Prioritizing Mitigations in Flight Path Management Accidents

By

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Executive Summary

Aviation is a very safe form of transportation; however, there is an ongoing effort to decrease risk and the rate of accidents. Prioritizing risk mitigations has, in the past, been somewhat subjective. The benefits of more objective data resulted in attempts to quantify accident types to determine what could be done most effectively. Using a data-driven method, results clearly showed the most common types of accidents. These included Loss Of Control – Inflight, Controlled Flight Into Terrain, and Runway Excursion.

Breaking down the total number of accidents by category provided a limited analysis of the data. Using modern software it is now possible to look further into the data for various co-occurring factors involved in the accidents. These co-occurrences were evaluated using a data clustering software named Pathfinder. The data was not only clustered but related by a strength index. The strength was determined by the frequency of occurrence shared by two specific categories divided by the total number of accidents in both categories. The strength index provided a means of quantification never before used.

The dataset provided by the Flight Deck Automation Working Group included 26 accidents with flight path management issues. The 26 accidents were divided into four categories: Loss Of Control – Inflight, Controlled Flight Into Terrain, Runway Excursion, and Landing Off Runway. Occurrences within the categories were analyzed for direct relationship with the accident (Level 1) and for secondary relationship (Level 2). Each relationship, both primary and secondary, was plotted by strength. Highest strengths

indicated higher co-occurrences. The relationship data was further analyzed by including the percentage of each accident category within the dataset.

This analysis resulted in values for specific occurrences which were the most significant. The top five accounted 92 percent of the total. The five most significant occurrences were GPWS/EGPWS, Threat: Crew Factors – Other, Crew to External Communications, Threat: ATC – Other, and Adverse Weather. Thus, the use of a data-driven prioritization for mitigations of the highest risk accident types proved to be effective.

Prioritizing Mitigations in Flight Path Management Accidents

Aviation is a very safe form of public transportation. Yet the flying public demands ongoing improvements in safety and continual reduction in risk. To date, effective risk mitigation has lowered the risk of a major accident from 0.329 per million flight hours in 1990 to 0.111 per million flight hours in 2009 (NTSB, n.d.).

Improving the safety and reliability of aircraft is an ongoing goal for the aviation community. Modern jets are significantly safer than earlier generations (BCA, 2009). One reason for this improvement has been the development and use of aircraft automation. As is often the case, this new technology brought with it new issues and risks.

The Federal Aviation Administration (FAA) recognized this and commissioned a report on some of the issues caused by automation in 1996. Within this extensive report the team identified "vulnerabilities in flightcrew management of automation and situation awareness" (FAA, 1996, p. 2). Since that report was completed, accidents have continued to occur due, in some part, to automation issues (e.g. mode awareness, lateral or vertical path deviation, or energy state).

The designs of new generation jets are increasingly using automation in numerous ways to maximize efficiency and simplify operation. This increase involves more complexity as automation interfaces with more systems and becomes a primary tool for the flight crew. To better understand the implication of the growing role of automation, the FAA through the Commercial Aviation Safety Team and the Performance-Based Operations Aviation Rulemaking Committee created the Flight Deck Automation Working Group (FltDAWG) to report on issues of flight path management, including automation, in commercial aviation operations. FltDAWG members include representatives from the Air Transport Association, the Airline Pilots Association, the FAA, and numerous industry manufacturers, operators and researchers.

The FltDAWG reviewed accidents, major incidents (defined as any event investigated by a governmental investigative agency that did not meet the International Civil Aviation Organization definition of an accident), and incidents from the NASA Aviation Safety Reporting System. Mishaps were limited to 26 accidents involving flight path management issues. These mishaps were selected to specifically include flight path management issues that were stated in the accident report. The aircraft involved were certified by the FAA as transport category aircraft and flown by professional pilots.

FltDAWG members read and coded specific end states (e.g. Controlled Flight into Terrain, loss of control in flight, runway excursion, and touchdown off runway). Additionally, the FltDAWG team categorized other factors related to the accident, such as inadequate pilot knowledge or communication errors. This categorization effort provided a complex view of factors present in the 26 accidents.

Problem Statement and Research Question

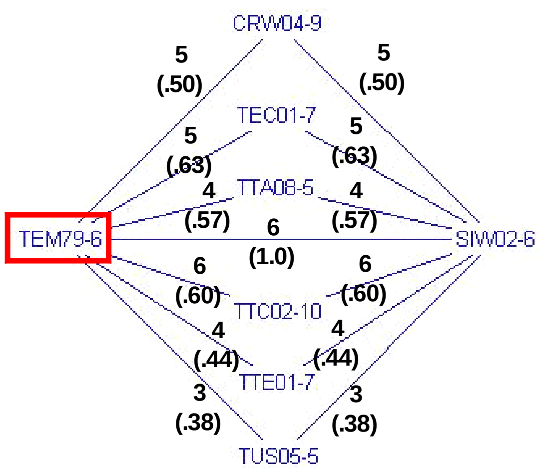
Empirical data for the prioritization of mitigations to reduce risks of airline accidents has been limited. Utilizing a data-clustering analysis technique that calculates the strengths of relationships, this research will show a data-driven prioritization for mitigations of the highest risk accident types.

Methodology

In the 26 accidents, there were co-occurrences that occurred in more than one accident type. If the factors occurring in multiple accident types could be analyzed and prioritized, improved mitigations could be focused on the highest risk factors.

Analysis of the factors requires the creation of subsets within each accident type and the subsequent correlation of these subsets into clusters. Once the clusters are created it is possible to utilize a software program to create a hierarchy. The software utilized in this analysis in named Pathfinder (Schvaneveldt, 1990). In Pathfinder the software uses networks that create a structure consisting of nodes (concepts) and links (relations). This data clustering program shows the strength of the relationships using "link weights, and intensional meaning of the concept . . . determined by its connection to other concepts" (Schvanevelt, Durso, & Dearholt, 1989, p. 252). Using Pathfinder, it is possible to determine the rate of co-occur in these different accident types. It is also possible to determine in which accidents a particular factor occurs. Pathfinder compiles data from each accident type, each factor, and each end state. Furthermore, it shows the co-occurrence rate. The significance of co-occurrence is referred to as the strength. The strength value is calculated by dividing the number of specific co-occurrences shared in an accident category (called the union) by the total number of occurrences of both factors combined (called the intersection).

For example, consider the accident category Controlled Flight Into Terrain. There are six such accidents in the dataset. In three of the accidents, an occurrence of Vertical Flight Path Deviation Low was present. There are five Vertical Flight Path Deviation Low accidents in the dataset. Using Pathfinder's union-divided-by-intersection formula, the strength would be calculated as the union equal three (3) divided by the intersection equal eight (8). The value of eight (8) is derived by taking the total number of accidents for each category, subtracting the common ones, and then adding the sums together; e.g. (6 - 3) + (5 - 3) + 3 = 8. Therefore, the strength would equal three (3) divided by eight (8), equaling 0.38. Ranking by strength of threats provides a quantifiable means of determining frequency of co-occurrence between co-occurrences and accident types. This is shown in Figure 1 (Controlled Flight Into Terrain) and Figure 2 (Vertical Flight Path Deviation Low). Figure 1 shows all of the co-occurrences related to the Controlled Flight Into Terrain accident category with the strength relationship. The complexity of relationships is also visible, as are the co-occurrences that relate to more than one category.



Code	Factor Name
TEM79	**TEM End State: Controlled Flight into Terrain**
CRW04	Issue: inter -pilot communication may be reduced (Issue 139)
SIW02	System: GPWS/EGPWS
TEC01	TEM Error: Crew -to -External Communications
TTA08	TEM Threat: TEM Threat ATC Other
TTC02	TEM Threat: TEM Threat Crew Factors Other
TTE01	TEM Threat: Adverse Weather
TUS05	TEM UAS: Vertical Flight Path Deviation - Low

Figure 1. The co-occurrences identified in Controlled Flight Into Terrain accidents.

In the initial dataset, there were six accident types which are referred to as end states. These end states include Controlled Flight Into Terrain, Loss of Control – Inflight, Runway Excursion, and Touchdown Off Runway. The categories Hard Landing and Mid-Air Collision are only represented by one accident each in the dataset. Therefore, hard landings and mid-air collisions were reviewed but not included due to their low numbers. The categories analyzed were selected due to the relatively high frequency of these types of accidents (BCA, 2009).

Using Pathfinder it is possible to create networks for each accident category. Additionally, it is possible to extend the analysis so that co-occurrences in each network are calculated as sub-networks. As can be seen in Figure 2, the interrelation of co-occurrences and accident types is complex. Utilizing the networks allow for clustering of occurrences that interrelate to each other. This method of analysis provides a more complete picture of the dataset. Reviewing each of the occurrences in the network shows how first level and second level can affect each other. The sub-networks can be reviewed to determine if any occurrences are significant in more than one accident category. By using clustered data in this way a unique data profile emerges.

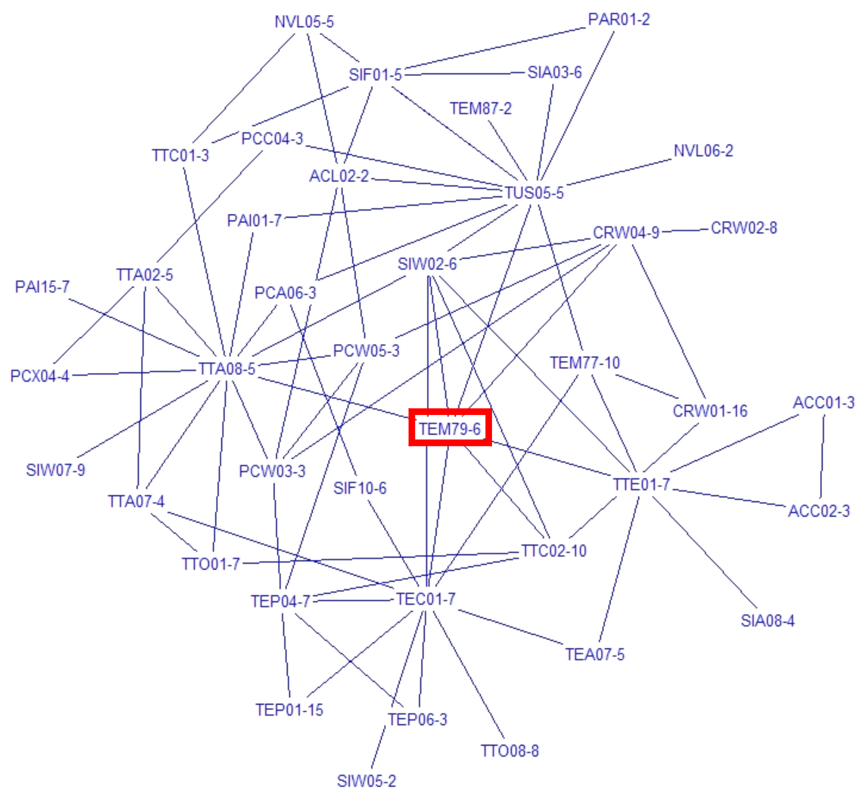


Figure 2. The relationship of co-occurrences to Controlled Flight Into Terrain accidents.

Then, by determining which co-occurrences take place in multiple accident categories, it is possible to rank them in order of frequency of co-occurrence. This ranking can be thought of as a measure of importance. Once the order of importance is established, the need for improvement in mitigations for specific co-occurrences in high-risk accident categories becomes clear and justified.

Analysis

The four accident categories contribute different amounts to the total. As shown in Figure 3, Controlled Flight Into Terrain was the leading category with six accidents, while Runway Excursions had five accidents, Loss of Control In-Flight had three, and Touchdown Off Runway had two. This is shown as a percentage breakdown in Table 1.

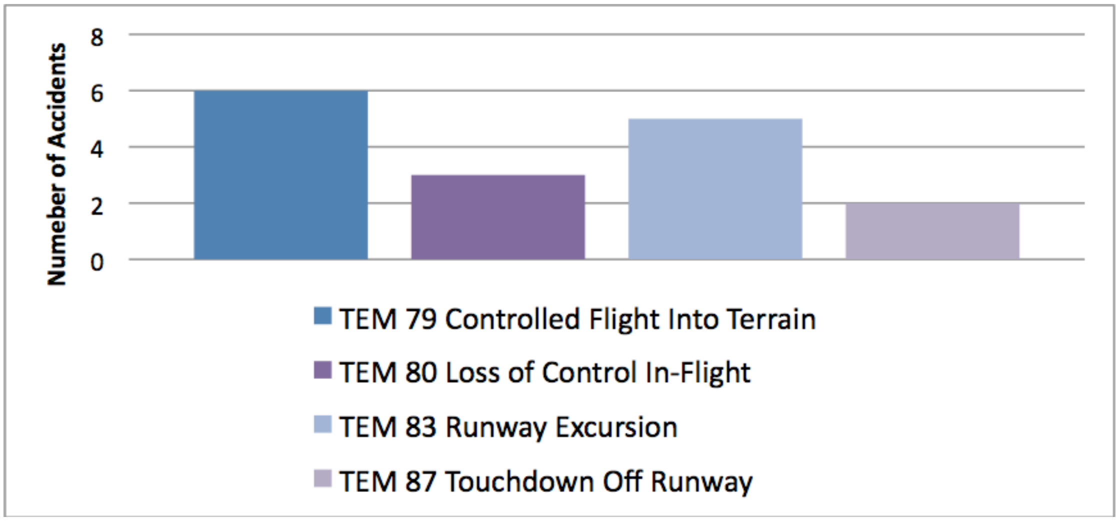


Figure 3. Number of accidents in the dataset by type.

Table 1

Accident Types Broken Down by Number and Percentage

	Number of Accidents	Percentage
TEM 79 Controlled flight into terrain	6	38%
TEM 80 Loss of control in flight	3	19%
TEM 83 Runway excursion	5	31%
TEM 87 Touchdown off runway surface	2	13%
Total	16	100%

Breaking the data down by accident type allowed co-occurrences to be prioritized according to percentage of the dataset total. Pathfinder software created levels of co-occurrence in the dataset based on the strength relationship between the accident category and co-occurrences. Appendix A displays the four accident categories with the strongest co-occurrences in Level 1 and the secondary co-occurrences in Level 2. Analysis of these levels showed the Level 1 factors for each accident category and then the Level 2 factors that co-occurred with the Level 1 factors. Utilizing strength values of the relationships created a hierarchy.

Table 2

Level 1 Co-occurrences in "Controlled Flight Into Terrain" Category

	Total # of accidents	Co-occurrences	Strength
TEM 79 Controlled Flight Into Terrain Level 1 co-occurrences	6	–	–
TEC 01 Crew to External Communications	7	5	0.63
TTC 02 Threat: Crew Factors – Other	10	6	0.60
TTA 08 Threat: ATC – Other	5	4	0.57
SIW 02 GPWS/EGPWS	6	6	1.00
TTE 01 Adverse Weather	7	4	0.44

Note. ATC = air traffic control; GPWS = Ground Proximity Warning Systems; EGPWS = Enhanced Ground Proximity Warning Systems.

In Table 2, the Level 1 co-occurrences are shown for the Controlled Flight Into Terrain category. It is noteworthy that the number of co-occurrences of Ground Proximity Warning Systems (GPWS)/Enhanced Ground Proximity Warning Systems (EGPWS) has a strength value of 1.00. In all six Controlled Flight Into Terrain accidents in the dataset, the flight crew received a GPWS/EGPWS warning. These six accidents contain direct references to GPWS/EGPWS warnings in the accident reports. One example of this is the American Airlines Boeing 757 accident in December 1995 near Cali, Colombia. The reports stated “there is no evidence that, before the proximity warning system (GPWS) alert, the flight crew recognized the proximity of terrain to the airplane’s present and future flightpath” (Ladkin, 1996, p. 35). This accident shows the importance of predictive flightpath warning. In 1996, Honeywell introduced the EGPWS (Honeywell, n.d.) to provide earlier warnings before potential disasters like this American Airlines accident.

Another Controlled Flight Into Terrain accident in the dataset that shows the importance of GPWS/EGPWS is the Airbus 320 accident near Sochi, Armenia on May 2, 2006. The report states, “Neither of the pilots fully fulfilled the FCOM requirements for crew actions in case of EGPWS activation stipulated in the QRH [Quick Reference Handbook] ‘EMERGENCY PROCEDURE’ Section” (IAC, 2007, p. 48). Had the pilots properly followed procedure after receiving an EGPWS warning, it is possible this accident could have been avoided.

These two examples show the diversity of factors co-occurring during an accident. In one case the lack of a timely warning allowed the crew to get to close to the terrain and escape, while the other provided warning but the pilots did not properly respond. FltDAWG members correctly identified GPWS/EGPWS as a factor in these flight-path management accidents. While there is co-occurrence in both accident examples, they require different mitigations to reduce the risks.

While there was the same number of co-occurrences of Threat: Crew Factors – Other, the strength relationship was only .60. This is due to there being a larger number of accidents in the dataset in which Threat: Crew Factors – Other was cited. By using this strength relationship, the prioritization of the Controlled Flight Into Terrain category can be determined. As shown in Table 2, the relationship hierarchy is GPWS/EGPWS (1.00), Crew To External Communications (0.67), Threat: Crew Factors – Other (0.60), Threat: ATC – Other (0.57), and Adverse Weather (0.44).

If there were only one category and one level of co-occurrence required in this analysis, then the listed hierarchy would provide all the needed mitigations. However, there are other categories of accidents and there are additional levels of co-occurrences. A more complete and useful matrix is necessary if maximum information is to be determined from the dataset.

The second accident category is Loss of Control – Inflight. Table 3 shows the co-occurrences for this accident category.

Table 3

Level 1 Co-occurrences in Loss of Control Category

	Total # of accidents	Co-occurrences	Strength
TEM 80 Loss of Control – Inflight Level 1 co-occurrences	4	–	–
SYS 45 EICAS/ECAM	2	2	0.50
OCC 02 Automation-Use Philosophy May Be Lacking	4	2	0.40
ACA 03 Failure Recovery May Be Difficult	4	2	0.33
SIW 06 Pre-Stall Stick Shaker/Pusher	4	2	0.33

Note. EICAS = Engine Indication and Crew Alerting System; ECAM = Electric Centralized Aircraft Monitor.

The hierarchy of risk in this category using the strength relationship calculation is EICAS/ECAM (0.50), Automation-Use Philosophy May Be Lacking (0.40), Failure Recovery May Be Difficult (0.33), and Pre-Stall Stick Shaker/Pusher (0.33).

It is noteworthy to mention that the co-occurrence of stick shaker/pusher has a strength relationship of 0.33, while stalls account for 50 percent of loss-of-control accidents (URIT, 2008). The limited number of accidents in the dataset partially accounts for this difference; however there is great significance in the criteria of there being flight path management issues for inclusion in the dataset. There appears to be a correlation between the lower strength relationships in the dataset, more so than if the total number of Loss of Control – Inflight accidents were considered. This apparent correlation could be the subject of future analysis.

Example accidents in this category include Pinnacle Airlines Flight 3701 on October 14, 2004 and American Airlines Flight 904 on May 12, 1997. In both accidents, the pilots failed to properly respond to the stall warning systems, (stick shaker and stick pusher) (NTSB, 2000, 2007). Therefore, the Level 1 co-occurrence stick shaker/pusher is present in these example accidents.

Runway excursions are the third category of accidents in the dataset. The strength relationships are shown in Table 4.

Table 4

Level 1 Co-occurrences in Runway Excursion Category

	Total # of accidents	Co-occurrences	Strength
TEM 83 Runway Excursion Level 1 co-occurrences	5	–	–
TUS 10 Undesired Aircraft State –	8	3	0.30

Other			
TEM 85 Ground Damage/ Injuries	5	2	0.25
TEA 08 CDU/MCDU	4	2	0.29
TUS 01 Speed Deviation – High	3	2	0.33
TEM 86 Loss of Control On Ground	3	3	0.60

Note. CDU = Control Display Unit; MCDU = Multi-Functional Control Display Unit

The hierarchy of risk using the strength relationship calculation is Loss of Control On Ground (0.60), Speed Deviation – High (0.33), Undesired Aircraft State – Other (0.30), CDU/MCDU (0.29), and Ground Damage/Injuries (0.25). Using only Level 1 co-occurrences, there is not a strong indication of areas in which mitigations are needed to reduce the number of accidents in this category. The leading co-occurrence is Loss of Control On Ground; this is understandable due to the usual sequence of events in this type of accident. A runway excursion is not planned or intended. It is, therefore, to be expected that loss of control on the ground would cause or follow a runway excursion.

Example accidents include Gulfstream G-GMAC at Teterboro, New Jersey on December 1, 2004 and the Trans Asia Airways Airbus A320 at Taipei Sungshan Airport on October 18, 2004. In both mishaps, aircraft handling issues resulted in both a runway excursion and loss of control on the ground (NTSB, 2004; ASC, 2004).

In these examples there is a benefit to using Level 1 and Level 2 co-occurrences to improve understanding of the overall risk and necessary mitigation. This benefit applies to all of the co-occurrences. Further analysis shows the interrelationship between Level 1 and Level 2 co-occurrences.

The final category of accidents analyzed was Touchdown Off Runway. As shown in Table 5, there were five Level 1 co-occurrences in this category.

Table 5

Level 1 Co-occurrences in Touchdown Off Runway Category

	Total # of accidents	Co-occurrences	Strength
TEM 87 Touchdown Off Runway Level 1 co-occurrences	2	–	–
SYS 46 Heading	2	1	0.33
TUS 05 Vertical Path Deviation – Low	5	2	0.40
TTE 02 Airport Conditions	3	2	0.67
TTA 03 ATC Error	3	2	0.67
SYS 48 Other Modes	2	1	0.33

The hierarchy of risk using the strength relationship calculation is Airport Conditions (0.67), ATC Error (0.67), Vertical Path Deviation – Low (0.40), Heading (0.33), and Other Modes (0.33). In this category, two of the Level 1 co-occurrences have a strength relationship of 0.67, indicating the need for mitigations. However, the quantity of accidents in the category is low.

In the dataset there are 19 Level 1 co-occurrences. Including Level 2 co-occurrences increases the number to 70. Definitions of the Level 1 and Level 2 categories are listed in Appendix B.

Level 2 co-occurrences arise in more than one accident category and relate to more than one Level 1 category. The most frequent Level 2 category with multiple relationships is GPWS/EGPWS, identified in the definitions as SIW 02. Figure 4 shows the frequencies of Level 2 Co-occurrences occurring greater than once.

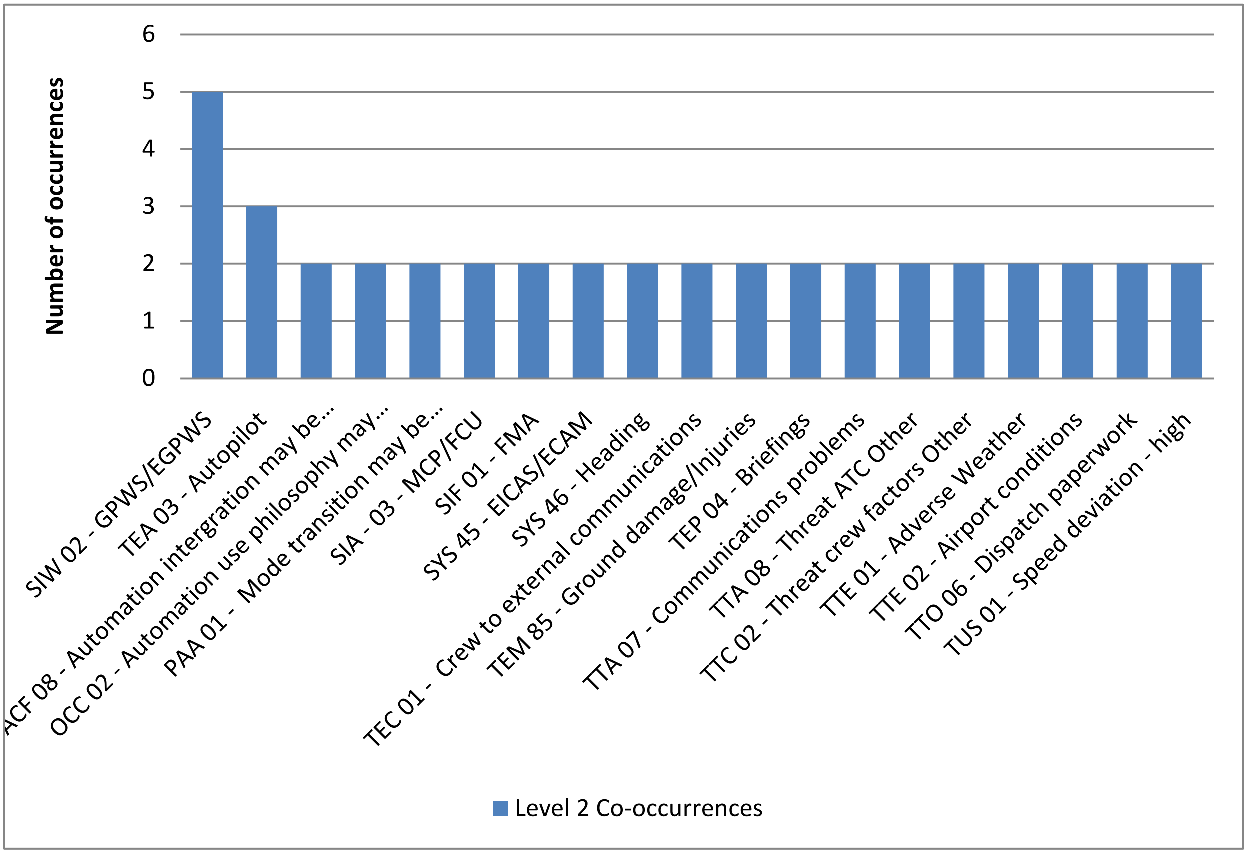


Figure 4. Frequencies of Level 2 co-occurrences greater than once.

In order to prioritize the categories for mitigations, it is necessary to consider frequency of occurrence, strength of occurrence, and percentage of the accident category in the dataset. Therefore, the strength values for each occurrence are added together, providing a combined strength value as shown in Table 6.

Table 6

Level 2 Co-occurrences Strength Totals Times Weighted Values

Level 2 Co-occurrence	Strength total	Weighted value	Strength multiplied by weighted value
SIW 02 GPWS/EGPWS	3.24	2.25	7.29
TEA 03 Autopilot	0.95	–	0.00
ACF 08 Automation Integration May Be Poor	0.66	–	0.00
OCC 02 Automation-Use Philosophy May Be Lacking	0.80	0.38	0.30
PAA 01 Mode Transition May Be Uncommanded	0.83	–	0.00
SIA 03 MCP/FCU	0.71	–	0.00
SIF 01 FMA	0.83	–	0.00
SYS 45 EICAS/ECAM	0.83	0.19	0.16
SYS 46 Heading	0.66	–	0.00
TEC 01 Crew to External Communications	1.26	1.88	2.36
TEM 85 Ground Damage/Injuries	0.58	0.63	0.36
TEP 04 Briefings	1.11	–	0.00
TTA 07 Communications Problems	1.32	–	0.00
TTA 08 Threat: ATC – Other	1.14	1.50	1.71

TTC 02 Threat: Crew Factors – Other	1.20	2.25	2.70
TTE 01 Adverse Weather	0.88	1.50	1.32
TTE 02 Airport Conditions	1.00	–	0.00
TTO 06 Dispatch Paperwork	1.00	–	0.00
TUS 01 Speed Deviation – High	0.73	0.63	0.46

Note. MCP = Mode Control Panel; FCU = Flight Control Unit; FMA = Flight Mode Annunciator.

Following the calculation of the strength total, it is necessary to factor in how frequently each occurrence takes place in each accident category and what percentage of the total dataset that category represents. In Table 6, the weighted value is the sum of the co-occurrences multiplied by the percentage of the category of accidents. There were no cases of a co-occurrence being applicable to more than one accident category.

Table 7 shows the prioritized co-occurrences and the products of the strength sums multiplied by the weighted values.

Table 7

Prioritization of Co-occurrences Based on Strength × Weighted Value

Co-occurrence	Strength × weighted value
SIW 02 GPWS/EGPWS	7.29
TTC 02 Threat: Crew Factors – Other	2.70
TEC 01 Crew to External Communications	2.36
TTA 08 Threat: ATC – Other	1.71

TTE 01 Adverse Weather	1.32
TUS 01 Speed Deviation – High	0.46
TEM 85 Ground Damage/Injuries	0.36
OCC 02 Automation-Use Philosophy May Be Lacking	0.30
SYS 45 EICAS/ECAM	0.16

Figure 5 shows this prioritization in a graphic format. This Pareto-style chart depicts the most frequent occurrence on the left, with frequency decreasing to the right.

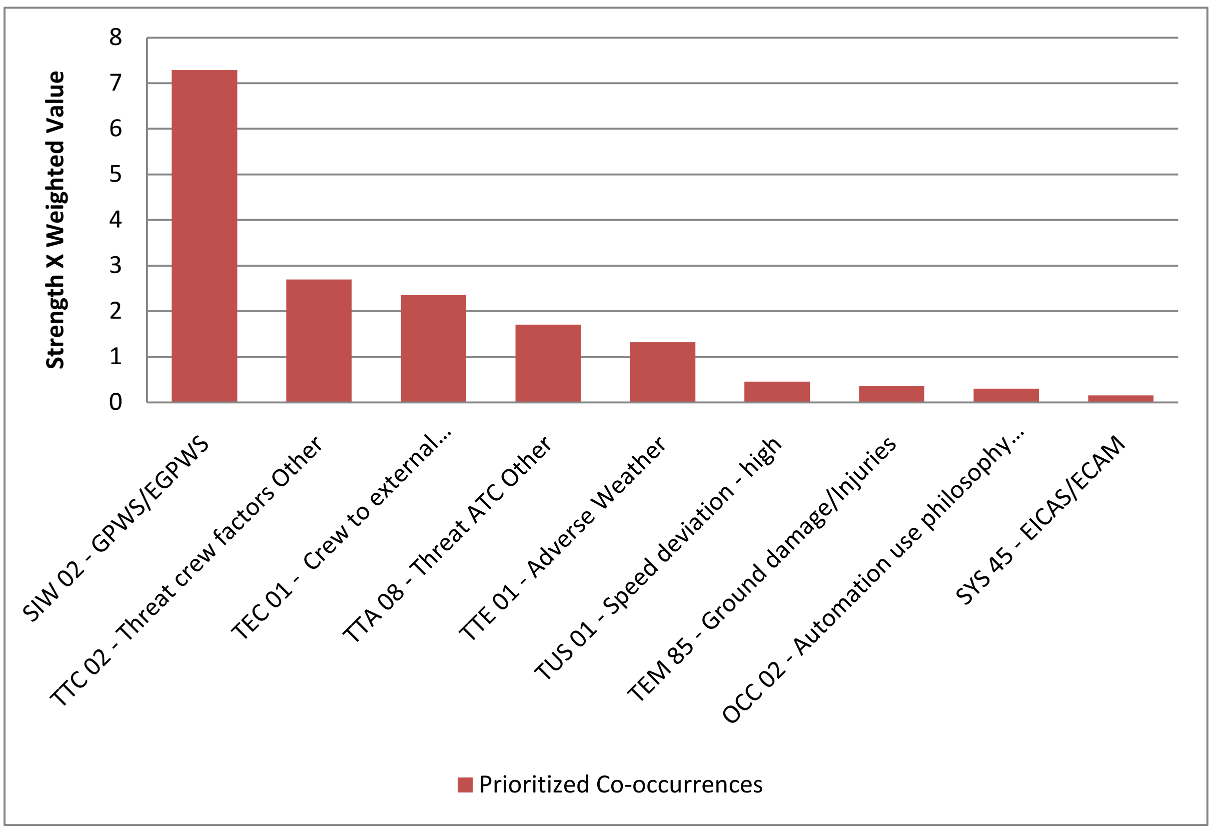


Figure 5. Prioritized co-occurrences based on calculation of strength × weighted value.

Further analysis shows that the top five categories account for 92% of the total. Therefore, it is clear that mitigations for the five categories of the strength totals times weighted values will provide the greatest benefit. This includes GPWS/EGPWS, Threat: Crew Factors – Other, Crew to External Communications, Threat: ATC – Other, and Adverse Weather.

Results

The flightpath management accidents selected by the FltDAWG occurred from 1994 to 2007. Over this period of time, there was a notable decrease in the number of Controlled Flight Into Terrain accidents. Furthermore, no aircraft equipped with EGPWS (also known as Terrain Awareness Warning System or TAWS) has suffered a Controlled Flight Into Terrain accident (Learmont, 2009). This fact alters the implications for some parts of the analysis since it predicts different risk factors for past versus future events. In this case, using past events to predict the future requires additional considerations.

Dataset analysis shows the most significant co-occurrence was GPWS/EGPWS. This would usually result in a recommendation for mitigations to lower the rate of Controlled Flight Into Terrain accidents. However, this mitigation is already in place, with results showing its effectiveness. From 1999 to 2008, 17 of 91 accidents (19%) were Controlled Flight Into Terrain. The percentage of Controlled Flight Into Terrain accidents has decreased, with Loss of Control – Inflight now being the highest category with 22 of 91 accidents (24%) during that same period (BCA, 2009). The installation of EGPWS (TAWS) has proven to be an effective mitigation.

The second most significant co-occurrence was the category of threats created by the flight crew. Although the percentage of flightcrew errors is decreasing (Baker, Qiang, Rebok, & Li, 2008), flight crew errors remains one of the most significant causes of accidents and, therefore, a high priority. Mitigations have included improved training in crew resource management, decision-making, and threat and error management. Considering the ambiguous name of this co-occurrence category (Threat: Crew Factors – Other), there is not a definitive area of focus. Therefore, it must be assumed that these flightcrew errors are nonspecific and variable.

Examples of accidents in this category include the American Airlines Boeing 757 crash in December 1995 in which the flight crew's errors caused the accident (Ladkin, 1996), and the November 2004 accident of a Gulfstream III in Houston, Texas in which the NTSB determined the probable cause as "the flight crew's failure to adequately monitor and cross-check the flight instruments during the approach. Contributing to the accident was the flight crew's failure to select the instrument landing system frequency in a timely manner and to adhere to approved company approach procedures, including the stabilized approach criteria" (NTSB, 2006, p. 21). In the total dataset there were ten accidents in which this co-occurrence was listed.

The third prioritized co-occurrence was Crew to External Communications. In these cases, the crew and air traffic control experienced communication issues. These issues included missed radio calls, misinterpretation of instructions, incorrect read-backs, or wrong clearances. Examples include American Airlines Flight 965 in December 1994 (Ladkin, 1996) and Gol Airlines Flight 1907 midair collision in September 2006 (AAIPC, 2008). In both accidents there was confusion between the pilots and the air traffic controllers. In the dataset there were seven accidents in which this co-occurrence was listed. There are seven accidents that share crew errors and crew-to-external errors.

The fourth prioritized co-occurrence was that of unspecified air traffic control threats. While this too is an ambiguous category, it was present in five accidents in the dataset including all crew-to-external accidents. Examples include the previously cited American Airlines Boeing 757 and the Gol Boeing 737 accidents.

The fifth prioritized co-occurrence was Adverse Weather. This category included thunderstorms, turbulence, poor visibility, wind shear, icing conditions, or instrument metrological conditions (i.e. flight solely by reference to instruments). Examples include the Gulfstream III, N85VT, accident in Houston, Texas in November 2004 (NTSB, 2006) and the Airbus A320 accident near Sochi Airport in May 2006 (IAC, 2007). In both cases there was inclement weather affecting the flights. Low visibility required instrument approach procedures to be flown to the runway. There were seven accidents with this co-occurrence in the dataset.

Recommendations

Decreasing numbers of Controlled Flight Into Terrain accidents correlates with the increasing numbers of EGPWS units in service. There are over 30,000 EGPWS units currently installed in the commercial fleet (Honeywell, n.d.) and that number is growing. The co-occurrence of GPWS/EGPWS is expected to be lower in the future than it has been in the past due to the continued effectiveness of EGPWS. Therefore, incorporation of this technology provides a reasonable mitigation for the GPWS/EGPWS co-occurrence category. Continued reduction in the number of Controlled Flight Into

Terrain accidents should be verified with monitoring the effectiveness of EGPWS and improvement of the technology when possible.

Crew-caused threats remain a challenge to safety in the aviation industry. While newer airplanes have an improved accident rate overall (BAC, 2009), crew-caused threats continue to be significant factor. The category Threat: Crew Factors – Other is the nonspecific grouping for threat factors caused by the crew. In the dataset there are six accidents in which this category was cited (all in Controlled Flight Into Terrain accidents). In each accident, there were procedural compliance issues. Inadvertent and/or intentional failure to follow standard operational procedures—such as initiating an immediate go-around below 500 feet when the approach is not fully stabilized—can contribute to an accident. Therefore, mitigating this risk should incorporate specialized training for pilots in which an emphasis is put on the importance of procedural compliance, duties in the event of non-compliance, crew resource management, and reporting of non-compliance. Strict adherence to operational procedure could result in a reduced the likelihood of these accidents and will probably prevent future accidents.

Crew to external communication errors and ATC threats are similar categories as both involve ineffective communication between pilots and external parties, including air traffic control. International flights can present language difficulties which can contribute to accidents, as was the case for American Airlines Flight 965 (Ladkin, 1996). However, international flights are not the only flights at risk for communication challenges. Communication skills are critically important, and for aviation workers that includes knowledge of standard phraseology to facilitate crew–external comprehension in both international and domestic airspace. While air traffic control can add complexity to flight path management, it is essential that pilots remain contextually aware and recognize when an instruction from air traffic control presents an unacceptable risk. In this context an unacceptable risk is defined as an ATC instruction that would result in a breach of standard operating procedure. One example would be an ATC-commanded rushed approach causing the approach to be unstable and thus requiring a go-around. Proper communications procedure requires that ATC be notified of the consequences of the rushed approach at the earliest possible time, thereby allowing alternative planning. To mitigate the communication risks, training programs using actual examples of communication breakdowns should be implemented. The use of real-world examples is important to show how other flight crews handled actual occurrences.

Flying in adverse weather is always a challenge. Low-visibility conditions, turbulence, or thunderstorms resulted in seven Controlled Flight Into Terrain accidents in the dataset. While EGPWS may be beneficial to avoid future Controlled Flight Into Terrain accidents, adherence to standard procedure will also be beneficial. By combining two aforementioned mitigations—EGPWS and procedural-compliance training—the risk of accidents during adverse weather can be reduced. Industry best practices for operations during adverse weather should be adopted in order for these mitigations to be effective.

Conclusions

By utilizing data provided by the FltDAWG, categorizing it to form the dataset, and analyzing this data using the Pathfinder software, it was possible to prioritize risk mitigations for four accident categories. These four categories—Controlled Flight Into Terrain, Loss of Control – Inflight, Runway Excursion, and Landing Off Runway—were frequent accident categories for commercial aviation from 1994 to 2008. These methods of analysis minimized subjectivity and produced an objective means to list and prioritize co-occurrences.

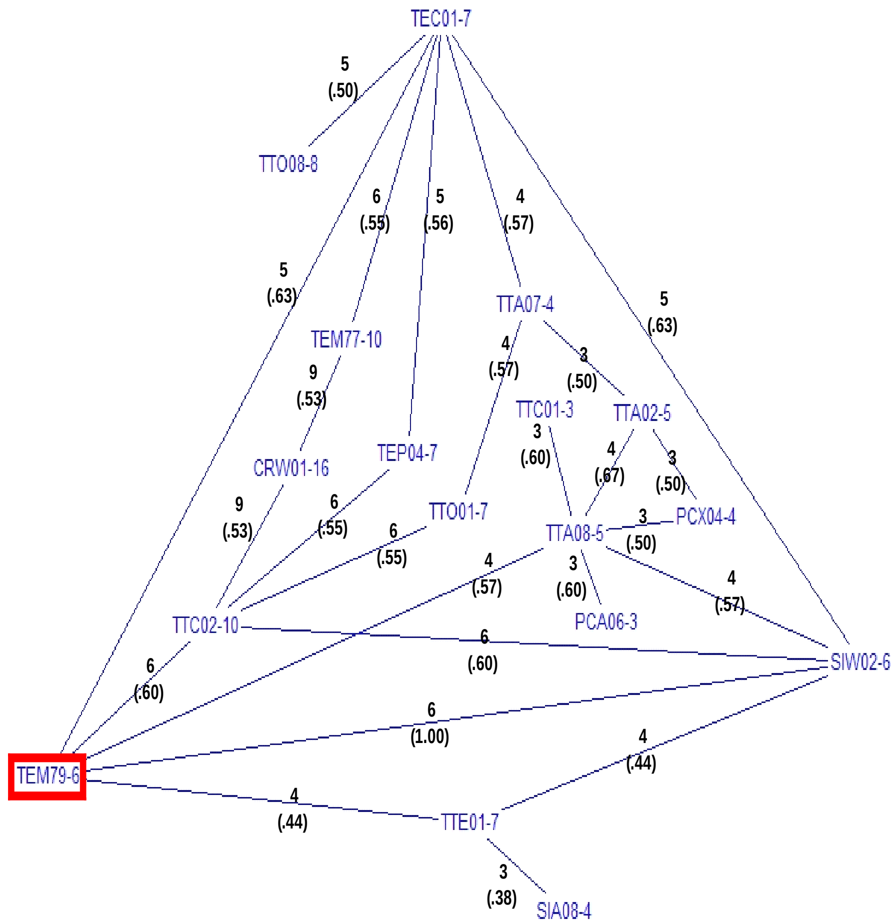
The data-driven approach allowed categories that co-occurred in the highest risk accident types (those that occurred most frequently) to be weighted based on that higher occurrence. Additionally, the ability to calculate the strength of the relationship between the occurrences permitted the construction of a hierarchy. After the hierarchy was normalized by adding Level 1 and Level 2 occurrences together and weighting them for accident type, a value was derived showing the relation of the risks.

Once this relationship was established, different mitigations for the top five risks were suggested. These recommendations were intended to create cost-effective options for the reduction of risk in airline operations. Cost effectiveness is obtained by utilizing mitigations to cover more than one co-occurrence category. Decreasing the frequency of co-occurrence results in fewer factors that can result in accidents, thereby reducing the overall risk.

This type of data-clustering analysis has only rarely been used for the analysis of aircraft accidents. Evaluation of the technique has shown it to be effective and useful. Future determination of risk mitigation priorities will benefit from this type of analysis to refine risk reduction cost-effectively. Thus the use of a data-driven prioritization for mitigations of the highest risk accident types proved to be effective.

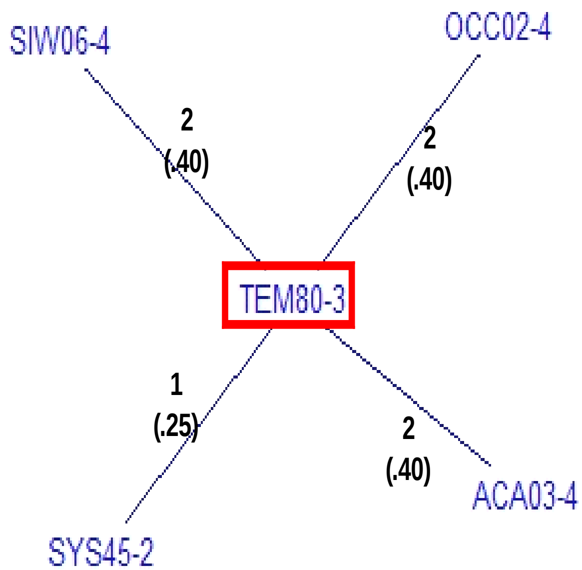
Appendix A:

Visual Representations of Levels of Co-occurrence



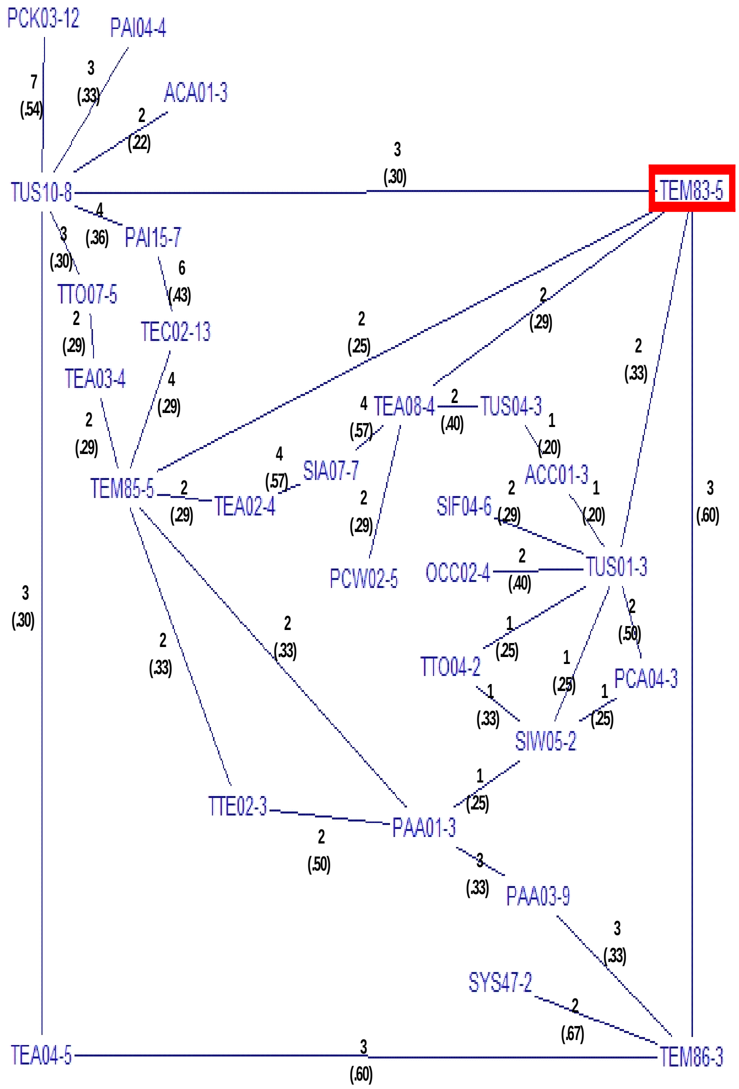
Code	Factor Name
TEM79	**TEM End State: Controlled Flight into Terrain**
CRW01	Issue: crew coordination problems may occur (Issue 084)
PCA06	Issue: automation use may be vulnerable to cockpit distractions (Issue 171)
PCX04	Issue: pilot centered situation awareness other (Issue 184)
SIA08	System: Autoflight Other
SIW02	System: GPWS/EGPWS
TEC01	TEM Error: Crew -to -External Communications
TEM77	TEM Error: Monitor
TEP04	TEM Error: Briefings
TTA02	TEM Threat: Controller Clearance/Instructions
TTA07	TEM Threat: Communications Problems
TTA08	TEM Threat: TEM Threat ATC Other
TTC01	TEM Threat: Fatigue
TTC02	TEM Threat: TEM Threat Crew Factors Other
TTE01	TEM Threat: Adverse Weather
TTO01	TEM Threat: Operator Operational Pressure
TTO08	TEM Threat: Policy/Procedures

Figure A1. First- and second-level co-occurrences for Controlled Flight Into Terrain. “Flight Deck Automation Group Report” by E. Lyall and J. Wilson, 2010. Manuscript in preparation.



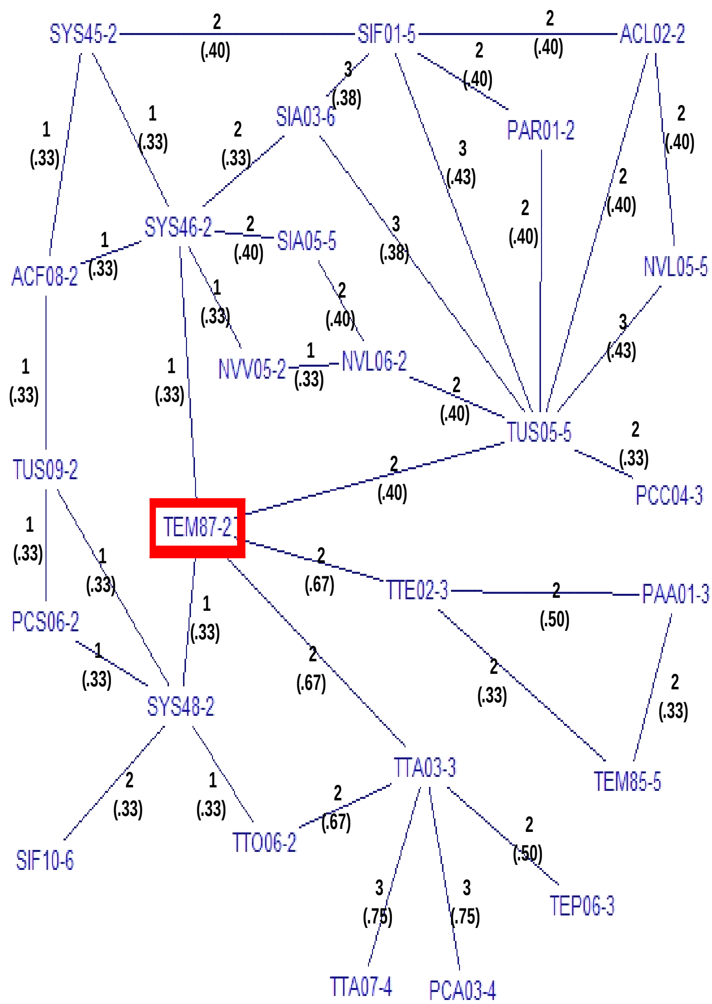
Code	Factor Name
TEM80	**End State: Loss of Control In -flight**
ACA03	Issue: failure recovery may be difficult (Issue 023)
OCC02	Issue: automation use philosophy may be lacking (Issue 101)
SIW06	System: Pre -stall stick shaker/pusher
SYS45	System: EICAS/ECAM

Figure A2. First- and second-level co-occurrences for Loss of Control – Inflight. “Flight Deck Automation Group Report” by E. Lyall and J. Wilson, 2010. Manuscript in preparation.



Code	Factor Name
ACA01	Issue: failure modes may be unanticipated by designers (Issue 024)
ACC01	Issue: automation may be too complex (Issue 040)
OCC02	Issue: automation use philosophy may be lacking (Issue 101)
PAA01	Issue: mode transitions may be uncommanded (Issue 044)
PAA03	Issue: mode awareness may be lacking (Issue 095)
PAI04	Issue: programming may be susceptible to error (Issue 170)
PAI15	Issue: displays (visual and aural) may be poorly designed (Issue 092)
PCA04	Issue: both pilots' attention simultaneously diverted by programming (Issue 075)
PCK03	Issue: automation behavior may be unexpected and unexplained (Issue 108)
PCW02	Issue: automation may lack reasonable functionality (Issue 109)
SIA07	System: CDU/MCDU
SIF04	System: ADI/EADI
SIW05	System: High speed limit warning
SYS47	System: Speed Mode
TEA02	TEM Error: FMC/FMGC
TEA03	TEM Error: A/P
TEA04	TEM Error: A/T and Associated Controls
TEA08	TEM Error: CDU/MCDU
TEC02	TEM Error: Pilot -to-Pilot Communications
TEM83	TEM End State: Runway Excursion
TEM85	TEM End State: Ground Damage/Injuries
TEM86	TEM End State: Loss of Control on Ground
TTE02	TEM Threat: Airport Conditions
TTO04	TEM Threat: Ground Maintenance
TTO07	TEM Threat: Manuals/Charts
TUS01	TEM UAS: Speed Deviation - High
TUS04	TEM UAS: Vertical Flight Path Deviation - High
TUS10	TEM UAS: TEM UAS Other

Figure A3. First- and second-level co-occurrences for Runway Excursion. "Flight Deck Automation Group Report" by E. Lyall and J. Wilson, 2010. Manuscript in preparation.



Code	Factor Name
TEM87	**TEM End State: Touchdown off runway surface**
ACL02	Issue: protections may be lost though pilots continue to rely on them (Issue 015)
NVL05	System: LOC
NVL06	System: VOR
NVV05	System: Altitude hold
PAA01	Issue: mode transitions may be uncommanded (Issue 044)
PAR01	Issue: pilots have responsibility but may lack authority (Issue 012)
PCA03	Issue: monitoring requirements may be excessive (Issue 005)
PCC04	Issue: pilots may be reluctant to assume control (Issue 026)
PCS06	Issue: pilot centered skill other (Issue 185)
SIA03	System: MCP/FCU
SIA05	System: F/D
SIF01	System: FMA
SIF10	System: Flight Instr Displays Other
SYS45	System: EICAS/ECAM
SYS46	System: Heading
SYS48	System: Other modes other
TEM85	TEM End State: Ground Damage/Injuries
TEP06	TEM Error: TEM Error Procedural Other
TTA03	TEM Threat: ATC Error
TTA07	TEM Threat: Communications Problems
TTE02	TEM Threat: Airport Conditions
TTO06	TEM Threat: Dispatch/Paperwork
TUS05	TEM UAS: Vertical Flight Path Deviation - Low
TUS09	TEM UAS: Incorrect Aircraft Configurations

Figure A4. First- and second-level co-occurrences for Landing Off Runway. “Flight Deck Automation Group Report” by E. Lyall and J. Wilson, 2010. Manuscript in preparation.

Appendix B:
List of Level 1 and Level 2 Categories

ACA 01	Failure mode may be unanticipated by designers.
ACA 02	Failure assessment may be difficult.
ACA 03	Failure recovery may be difficult.
ACC 01	Automation may be too complex.
ACF 08	Automation integration may be poor.
ACL 02	Protections may be lost though pilots continue to rely on them.
ACL 03	Manual operation may be difficult after transition from automated control.
CRW 01	Crew coordination problems may occur.
NVL 05	LOC [Localizer]
NVL 06	VOR [Very High Frequency Omni Directional Range]
NVV 05	Altitude hold
OCC 02	Automation-use philosophy may be lacking.
PAA 01	Mode transition may be uncommanded.
PAI 04	Programming may be susceptible to error.
PAI 15	Displays (visual and aural)
PAR 01	Pilots have responsibility but may lack authority.
PCA 03	Monitoring requirements may be excessive.
PCA 04	Both pilots attention simultaneously diverted by programming
PCA 06	Automation use may be vulnerable to cockpit distraction
PCC 04	Pilots may be reluctant to assume control.
PCK 03	Automation behavior unexpected or unexplained

PCS 06	Pilot-centered skills – Other
PCW 02	Automation may lack reasonable functionality.
PCX 04	Pilot-centered situation awareness – Other
SIA 03	MCP/FCU
SIA 05	F/D [Flight Director]
SIA 07	CDU/MCDU
SIA 08	Autoflight – Other
SIF 01	FMA
SIF 04	ADI/EADI
SIF 10	Flight instrument displays – Other
SIW 02	GPWS/EGPWS
SIW 05	High speed limit warning
SIW 06	Pre-stall stick shaker/pusher
SYS 45	EICAS/ECAM
SYS 46	Heading
SYS 47	Speed mode
SYS 48	Other modes – Other
TEA 02	FMC/FMGC
TEA 03	Autopilot
TEA 04	A/T and associated controls
TEA 06	Information management
TEA 08	CDU/MCDU
TEC 01	Crew to external communications

TEC 02	Pilot-to-pilot communications
TEM 77	Monitor
TEM 85	Ground damage/injuries
TEM 86	Loss of control on ground
TEP 04	Briefings
TEP 06	Error procedural – Other
TTA 02	Controller clearance/instructions
TTA 03	ATC error
TTA 07	Communications problems
TTA 08	Threat: ATC – Other
TTC 01	Fatigue
TTC 02	Threat: Crew Factors – Other
TTE 01	Adverse weather
TTE 02	Airport conditions
TTO 01	Fatigue
TTO 04	Ground maintenance
TTO 06	Dispatch paperwork
TTO 07	Manuals/charts
TTO 08	Policies/Procedures
TUS 01	Speed deviation – High
TUS 02	Speed deviation – Low
TUS 04	Vertical flight path deviation – High
TUS 05	Vertical flight path deviation – Low

TUS 07	Altitude deviation – Low
TUS 09	Incorrect aircraft configurations
TUS 10	Undesired aircraft state – Other

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