Investigation of Asymmetric Thrust Detection with Demonstration in a Real-Time Simulation Testbed

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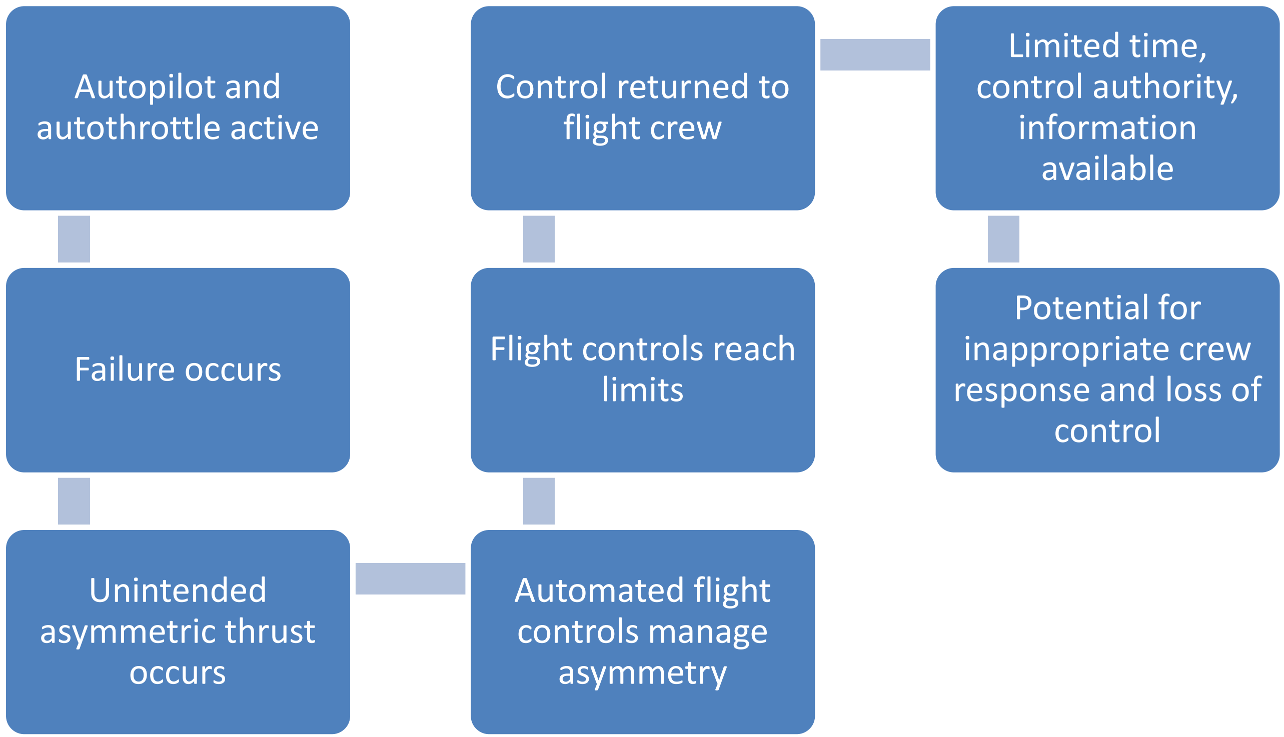
Outline

- Motivation and Background
- Asymmetric Thrust Detection Methods
- Results
- Conclusions

Motivation and Background

- Asymmetric thrust cited as cause of several loss of control aviation incidents and accidents
- Crew response may be inappropriate and exacerbate the situation
- Need recognition and response to unintended asymmetric thrust conditions
- Feasibility study initiated to evaluate three asymmetric thrust detection methods

Typical Sequence for Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR)



Example PSM+ICR

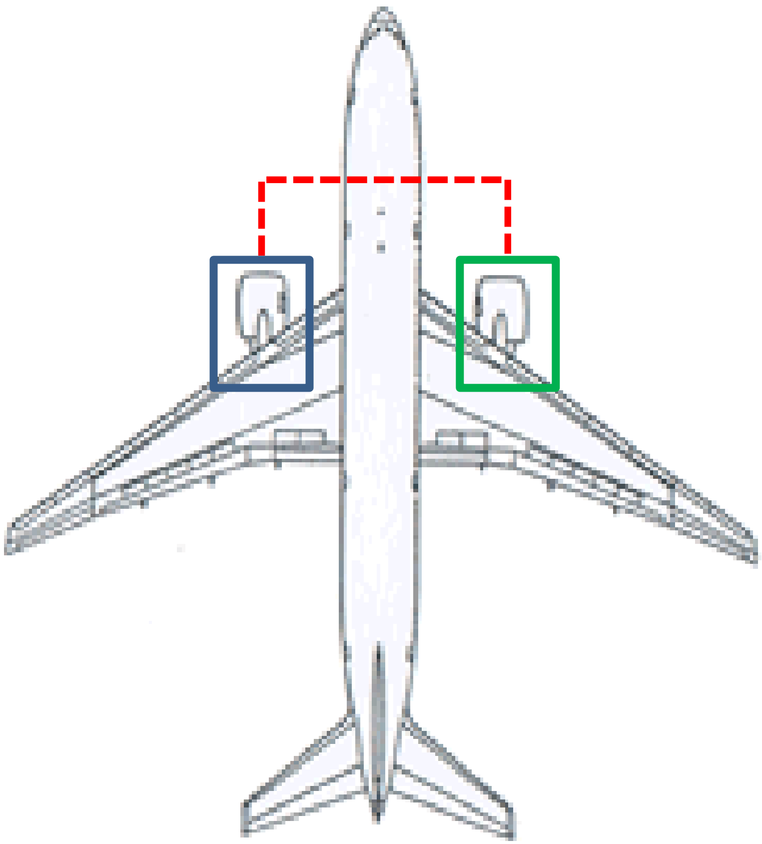
Event #74 in PSM+ICR Report

- March 31, 1995, Flight 371 for Tarom Romanian Airlines (Airbus A310), departs Balotesti, Romania for Brussels, Belgium
- Autothrottle was engaged as the aircraft was ascending through 2,000 ft when the flaps were retracted
- With reduction in drag from flaps, the autothrottle moved to decrease power
- However, number 2 (right) engine throttle was stuck in the take-off throttle position
- To reduce airspeed, the number 1 (left) engine throttle was decreased until it went to idle developing an asymmetric thrust condition
- Asymmetric thrust was not apparent since the aircraft was in a left turn for a heading change
- Roll due to thrust asymmetry was not noticed until the pitch attitude suddenly dropped
- Aircraft continued to roll over and crashed with no survivors

“Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR), Aerospace Industries Association and the European Association of Aerospace Industries Project Report, Vol. 1, November 1 (1998).

Asymmetric Thrust Detection Methods

- Two methods based on estimated thrust for cross wing comparison of two engines
  - Kalman Filter
  - Table Lookup



Estimated Thrust: Kalman Filter Method

$$\dot{\hat{x}}_{xq} = \left(A_{xq} - KC_{xq}\right)\Delta\hat{x}_{xq} + B_{xq}\Delta u + K\Delta y$$

$$\Delta\hat{y} = C_{xq}\Delta\hat{x}_{xq} + D\Delta u$$

$$\Delta\hat{z} = F_{xq}\Delta\hat{x}_{xq} + G\Delta u$$

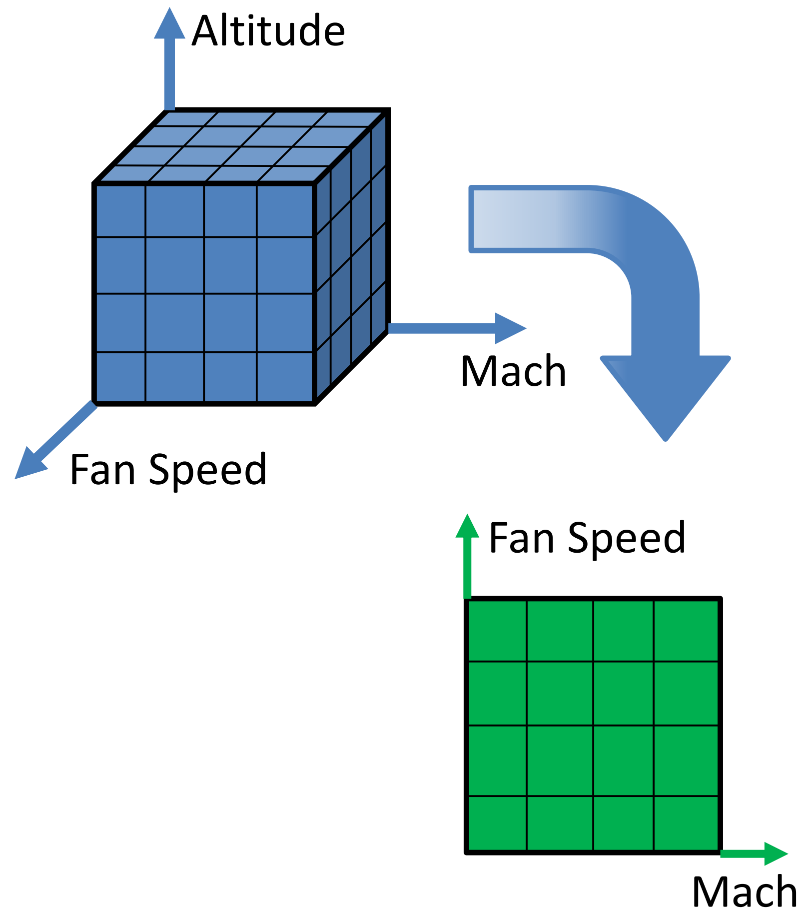
x – state vector
y – sensed output vector
u – actuator command vector
z – unmeasured output vector (net thrust)
A,B,C,D,F,G – state space matrices
K – Kalman gain matrix

- Piecewise linear model used to estimate non-measured parameters
- Kalman filter provides estimates that account for performance degradation over time

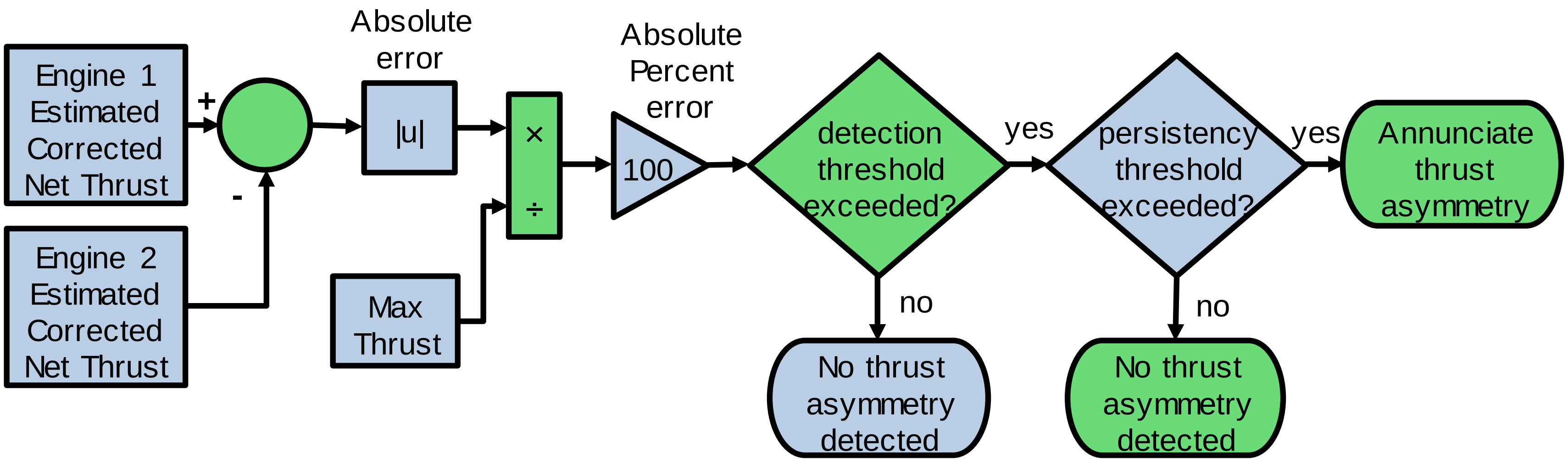
Estimated Thrust: Table Lookup Method

- Thrust tables calculated over entire flight envelope
  - Altitude
  - Mach
  - Fan Speed

- Thrust tables reduced through parameter correction to sea level conditions
  - Mach
  - Fan Speed

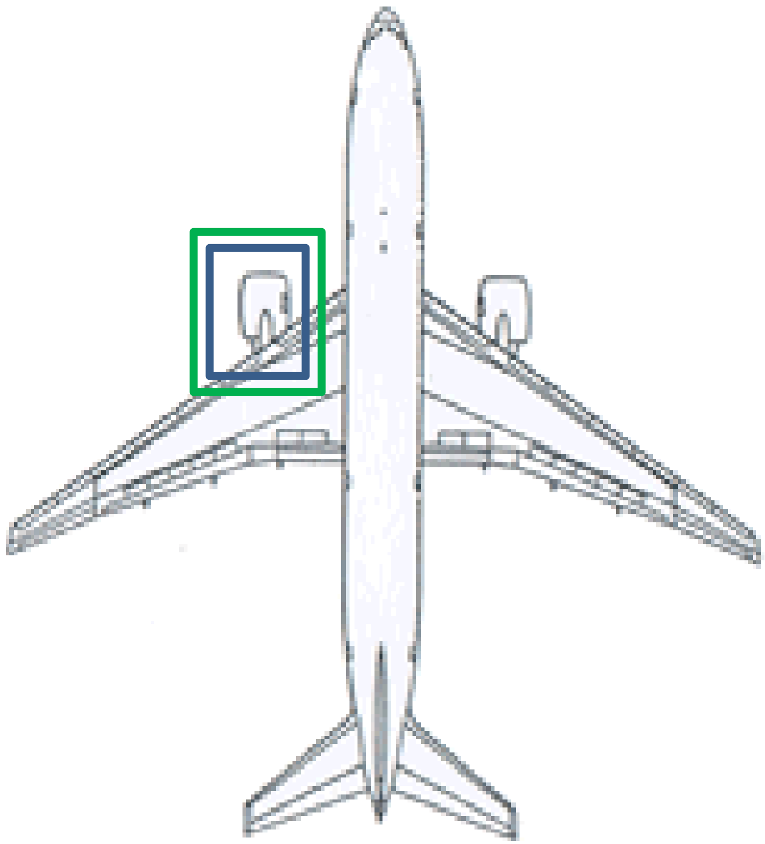


Thrust Estimation Asymmetric Detection Logic



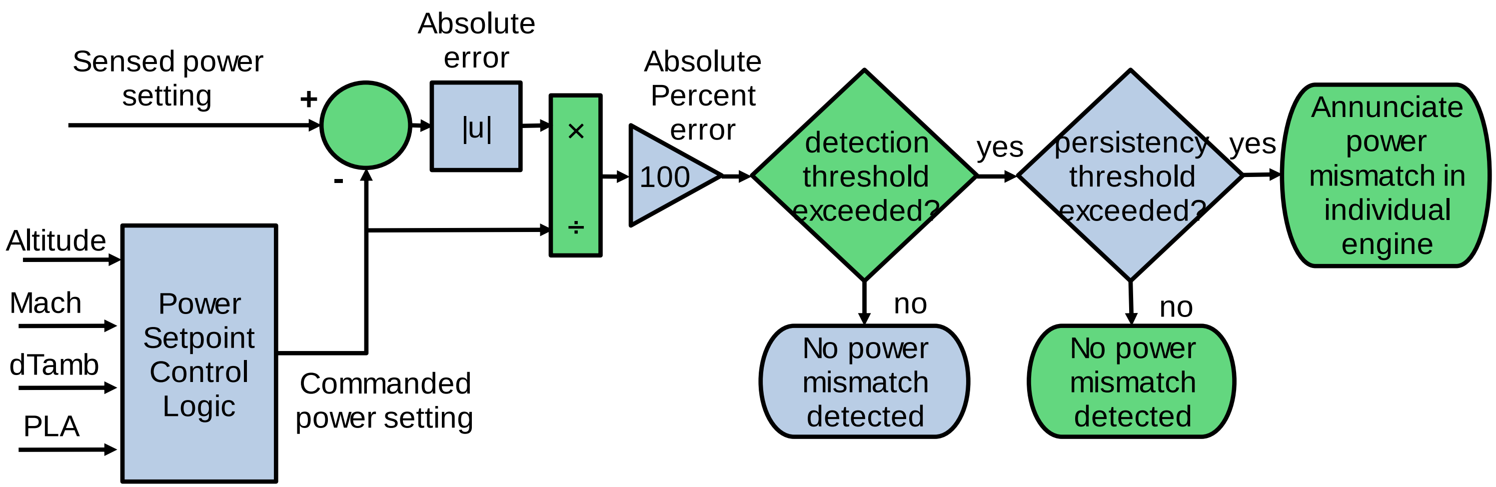
Asymmetric Thrust Detection Methods

- One method based on engine pressure ratio to compare commanded vs sensed signals for one engine



Engine Pressure Ratio Method and Detection Logic

- Engine Pressure Ratio (EPR)
  - $EPR = \frac{Engine\ Exit\ Pressure}{Engine\ Inlet\ Pressure} = \frac{P5}{P2}$
  - Commanded
  - Sensed
- EPR Method for Asymmetric Thrust Detection Logic

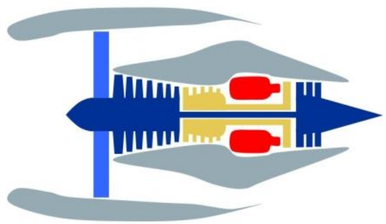


Results

- Asymmetric thrust detection sensitivity study
  - Accuracy of detection methods determined from Monte Carlo study to establish statistical baseline
- Piloted flight simulation evaluation
  - Real time demonstration of typical asymmetric thrust conditions

Linear Turbofan Engine Model Example

The asymmetric thrust detection methods were evaluated using the NASA Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k) high-bypass turbofan engine model.



Sensor Measurements	
Nf	Fan speed
Nc	Core speed
P2	Inlet total pressure
T2	Inlet total temperature
P25	HPC inlet total pressure
T25	HPC inlet total temperature
Ps3	HPC exit static pressure
T3	HPT exit total temperature
P5	LPT exit total pressure
T5	LPT exit total temperature

Actuators	
Wf	Fuel flow
VSV	Variable stator vane
VBV	Variable bleed valve

Inputs	
Alt	Altitude
MN	Mach number
PLA	Power lever angle
dTamb	Ambient temperature deviation relative to standard day conditions
Det	Performance deterioration level
Noise	Measurement noise enabled or disabled (discrete input)

Statistical Baseline

Monte Carlo Simulation Results

- Based on data from commercial aircraft flight profiles
- 216 data sets of 10 minute segments of cruise condition flight data with no thrust asymmetry played back through C-MAPSS40k
- Simulated engine deterioration and sensor noise provided realistic variance in the data
- Establish common false positive rate of 2 per 216 trials

Method	Threshold	Persistency	False Alarms
Kalman filter	0.187 %	6.5 sec	2 of 216 trials
Table lookup	0.087 %	6.5 sec	2 of 216 trials
Sensed and commanded EPR comparison	0.95%	6.5 sec	2 of 216 trials

Statistical Baseline

Monte Carlo Failure Simulation Results

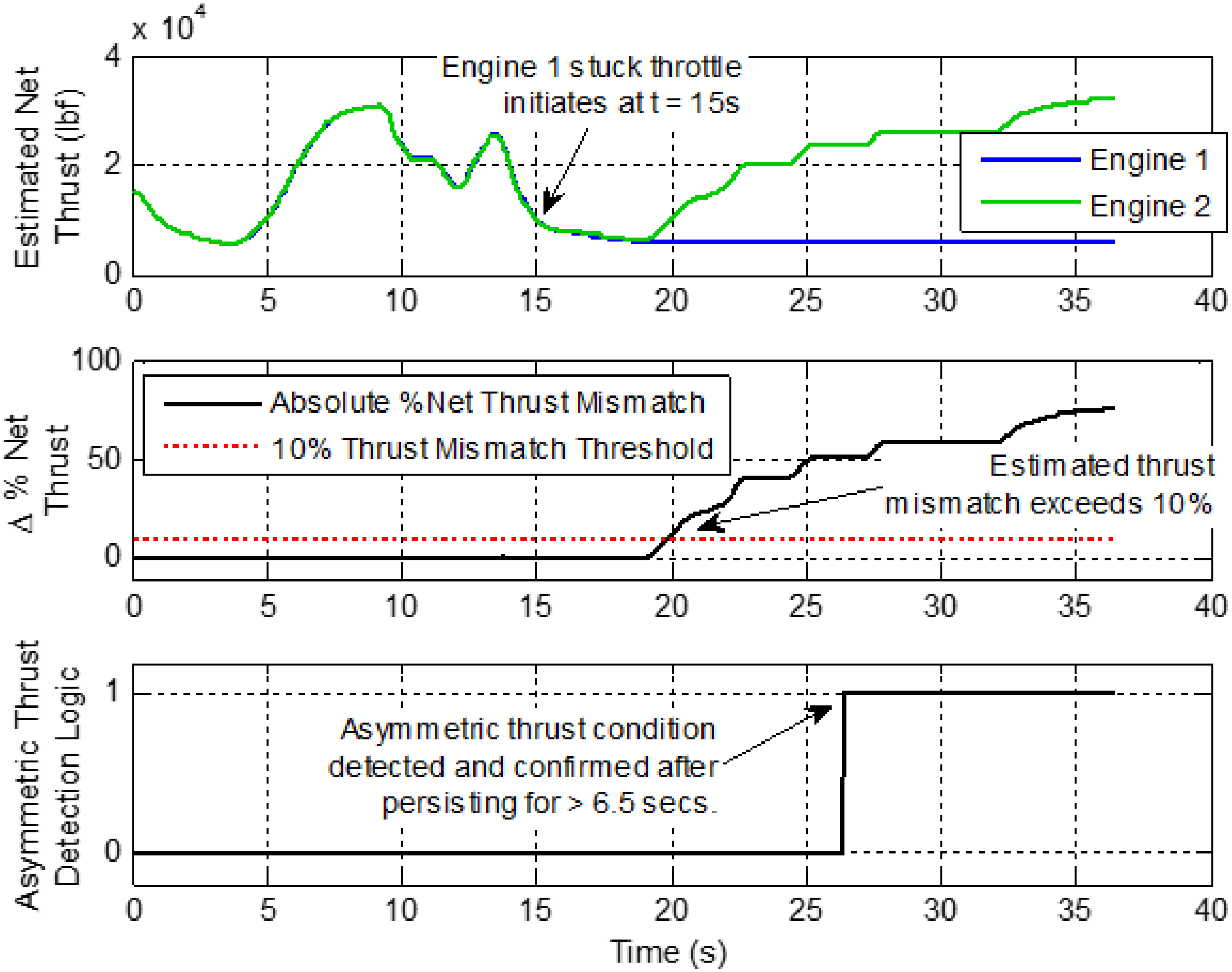
- Uncommanded linear increase in PLA introduced to one engine
- Simulated engine deterioration and sensor noise provided realistic variance in the data
- Average percent of corrected thrust at time of detection calculated for all 216 trials

Method	Average percent of corrected thrust asymmetry at time of detection	Standard Deviation
Kalman filter	0.9664%	2.7792%
Table lookup	0.7647%	2.1976%
Sensed and commanded EPR comparison	2.7672%	4.0936%

Flight Simulator

- In original configuration, the NASA Glenn flight simulator is a FAA approved Advanced Aviation Training Device (AATD)
- For this study, it was configured to operate the Transport Class Model (TCM) developed by NASA Langley with two copies of C-MAPSS40K developed by NASA Glenn
- Asymmetric thrust conditions were introduced with pilot-in-the-loop to examine pilot reactions and to visualize the dynamic effect on the aircraft

Flight Simulator Results



Conclusions

- Realistic asymmetric thrust events were successfully tested with the NASA Glenn flight simulator
- All three methods were capable of detecting the current industry standard of 10% thrust asymmetry
- Additional studies would need to investigate applicability and methods for annunciation of an asymmetric condition to the pilot
- Investigate a hybrid of two methods to provide detection and engine identification

Acknowledgements

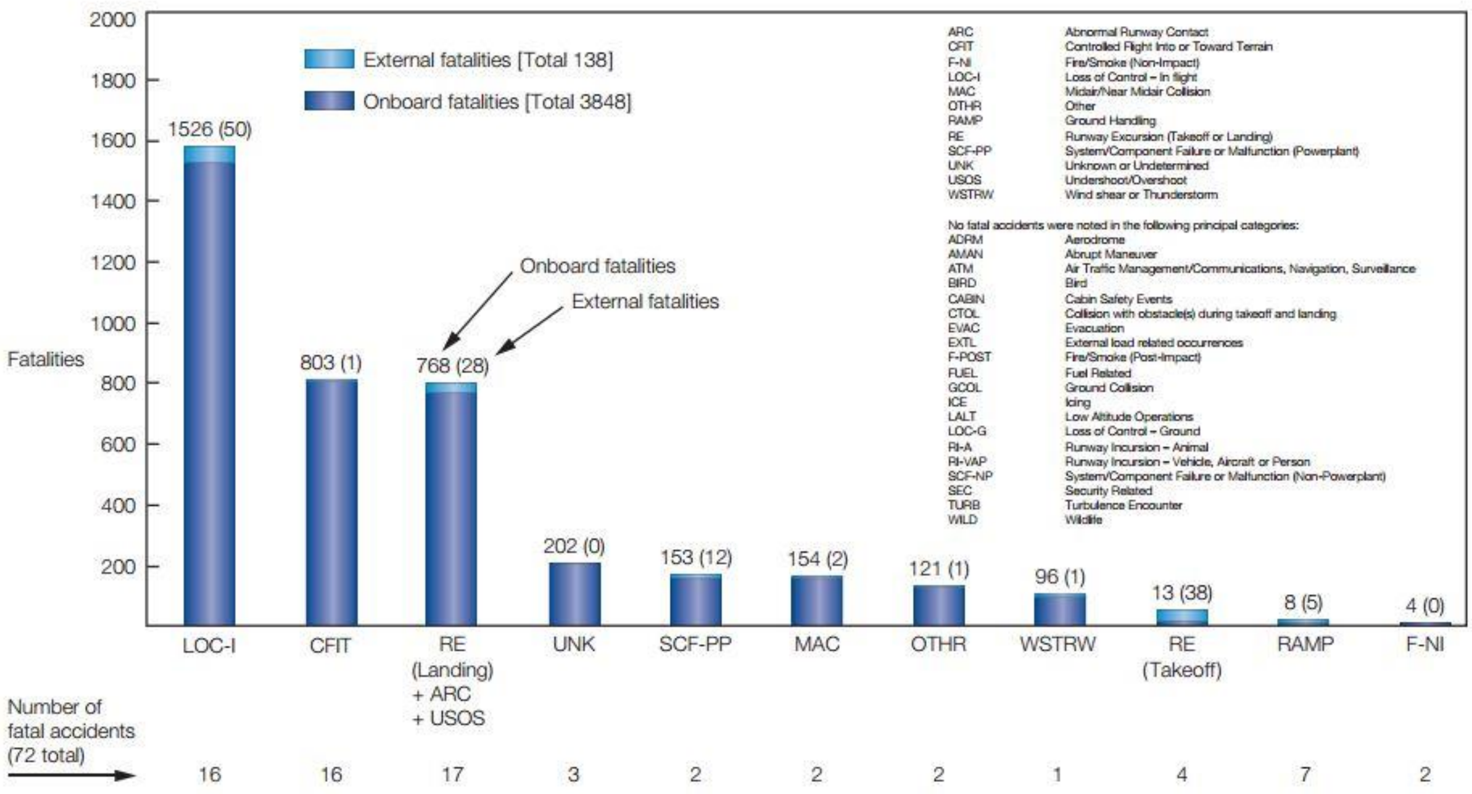
This work was conducted under the NASA Aviation Safety Program, Vehicle Systems Safety Technologies Project

Backup Slides

Background

Fatalities by CICTT Aviation Occurrence Categories

Fatal Accidents | Worldwide Commercial Jet Fleet | 2004 through 2013



Note: Principal categories as assigned by CAST.

For a complete description of CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories go to http://www.intlaviationstandards.org/

Statistical Summary of Commercial Jet Airplane Accidents, Boeing 2014
http://www.boeing.com/news/techissues/pdf/statsum.pdf