Aircraft Loss of Control Causal Factors and Mitigation Challenges

Steve Jacobson
NASA Loss of Control Study team Lead
NASA Dryden Flight Research Center
Edwards, CA

Outline

- Introduction
- NASA Loss of control study team approach
- Background on aircraft loss of control accident statistics
- Causal factors
- Recommended mitigations
- Supporting Research

Abstract

Loss of control is the leading cause of jet fatalities worldwide. Aside from their frequency of occurrence, accidents resulting from loss of aircraft control seize the public's attention by yielding a large number of fatalities in a single event. In response to the rising threat to aviation safety, the NASA Aviation Safety Program has conducted a study of the loss of control problem. This study gathered four types of information pertaining to loss of control accidents: (1) statistical data; (2) individual accident reports that cite loss of control as a contributing factor; (3) previous meta-analyses of loss of control accidents; and (4) inputs solicited from aircraft manufacturers, air carriers, researchers, and other industry stakeholders. Using these information resources, the study team identified the causal factors that were cited in the greatest number of loss of control accidents, and which were emphasized most by industry stakeholders. This report describes the study approach, the key causal factors for aircraft loss of control, and recommended mitigation strategies to make near-term impacts, mid-term impacts, and Next Generation Air Transportation System impacts on the loss of control accident statistics.

Loss of Control defined

Source	Definition
2000 CAST JSAT Report on Loss of Control	**Loss of control to includes significant, unintended departure of the aircraft from controlled flight, the operational flight envelope, or usual flight attitudes, including ground events.** "Significant" implies an event that results in an accident or incident. This definition excluded catastrophic explosions, CFIT, runway collisions, complete loss of thrust that did not involve loss of control, and any other accident scenarios in which the crew retained control. **This does include loss of control, due to aircraft design, aircraft malfunction, human performance, and other causes**

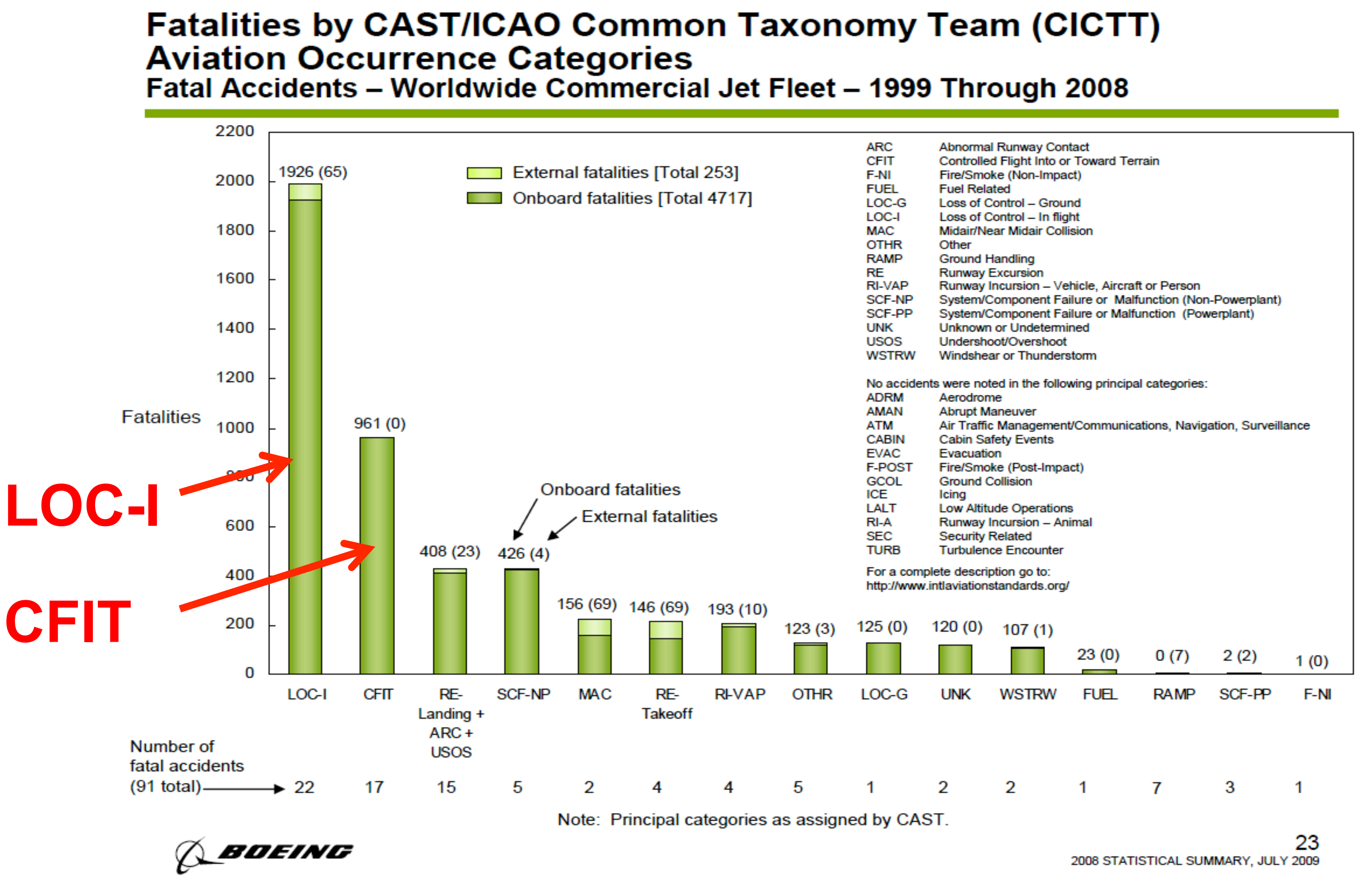
Current NASA LOC Research: IRAC-FAST Objectives

Can Modern Control Systems Help the Pilot Out Even More Than Traditional Methods????

- The above were survivable accidents; IRAC maybe able to help more.
- Objectives
  – Regain a Stable Platform
    - Evaluate Robustness metrics for nonlinear adaptive systems
  – Maneuverability (can you fly it around)
    - Control vehicle within new constraints / structural loads etc..
  – Provide the ability to safely land the airplane
    - Develop safest recovery trajectory

The current IRAC work falls under the mitigation categories of Avoidance and Recovery

Boeing's Annual Report (International accidents included)



LOC Study team objective

- This study team is to provide a systematic, data-driven analysis of the fundamental research required to address loss of control,
- Fourth Quarter CY09
- Study team expertise
  - All four NASA research centers represented
  - Skills on the team: flight control, flight dynamics, loss of control, flight research, aircraft icing, human factors, flight training, pilot-human automation, human performance, and human error.
- A hybrid approach was adopted

LOC Study Team Approach (3 months)

- Review statistical data; Statistics are good at categorizing accidents but don't provide much insight into mitigations
- Review some individual accident reports that cite loss of control as a contributing factor;
- Interviewed stakeholders
- Review previous meta-analyses of loss of control accidents;

LOC Study Team Approach (cont…)

- Identified causal factors that were cited in the greatest number of loss of control accidents, and which were emphasized most by industry stakeholders.
- For each causal factor that was linked to loss of control, the team solicited ideas about what solutions are required and future research efforts that could potentially help avoid their occurrence or mitigate their consequences when they occurred in flight

Analysis of accidents in the Boeing Statistical Summary LOC-I category

Causal factor category	# Accidents as Primary CF	# Accidents as Contributing CF
Pilot/human induced	16	22
Environmental induced	4	5
Systems induced	2	7

LOC-I Accidents that occurred in each causal factor category 1999-2008

Accidents identified from the LOC-I category in the Boeing Statistical Summary of Commercial Jet Airplane Accidents1999 - 2008

Analysis of accidents in the Boeing Statistical Summary LOC-I category

Causal factor	# Accidents w/CF
Pilot/human induced	
Improper Procedure	10
Spatial disorientation	6
Poor energy management	6
Distraction	5
Improper training	5
Poor design	2
Environmental induced	
Weather	3
Icing	2
Wake vortex	1
Systems induced	
Aircraft systems failures	5
Poor Design	2

Causal factors contributing to LOC-I commercial aircraft fatalities 1999 - 2008

Analysis of accidents in the Boeing Statistical Summary LOC-I category

Region	Number of fatal accidents
Asia (ex China)	6
Europe	5
Africa	4
Latin America/Caribbean	3
CIS	2
Middle East	1
USA/Canada	1
China	0

Regions where fatal LOC-I commercial aircraft fatalities occurred 1999-2008

Analysis of accidents in the Boeing Statistical Summary LOC-I category

Phase of flight	Number of fatal accidents
Climb	6
Take off	5
Final approach	3
Initial climb	2
Cruise	2
Initial approach	2
Landing	2

Flight phase where fatal loss of control accidents occur 1999 - 2008

Observations from the accidents in the Boeing Statistical Summary, LOC-I

- Finding 1: Out of the 22 accidents in the LOC-I occurrence category, the leading causal factors come from pilot/human induced category
- Finding 2: For large aircraft, the majority (95%) of recent LOC-I fatal accidents occur outside of the United States and Canada.
- Finding 3: The majority (81%) of recent LOC-I accidents occur during flight phases where the aircraft is relatively close to the ground where there is little time for action, and where circumstances are unforgiving of mistakes.

Observations from the accidents in the Boeing Statistical Data

- Finding 4: Flight crew deviation from prescribed procedure is a very significant factor in loss of control accidents.
- Finding 5: Spatial disorientation is a problem, but it occurs primarily outside of the United States.
- Finding 6: Poor energy management (e.g. aerodynamic stall) is a significant factor in loss of control accidents.

The Boeing Data only focus on Aircraft greater than 60,000 lbs.
Further Insight into smaller AC were needed

NASA Systems Analysis Report of Aircraft Loss of Control

- “Causal Factors and Adverse Conditions of Aviation Accidents and Incidents Related to Integrated Vehicle Aircraft Control” NASA TM-2010-216261
- Examines, Part 121, Part 135 scheduled and nonscheduled operations, and Part 91
- Dataset includes accidents and incidents from 1988 - 2004

Type of events	Operation Category				
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 91	Part 91, 135, & 121 Combined
Total Flight Hours	251,751,143	25,353,146	49,588,000	441,207,000	767,896,289
Total Accidents	630	217	1115	24473	26435
LOC Accidents	26 (4% of Total Accidents)	32 (15% of Total	198 (18% of Total Accidents)	4961 (20% of Total Accidents)	5217 (20% of Total Accidents)
LOC Accidents per million flight hours	0.10	1.26	4.03	11.24	6.79
Fatal Accidents	62 (10% of total accidents)	49 (23% of total accidents)	293 (26% of Total Accidents)	4815 (20% of Total Accidents)	5289 (20% of Total Accidents)
Fatal LOC Accidents	**21 (81% of LOC accidents)**	**19 (59% of LOC accidents)**	**128 (65% of LOC Accidents)**	**2635 (53% of LOC Accidents)**	**2803 (54% of LOC Accidents)**
Total Fatalities	2165	328	698	9146	12337
Fatalities in LOC Accidents	**1186 (55%)**	**161 (49%)**	**285 (41%)**	**5178 (57%)**	**6810 (55%)**
Total Incidents	7808	2234	2201	29520	41,763
LOC Incidents	38	5	8	81	132
LOC Incidents per million flight hours	**0.151**	**0.197**	**0.161**	**0.18**	**0.17**

Observations from the data in the NASA Systems Analysis study on LOC

- Finding 7: More than half of LOC-I events result in an accident and more than half of those accidents are fatal.
- Finding 8: In approximately 1/3 of Part 121 loss of control accidents, loss of control was due to a system component failure.
- Finding 9: Approximately 34% of all fatal Part 121 accidents are LOC accidents
- Finding 10: In approximately 1/3 of Part 121 accidents, the NTSB determined control was not possible.

Mitigations

- Mitigation Hierarchy (From system Safety Fundamentals)
  - Design/Eliminate the hazard
  - Safety devices to minimize risk
  - Detect/Warn
  - Procedures/Training
  - Placards

Mitigation Classification for LOC

- **Avoid:** Avoidance is usually tied to design of systems that eliminate the hazard and safety mitigations but may also include standard operating procedures and training to avoid loss of control scenarios.
- **Detect:** Detection is tied to the detect/warn category of mitigations and these mitigation strategies but may also include training to recognize the onset of a hazardous situation.
- **Recover**: Recovery is the last line of defense and has strong ties to the procedures/training category, but may also benefit from automatic systems, safety devices and warning devices to aid in the recovery of the vehicle.

Mitigation Development strategy

- **Near term impact (5-10 yrs):** LOC Training, Better standard operating procedures
- **Mid Term impact (5 – 20 yrs):** IVHM, improved displays, aircraft attitude and energy management tools, envelope protection/limiting, improved automation and warning systems, adaptive control
- **NextGen impact (Long term):** Aircraft design, system architectures, improved V&V

Mitigations and statistical summaries

- Statistical Summaries don’t do a good job of pointing to mitigations due to the loss of the supporting details.
- Understanding the details of accidents are important
- Discussing candidate mitigations with stakeholders provides good insight into mitigations

Stakeholders consulted during the Aircraft LOC Study

- Regulatory agencies
  - FAA
  - NTSB
- Operators
  - Air Line Pilots Association (ALPA)
  - Commercial pilots
  - Safety directors for Airlines
- Manufacturers
  - Boeing
  - Airbus
  - Honeywell
- Other organizations
  - CAST members
  - NASA
  - CALSPAN
  - Flight Safety

Stakeholder feedback: Research Needs

Envelope protection, envelope limiting and energy management (Avoid LOC). Stakeholders indicated that a high-priority mitigation toward preventing LOC is inhibiting an otherwise healthy aircraft from entering an unsafe condition.

1) Envelope protection: understand the benefits and identifying potential hazards
2) Envelope limiting:
3) Displays and automation for improved energy management
4) Automatic use of the propulsion system for envelope protection:
5) Partnerships to participate in verification and validation of these technologies.

Stakeholder feedback: Research Needs (Continued….)

Improved automation for human factors Mitigation (Avoid LOC). Stakeholders indicated that complexity of automatic systems, poor system architecture and a lack of human factors considerations in automatic systems are a key causal factor in aircraft loss of control. Potential mitigations include;

- 1) Reduced complexity in automation interfaces
- 2) Improved models of systems for increased pilot understanding
- 3) Improved feedback to the pilot about the state of automatic systems
- 4) Improved coordination between autopilot and autothrust systems
- 5) Automatic prevention of loss of control and pilot aids for recovery from a loss of control event.
- 6) Reduced "startle factor" for changes in automation ("bark before bite")

Stakeholder feedback: Research Needs (Continued….)

Training for upset recovery and prevention (Avoid, Detect, and Recover from LOC).

- Stakeholders are widely divided on the topic of training for loss of control recovery and prevention.
- Pilot unions and operators are at odds with regard to upset prevention and recovery training.

Key needs toward addressing LOC prevention and recovery training:

1) Research to develop training products for externally-induced loss of control (icing, wind shear, wake vortex, turbulence, heavy rain).

Stakeholder feedback: Research Needs (Continued….)

Key needs toward addressing LOC prevention and recovery training:

2) Identify the most effective way to train pilots to mitigate loss of control events:

a) Determine effective ways to utilize the URTA in training.

b) ID advantages and hazards with using motion-based and fixed-based simulations for training.

c) Perform research to understand where motion in simulation is most effective (seat cushion, gyroscopic devices, in-flight simulation, aerobatic training).

d) Prevention and recovery training: perform research that would give regulators, manufacturers, and operators guidance on the effective use of prevention training and the appropriate use of recovery training.

e) Research to determine when URT should be introduced to pilots during their career and how often to train for upset recovery to maintain proficiency.

Stakeholder feedback: Research Needs (Continued….)

Aerodynamic and dynamic model development for upset prevention and recovery (Recover).

- Stakeholders concerned about adequately modeling aircraft dynamics beyond the nominal flight envelope or in the presence of external influences such as wake vortex or icing.
- Inaccurate modeling may lead to negative training (AA587).
- key needs in the areas of aerodynamic and dynamic model development for upset prevention and recovery are:

1) Methods for accurate and cost-effective modeling outside the normal flight envelope

2) Development of generic models for upset prevention and recovery that include:

- Multiple configurations, Generic trends in models that can be used in training, Evaluate the effectiveness of generic models in training for specific aircraft types, Generic models that do not contribute to negative training

3) Research to determine control effectors most appropriate for loss of control recovery: Control effectiveness in unusual attitudes, Use of the propulsion system as an effector, Control allocation strategies.

Stakeholder feedback: Research Needs (Continued….)

Detection and notification of pending upset condition (Detect). Stakeholders consistently emphasized the need to identify the development of a pending upset condition and provide the crew with sufficient information so they can take appropriate action to prevent an upset. Quite often the crew are caught off guard at the onset of an upset condition and have only seconds within which to identify the correct response. Incorrect responses may lead to an unrecoverable condition. Technologies are needed that:

1) Identify and warn of degraded energy states
2) Provide asymmetric thrust detection and notification
3) Identify and notify of spatial disorientation
4) Predict and mitigate PIO
5) Detect icing conditions and buildup and provide notification
6) Detect aircraft aerodynamic changes using real time system identification.

Causal factors

Human Induced	Systems Induced	Externally Induced
– **Manual handling errors** – **Poor Energy Management** – **Automation Effects On Human Induced Loss-Of-Control** – **Spatial Disorientation** – **Improper Procedures**	– **Poor systems design** – **Poor energy management** – **Poor redundancy management** – **Autopilot modes leading to loss of control** – **Erroneous sensor data** – Pilot induced oscillation – Loss of control power, authority, or effectiveness – Display errors – Propulsion system faults/ failures/damage – Fire	– **Icing** – **Turbulence** – Degrading Visibility – Heavy Rain – Low-Level Windshear

Human induced LOC: Manual Handling Errors

CF: Inadequate Pilot Training for Upset Prevention and Recovery: inappropriate or erroneous control inputs by the flight crew in response to abnormal events or flight regimes.

Mitigation: Improved upset recovery training

- Study the impact of upset recovery training during transitional flight training
- Study the effectiveness of providing pilots with an enhanced understanding of the behavior of an aircraft near or outside the limits of normal flight regimes.
- Manual control strategies during upset recovery
- Development of aerodynamics and dynamic models for out of envelope conditions (including generic models)
- Understanding the importance of simulator motion in upset recovery training.
- Evaluate the use of In-flight simulators for Upset Recovery Training.

Human induced LOC: Manual Handling Errors

CF: Atrophy Of Manual Flying Skills

Mitigation: Provide pilots with increased opportunity to exercise manual flying skills.

– Assess how specific automated systems, both inside and outside the cockpit, are affecting the retention of manual flying skill.
– Develop guidelines for frequency of manual flight time for normal and abnormal operations in order to maintain pilot proficiency.
– Identify ways in which manual navigation, guidance, and control skills can be regularly practiced during normal flight operations in order to keep manual skills sharp.

CF: Poor Aircraft Handling Qualities During Upset Events

Mitigation: Develop automatic control mechanisms to prevent LOC, recover or aid in the recovery of the airplane

– Control aids for prevention and recovery from LOC .

Human induced LOC: Poor Energy Management

CF: Poor Energy Management

Mitigation: Improve pilot awareness of energy state.

- Display and alerting methodologies for critical aircraft configuration states.
- Design criteria and methodologies for low energy alerting and warning systems.
- Improved envelope protection and envelope limiting systems to maintain energy state.

Human induced LOC: Automation Effects On HI-LOC

CF: Automation Confusion/Mode Confusion

- ***Pilot misunderstanding of automation***
- ***Poor feedback to the pilot about the state of automation systems***
- ***Lack of understanding of automation systems by the pilot***
- ***Failure of automation system***

Mitigation: Develop more simple pilot interfaces to prevent confusion about automation.

– Human Centric Pilot interfaces.
– Human Centric Verification and Validation Methods .
– Develop Human Centric Models of Automatic Systems
– Procedures-plus-concepts training
– Research to determine most appropriate information to display to the pilot about the state of the automation

Systems Induced Loss of Control

- Flight critical components are designed to have a failure rate of 10^{-9} per hour of operation
- System/Component failure is a trigger for LOC in;
  - 1/3 of Part 121 LOC accidents
  - 11% of Part 135 LOC accidents
  - 8% of Part 91 LOC accidents

Systems Induced Loss of Control Causal factors

- Poor systems design
  - Poor energy management
  - Poor redundancy management
  - Autopilot modes leading to loss of control
  - Pilot induced oscillation (PIO)
- Air traffic operations
  - Unstable approaches
- Aircraft system faults/failures/damage (non propulsion)
  - Erroneous sensor data
  - Loss of control power, authority, or effectiveness
  - Automation and display errors
- Propulsion system faults/failures/damage
- Fire

Systems Induced LOC: Faults, Failures and Damage

Non fly-by-wire-aircraft (Commuter and GA)

Causal Factor: Poor energy management due to faults, failures or damage

Mitigation: Loss of control prevention and recovery systems for non-fly-by-wire aircraft:

- Participate in the development of automatic LOC prevention and recovery systems for non-fly-by-wire aircraft
- Participate in the development of techniques and guidance for recovery from LOC for non-fly-by-wire aircraft.

Other Systems related Mitigations and Research

- System Safety analysis of NextGen operations
- Forensics and trend prediction
  - Data mining FOQA, ASIAS and ASRS data for LOC trend information, causal factors and precursors to LOC

Environmentally Induced LOC

- Not as significant of a factor as human induced LOC

Causal Factor	Part 121 and 135 Scheduled (40 LOC accidents)	Part 135 Unscheduled (159 LOC accidents)	Part 91 (4287 LOC accidents)
Icing	54%	27%	6%
Turbulence	11%	22%	20%
Degrading Visibility	9%	14%	18%
Heavy Rain	6%	5%	2%
Low-Level Windshear	4%	3%	2%

Mitigation and Technical Challenges

- Improved health monitoring of aircraft systems
- Improved modeling in adverse conditions such as out-of-envelope flight
- Research to support loss of control training
- Maneuvering boundary identification and envelope limiting
- Pilot increased awareness about the health and state of the aircraft
- Integrated aerodynamics and propulsion control
- Automatic control system technology to provide good handling qualities
- Data mining for trend identification
- System Safety Analysis of NextGen operational impact
- Research to support improved verification and validation of complex systems.

Conclusions

- Human induced LOC causal factors are a stronger contributor to LOC accidents when compared to Systems induced and Environmentally induced causal factors.
- Avoidance and detection mitigations should be higher priority than recovery based mitigations but……
- Recovery based mitigations are important for coverage of "breaking the chain" of events.
  - Prevention and Recovery Training may have a nearer term impact than technology based solutions.
- New technologies and NextGen operations may introduce new and unforeseen LOC hazards.
  - Hazard analysis is required
  - Data mining of FOQA, NTRS and ASRS
- Verification and Validation methods need improvement to keep pace with NextGen complexities