating the use of EGPWS, the most significant initiating event prior to a CFIT conflict is Human Factors.
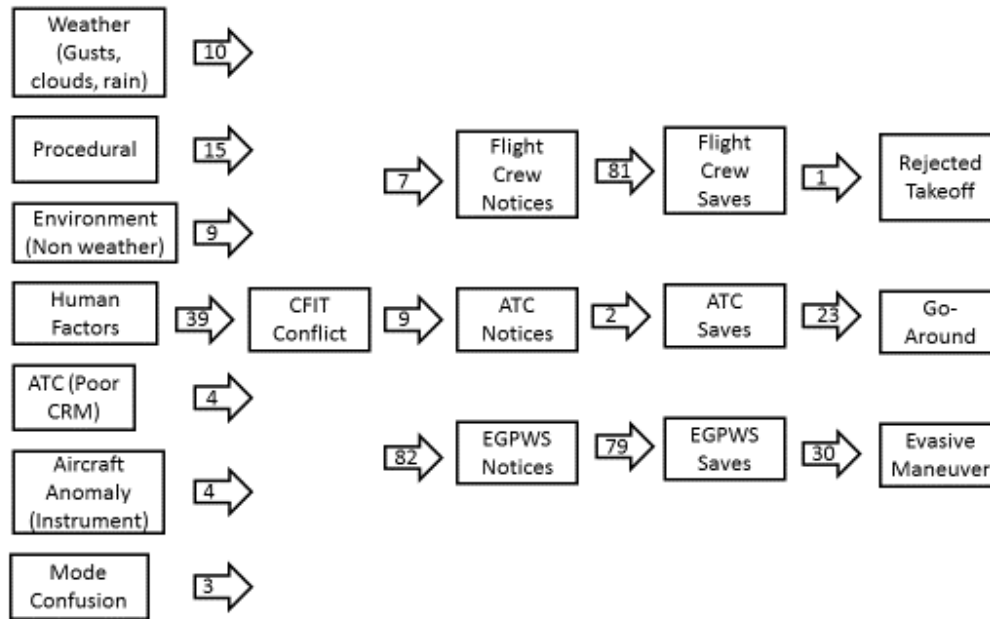
Figure 6 — EGPWS ESD

The same level of detail can be applied to the Aircraft Operations Centric ESD safety nets. One example ESD for ECAM is given in Figure 7. The ESD for ECAM includes color-coded final paths to indicate whether the aircraft is healthy and can continue flight (green) or needs to end flight safely (red). An important observation from this ESD for ECAM is that the flight crew did not notice the component failure in any incident report, indicating the significance of SNs in aircraft operations. It is also important to note that the majority of the flights did not have a successful fix of the SCF from following the QRH in order to continue to the destination with a healthy aircraft.

An ESD can also be developed for soft safety nets in a similar manner. A soft SN ESD may have many different causal factors leading up to a dangerous situation. Soft safety nets such as CRM, ATC support, and training may be utilized in order to prevent an incident and/or accident. However, significantly fewer of the 445 reviewed reports for 2015 give credit to soft SNs for accident/incident prevention. A proper construction of soft safety net ESDs may require a review and study of ASRS reports across multiple years, which is beyond the current study scope.
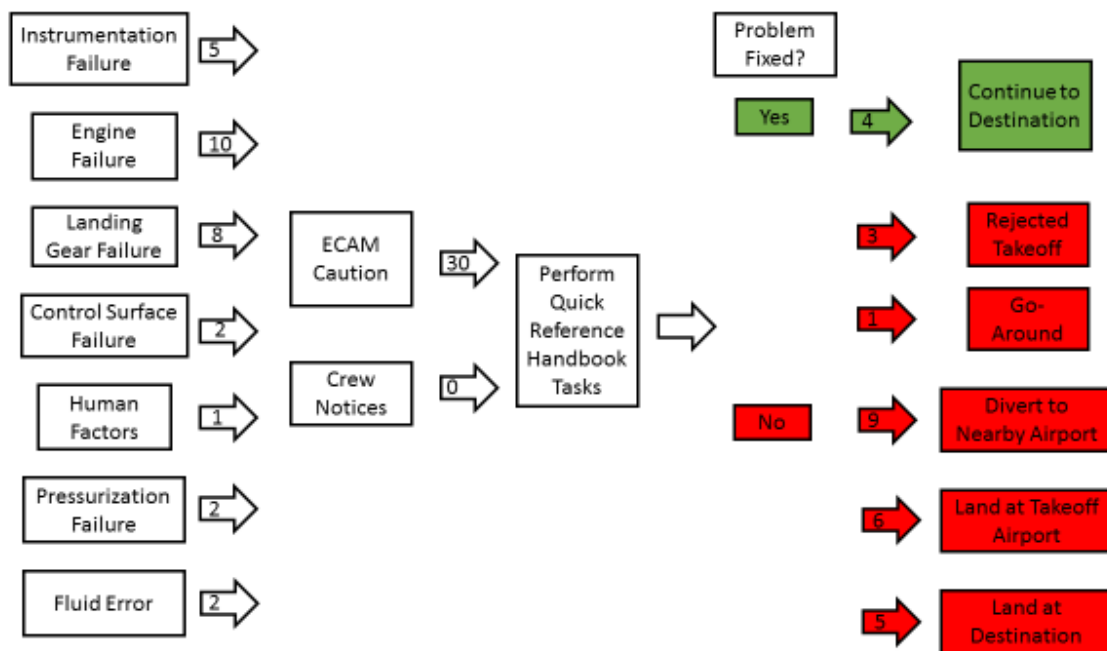
Figure 7 — ECAM ESD

Conclusions

Today in the U.S., commercial aviation enjoys an unprecedented safety record, primarily due to reactive safety measures that were put in place in response to past accidents. However, with the decrease in both fatal and total accidents over the years, NASA has been focused on investigating incidents in order to maintain or further improve commercial aviation safety while developing next-generation safety technologies. As part of this effort, more than 400 incidents that took place in 2015 were examined to identify and classify safety nets that prevented accidents. Although restricting the search to a single year may have resulted in a limited scope in identifying the safety net effectiveness, the study revealed a large number of causal factors and their interactions with safety nets. Additionally, the positive outcomes in all of the reports researched in this study might indicate that hard safety nets are critically employed in overcoming the adverse conditions in flight. Finally, despite the effective use of safety nets, the ESDs indicated breakdowns for human factors as well as aircraft and airspace operations that could have potentially led to an accident. The ESDs that were developed within this study could further be used to identify potential areas of improvement within the NAS.

References

Ale, B., Bellamy, L. J., Cooke, R., Duyvis, M., Kurowicka, D., Lin, P., ... Spouge, J. (2009, March 2). *Causal Model for Air Transport Safety* [Final Report]. Retrieved from Netherlands Ministry of Transport

Aviation Safety Reporting System (ASRS). (n.d.). Retrieved November 2016 – March 2017, from NASA Ames Research Center website: https://asrs.arc.nasa.gov/

CAST/ICAO Common Taxonomy Team, (2013, April). *Positive Taxonomy, Definition and Usage Notes* [Version 1.2]

CAST/ICAO Common Taxonomy Team. (2017, December). *Aviation Occurrence Categories Definitions and Usage Notes*. [Version .4.7]

Dorr, L. (2017, December 29). *Fact Sheet - Commercial Aviation Safety Team*. Retrieved April 20, 2018, from Federal Aviation Administration website: https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22455

Evans, J. K. (2014). Frequency of Specific Categories of Aviation Accidents and Incidents During 2001-2010. *NASA/CR - 2014-218184*

Hadley, E. (2016, May 4). *What's the Difference Between an Accident and an Incident?* Retrieved 2018, from Aircraft Owners and Pilots Association website: https://pilot-protection-services.aopa.org/news/2016/may/04/did-i-just-have-an-accident-or-an-incident

Reason, J. T. (1997). *Managing the Risks of Organizational Accident*. Hampshire, UK: Ashgate.

Roelen, A. L., & Wever, R. (2005, November). *Accident scenarios for an integrated aviation safety model* (NLR-CR-2005-560). Retrieved from National Aerospace Laboratory NLR website: http://www.nlr-atsi.nl/fast/downloads/CATS/App%203%20NLR%201%20-%202005-560-cr.pdf

Roelen, A. L.C., van Doorn, B. A., Smeltink, J. W., Verbeek, M. J., & Wever, R. (2008, October). *Quantification of Event Sequence Diagrams for a causal risk model of commercial air transport* (NLR-CR-2008-646). Retrieved from National Aerospace Laboratory NLR website: http://www.nlr-atsi.nl/fast/downloads/CATS/App%204a%20NLR%2013%20-%202008-646.pdf

Quick Reference Handbook (QRH). (2017). Retrieved 2018, from SKYbrary website: https://www.skybrary.aero/index.php/Quick_Reference_Handbook_(QRH)

Smith, B. E., Evans, C. (2017). Current Safety Nets within the U.S. National Airspace System. *NASA/TN - 2017-49109*,

Stephens, C., Ferrante, O., Olsen, K., & Sood, K. (2008). Standardizing International Taxonomies. *ISASI Forum January - March 2008*, 8-13.