National Aeronautics and Space Administration

Aircraft Loss of Control Study

Steve Jacobson
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 Accidents
- Causal factors
- Recommended mitigations
- Supporting Research

Abstract

Loss of control has become 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 large numbers of fatalities in a single event. In response to the rising threat to aviation safety, NASA's 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 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.

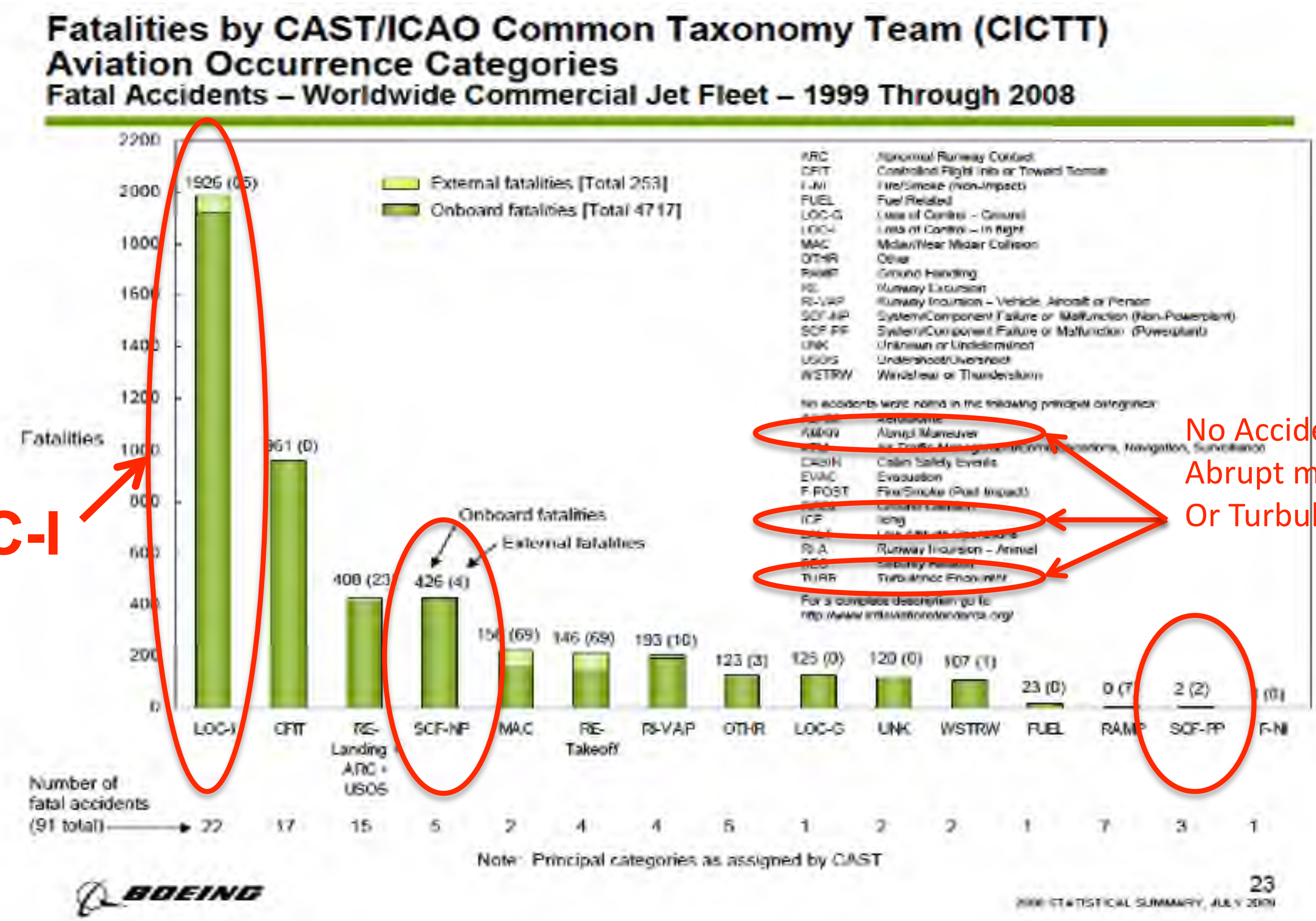
Loss of Control defined

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**

Loss of Control defined

Source	Definition
Airplane Upset Recovery Training Aid (2008)	While specific values may vary among airplane models, the following unintentional conditions generally describe an airplane upset: • Pitch attitude greater than 25 deg, nose up. • Pitch attitude greater than 10 deg, nose down. • Bank angle greater than 45 deg. • Within the above parameters, but flying at airspeeds inappropriate for the conditions.

Boeing's Annual Report (International accidents included)



LOC-I

No Accidents for
Abrupt maneuver, Icing
Or Turbulence encounter

So what's in there?

NASA AvSafe Loss of Control Study

Team Chartered in October through December

Role	Name	Center	Areas of Expertise
Team lead	Steve Jacobson	NASA DFRC	Flight research, flight dynamics
Member	John Foster	NASA LaRC	Flight research, flight dynamics, CAST loss of control study team
Member	Gautam Shah	NASA LaRC	Flight research, flight dynamics, CAST loss of control study team, API, Flight Control, IRAC
Member	Gene Addy	NASA GRC	Icing, Icing research tunnel, API for Icing in IRAC
Member	Andy Reehorst	NASA GRC	Icing, flight test, CAST JSIT and JSAT (LOC and Remaining Risk)
Member (primary)	Stephen Casner	NASA ARC	Human factors, flight training, pilot-automation interaction
Member (backup)	Jessica Nowinski	NASA ARC	Human factors, Human performance and Human Error, PM for IIFD

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,
- There is a lot of data out there and three months is not enough time to thoroughly analyze the data with seven people
- 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;
- Review previous meta-analyses of loss of control accidents;

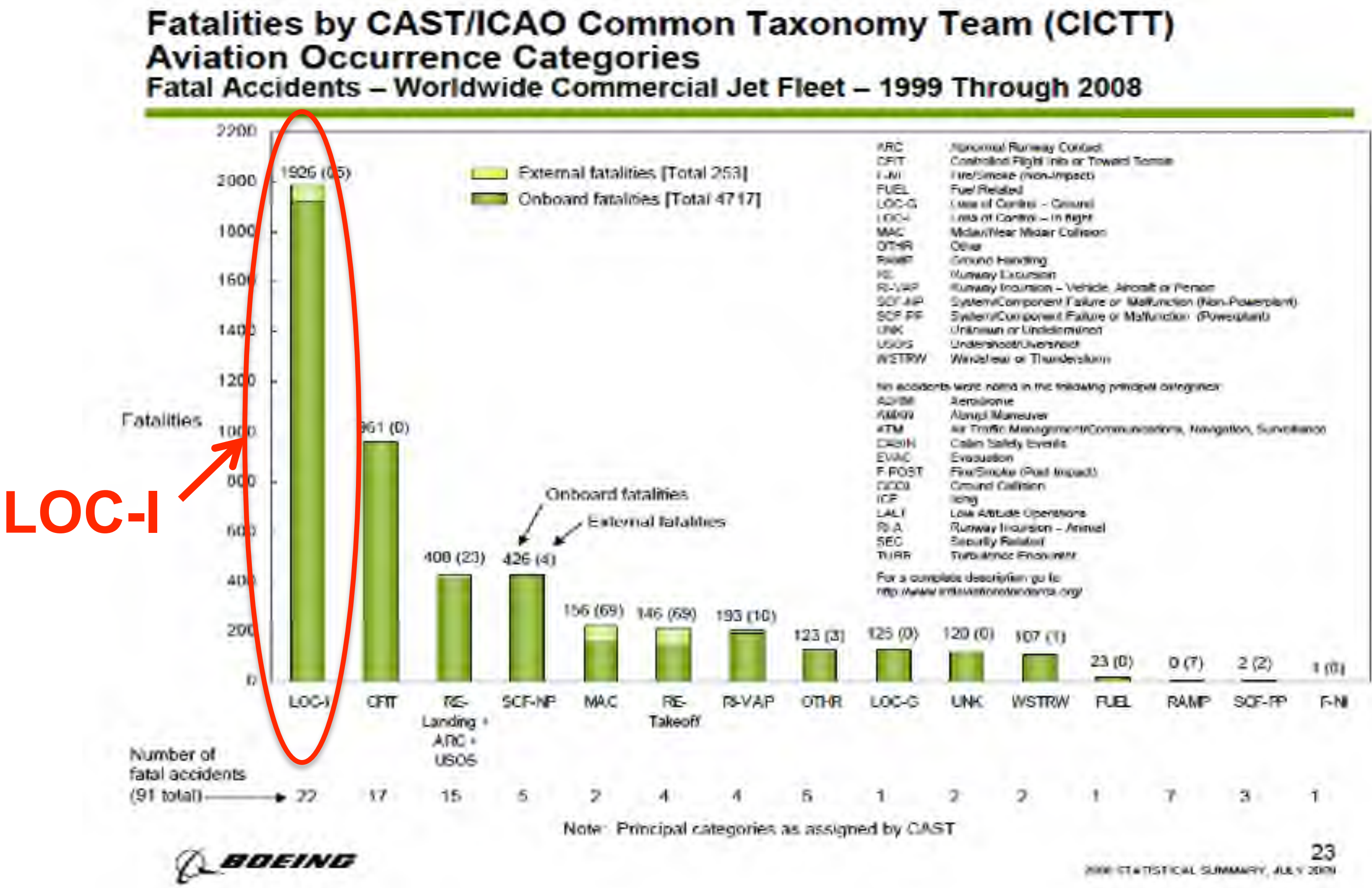
LOC Study Team Approach (cont…)

- 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
- Recommend priority to NASA on Mitigations and Research (not discussed in this presentation)

Background on Aircraft Loss of Control

- Much of the research focus has been on scheduled commercial transport aircraft (Part 121 operations)
- Other considerations for LOC
  - Part 135 (Commuter and on demand operations)
  - Part 91 (private operations or GA)

Boeing’s Annual Report (International accidents included)



So what’s in there?

Boeing Statistical data

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

Based on Boeing Statistical Summary of Commercial Jet Airplane Accidents1999 - 2008

Boeing Statistical data

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

Based on Boeing Statistical Summary of Commercial Jet Airplane Accidents1999 - 2008

Boeing Statistical data

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

Based on Boeing Statistical Summary of Commercial Jet Airplane Accidents1999 - 2008

Boeing Statistical data

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

Based on Boeing Statistical Summary of Commercial Jet Airplane Accidents1999 - 2008

Observations from the accidents in the Boeing Statistical Data

- 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
- Currently completing the review process
- Examines, Part 121, Part 135 scheduled and nonscheduled operations, and Part 91

Data from NASA Systems Analysis Report of Aircraft Loss of Control

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)	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**

NASA LOC SA report continued

Type of events	Operation Category				
	Part 121	Scheduled Part 135	Non-Scheduled	Part 91	Part 91, 135, & 121
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.

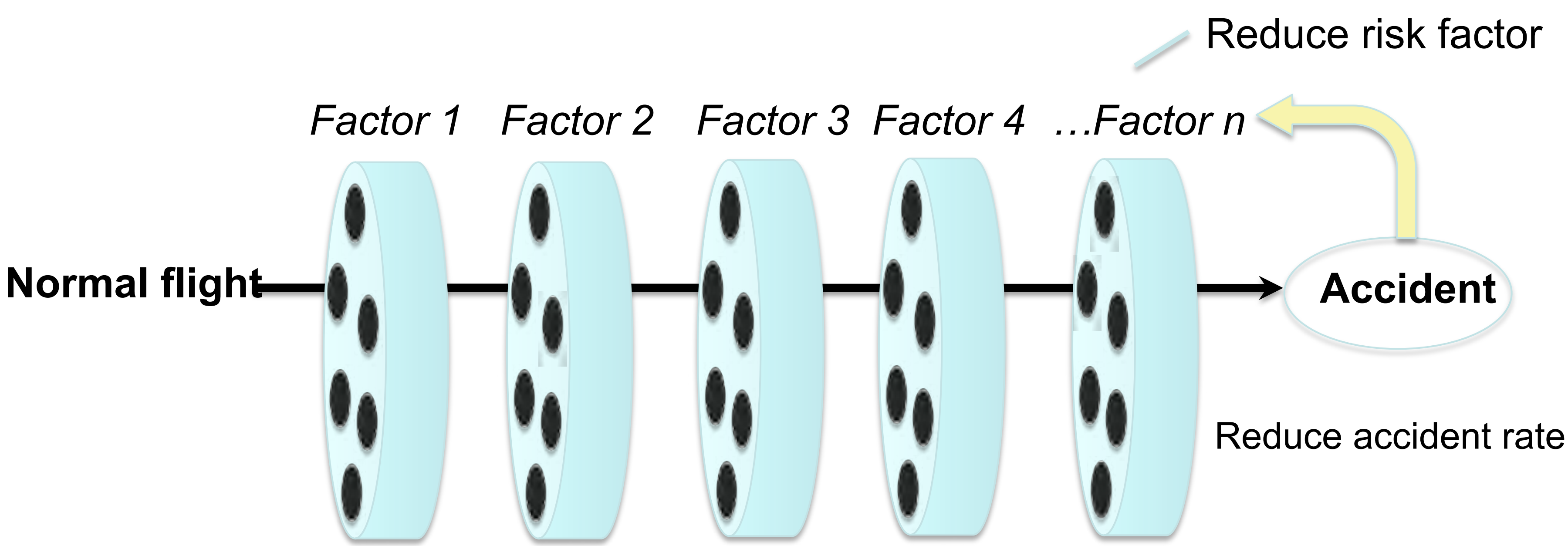
Mitigations

- ! Mitigation Hierarchy
  - –!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.

Accident elimination through elimination of multiple causal factors



Break the chain of events at multiple points and prevent the event
Due to the myriad of causal factors for LOC,
multiple strategies are warranted that include …
Avoidance, Detection and Recovery

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

NASA LOC Work: IVHM and IIFD

Upset recovery training for civil aviation

- General Aviation: Level stall recovery
- Commercial Aviation:
  - Stall prevention, including stick shaker
  - No stick pusher training in simulation
- Upset Recovery Training Aid
- FAA training rules are in the revision process

Loss of Control training in civil aviation is almost nonexistent

Upset Recovery Training Aid

http://www.faa.gov/pilots/training/

- Developed by Boeing, Airbus and Flight Safety (revised Nov, 2008)
  - Defines Upsets
  - Examines Causes
  - Aerodynamics
  - Recovery techniques
- Report, Briefing material, Videos
- Optional: Not widely adopted by industry

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

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 researchers
  - CALSPAN
  - Flight Safety

Stakeholder feedback: Research Needs

- **Training for upset recovery and prevention**
  - Identify the most effective way to train pilots to mitigate loss of control events
  - motion based vs. fixed based simulations
  - Prevention vs. Recovery training:
  - Conduct research that may be used to develop training products
- **Aerodynamic and dynamic model development for upset recovery and prevention**
- **Envelope protection, envelope limiting and energy management**

Causal factor categories

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

Human induced LOC: Manual Handling Errors

CF: Inadequate Pilot Training for Upset Recovery

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 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

Human induced LOC: Spatial Disorientation

CF: Spatial Disorientation

Mitigation: Train pilots to better recognize, avoid, and recover from spatial disorientation

Mitigation: Enhanced pilot warning and alerting systems for spatial disorientation

Mitigation: Enhanced envelope protection and envelope limiting technologies.

–! Understanding the causes and effects of spatial disorientation..

–! Spatial disorientation detection and recovery aids .

–! Strategies for using envelope protection and envelope limiting without introducing additional hazards .

* New CAST group is forming on SD and Energy management

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%

Environmentally Induced LOC: Icing

- Causal Factor: In-flight or ground Icing leading to:
  - Increased stall speed
  - Nonlinear flight dynamics
  - Propulsion system degradation
  - Air data problems
- Mitigations:
  - improved weather nowcast and forecast products
  - remote icing weather sensors
  - Operator and ground crew training
  - Development of advanced computational icing prediction methods.
  - Developing experimental icing databases making aircraft icing tolerant through the improvement of certification standards
  - Automated detection of ice accretion

Environmentally Induced LOC Icing

- Icing Mitigations:
  - improved weather nowcast and forecast products
  - remote icing weather sensors
  - Operator and ground crew training
  - Development of advanced computational icing prediction methods.
  - Developing experimental icing databases making aircraft icing tolerant through the improvement of certification standards
  - Automated detection of ice accretion
  - Develop flight dynamic models for ice contaminated wings.
  - Automated recovery from contaminated wing stall.
  - Detect HIWC conditions
  - Detect ice buildup in rotating and reciprocating engines.
  - Develop air data blockage detection technology

Systems Induced LOC: Poor design

Causal Factor: Poor design

- Lack of coordination between autopilot and autothrottles
- Poor use of redundancy management
- Poor indication to the pilot on the state of the automation
- Autopilot surprises the crew

- Mitigations
  - Verification and Validation (V&V) of complex systems
  - Integrated aerodynamic and propulsion control.

Systems Induced LOC: Faults, Failures and Damage

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

- –! Improved control during system faults, failures and damage
- –! Improved modeling of flight dynamics under failure/damage conditions.
- –! Advanced Control strategies for retaining good flying qualities during a failure or damage
- –! Advanced Control strategies for low-energy conditions
- –! Flight planning and Guidance tools for operation during failures and damage
- –! Relevant Maneuvering Envelope ID Technologies
- –! Automated Identification of Stability Boundaries
- –! Identification of Maneuvering Boundaries based on Structural Limits.
- –! Adaptive Guidance Technologies

Systems Induced LOC: Faults, Failures and Damage

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

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.

Systems Induced LOC: Erroneous sensor data

Causal Factor: Erroneous Sensor Data leads to lack of reliable airspeed, altitude and attitude

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

- –! Improved verification and validation of complex systems.
- –! Monitoring, Recognition, and Annunciation of Erroneous Sensor Data.

Propulsion system induced LOC Causal Factors (5% of LOC accidents)

- Asymmetric thrust
- Engine core ice accretion
- Engine fire
- Blade failure
- Thrust reverser deployment
- Thrust reverser control
- Combustor can failure
- Ice ingestion
- Bird ingestion
- Fuel system malfunction
- Throttle/power level incorrect
- Speedbrake/spoiler
- Fuel control
- Propeller pitch change mechanism
- Engine control
- Propeller blade

Propulsion system induced LOC Mitigations

- Asymmetric thrust detection
- Automatic compensation for Asymmetric Thrust
- Integrated Aerodynamic and Propulsion Control
- Development of robust propulsion control systems
- Characterize and eliminate turbofan engine core icing

Other Mitigations and Research

- System Safety analysis of NextGen operations
- Data mining of incident/accident reports and FOQA data to identify causal factors in loss of control.

Conclusions

- NASA is currently adjusting the research portfolio within Aviation Safety
- NASA priority for LOC research will be based on
  - Importance of causal factors
  - Relevance to NASA mission
  - Availability of resources
  - Skill mix required to perform the research