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Model-Based Analysis of Standard Operating Procedures' Role in Abnormal and Emergency Events

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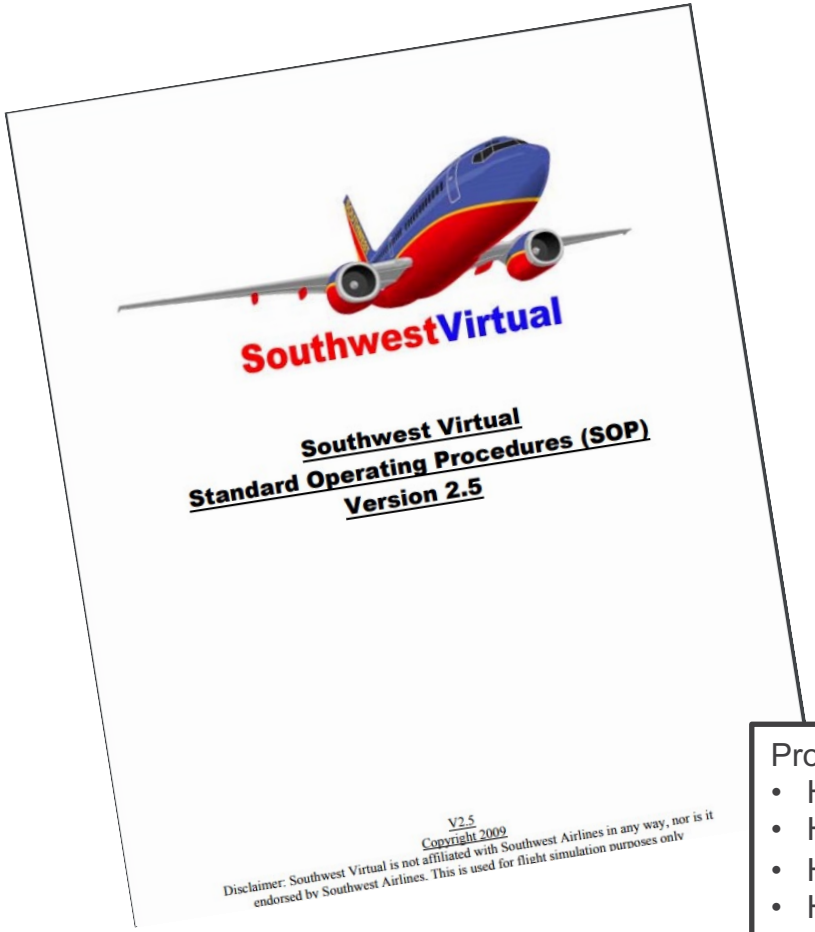
Introduction - Standard Operating Procedures



1) What must be accomplished/Tasks
   - Each Operator Action that must be executed in a sequence
2) When (under what conditions)
3) Who is responsible for each step
4) How each step is performed/Functions
5) How to confirm

Procedures define:
- Human-Machine Interaction
- Human Automation Interaction
- Human-Human Interaction
- Human-External Actors Interaction

Types of Operator Actions:
- Info gathering
- Info processing
- Conditional branching
- Decision-making
- Waiting/Timing
- Action
- Verification
- Validation

Introduction – Process of Developing SOPs

- Airline operators required to provide flight crew with procedures regulated by FAA
- Original Equipment Manufacturers (OEMs) supply customers with procedures promoting ideal use of technology
- Customers modify procedures based on company's policies and philosophies
- Modifications are approved by Principal Operations Inspector (POI)

Introduction – FAA Advisory Circulars

- AC 120-71B: “Standard Operating Procedures and Pilot Monitoring Duties for Flight Deck Crewmembers”
  - Provides guidance for design, development, implementation and updating of SOPs
  - Provides characteristics of good SOPs:
    - Write steps as imperative
    - Use short sentences
    - Use active verbs
    - …..
- Dictates requirements for procedural updates
  - Must be approved by Principal Operations Inspector (POI)
  - POIs: FAA employees assigned to airlines to oversee airline operations

Introduction – FAA Advisory Circulars

- AC 120-92B: “Safety Management Systems (SMSs) for Aviation Service Providers”
  - All airlines are required to implement an SMS
  - Describes requirements, guidance, and methods for developing and implementing an SMS
- SMS: Preventive approach to manage safety, identify hazards, and manage risk
- “Managers that have the authority to implement changes in … procedures must use the SMS processes” (FAA 2015, p.14)
- Airlines must update SOPs in accordance to SMS
- POIs oversee the process
- AC 120-92B and AC 120-71B do not provide instructions on how to test or evaluate the SOP.
  - No mention of the role of TIME as a measure of SOP performance

Introduction – Evaluating SOPs

- Industry methods for evaluating SOPs:
  - Review by Subject Matter Experts (SMEs)
    - Experts in the field. Don't represent novice or intermediate pilots
  - Human-in-the-loop testing
    - Expensive
    - Requires simulator time and flight-crew time
    - Cannot test every combination of operator/environment condition

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- Overview of Metrics for Measuring SOP Performance
- Method to Analyze SOPs' Role in Aviation Accidents
- Results
  - Taxonomy of SOP Issues Leading to Aviation Accidents
- Conclusions

Overview of Metrics for Measuring SOP Performance

- SOP Performance Metrics:
  - Time on Procedure (ToP): The time to complete all actions of the SOP.
    - Different each run due to varying level of expertise of operators
  - Allowable Operational Time Window (AOTW): The time in which the procedure must be completed.
    - Different due to environmental factors
  - Procedure Buffer Time (PBT): AOTW – ToP
    - Distribution
  - Probability of Failure to Complete (PFtC): Probability PBT < 0.
    - Left tail of the PBT Distribution.
    - Higher PFtC = Unreliable SOP

Overview of Metrics for Measuring SOP Performance

-Time on Procedure (ToP): The time to complete all actions of the SOP.
-Allowable Operational Time Window (AOTW): The time in which the procedure must be completed.
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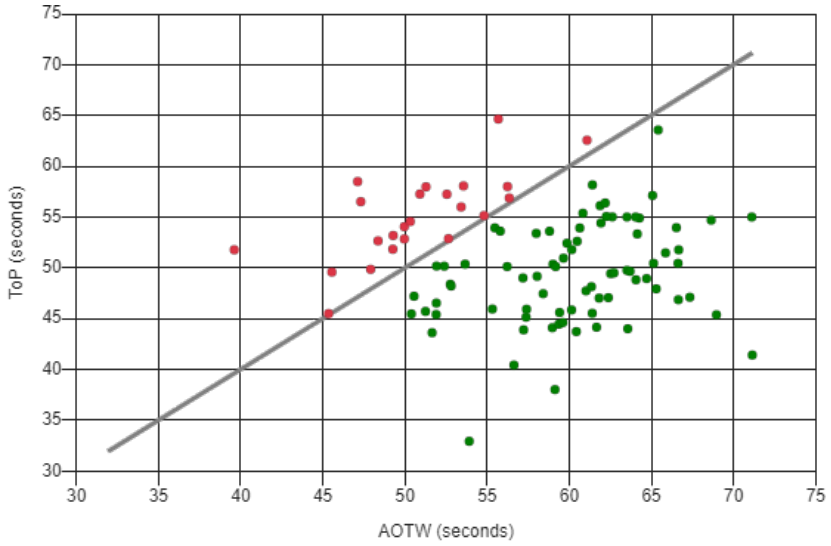

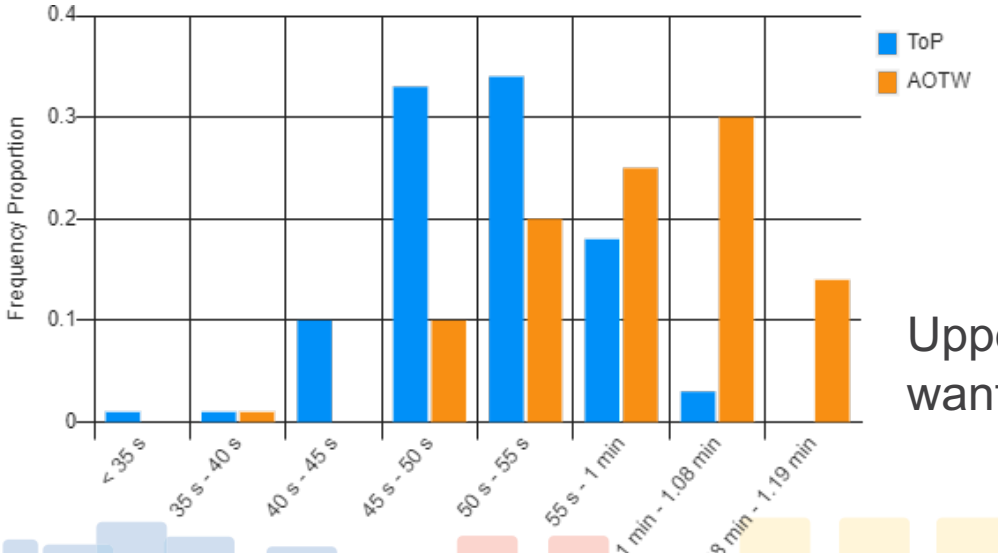

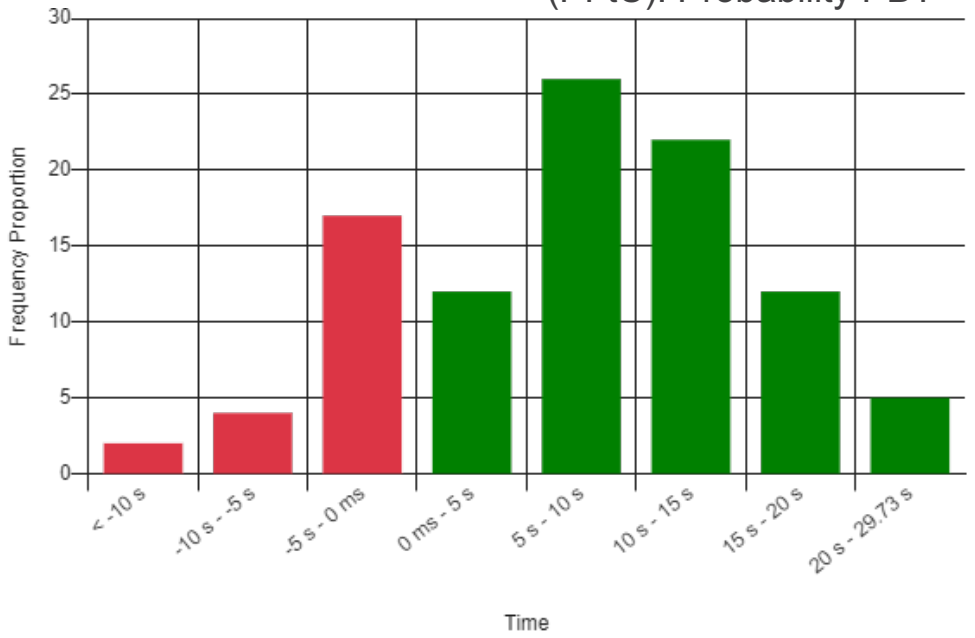

Upper Left: ToP vs AOTW. Lower Left: AOTW and TOP (Intersection not wanted). Middle Right: PBT (PFtC = P(PBT <0))

Overview of Metrics for Measuring SOP Performance

-Time on Procedure (ToP): The time to complete all actions of the SOP.
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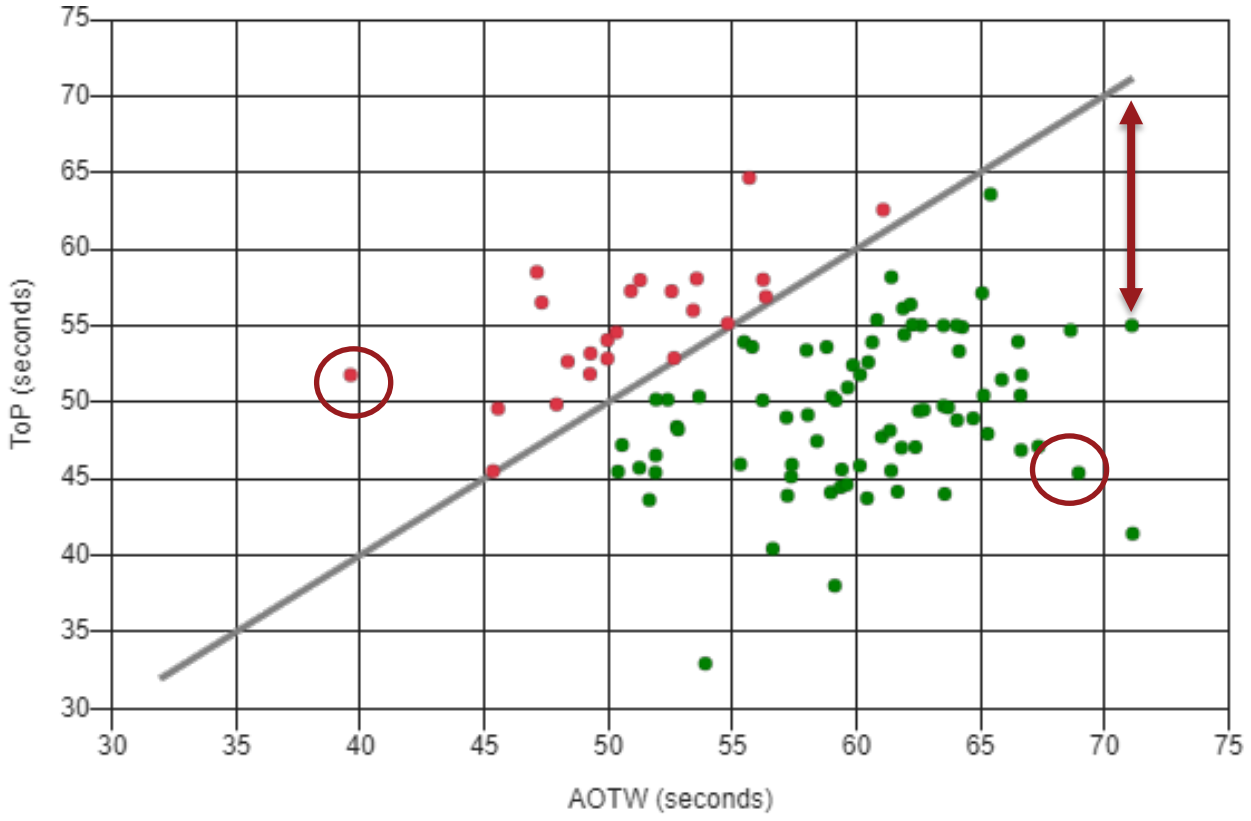

AOTW VS ToP Runs:
Red: Runs where ToP exceeded AOTW
Green: Runs where ToP was less than AOTW

Overview of Metrics for Measuring SOP Performance

-Time on Procedure (ToP): The time to complete all actions of the SOP.
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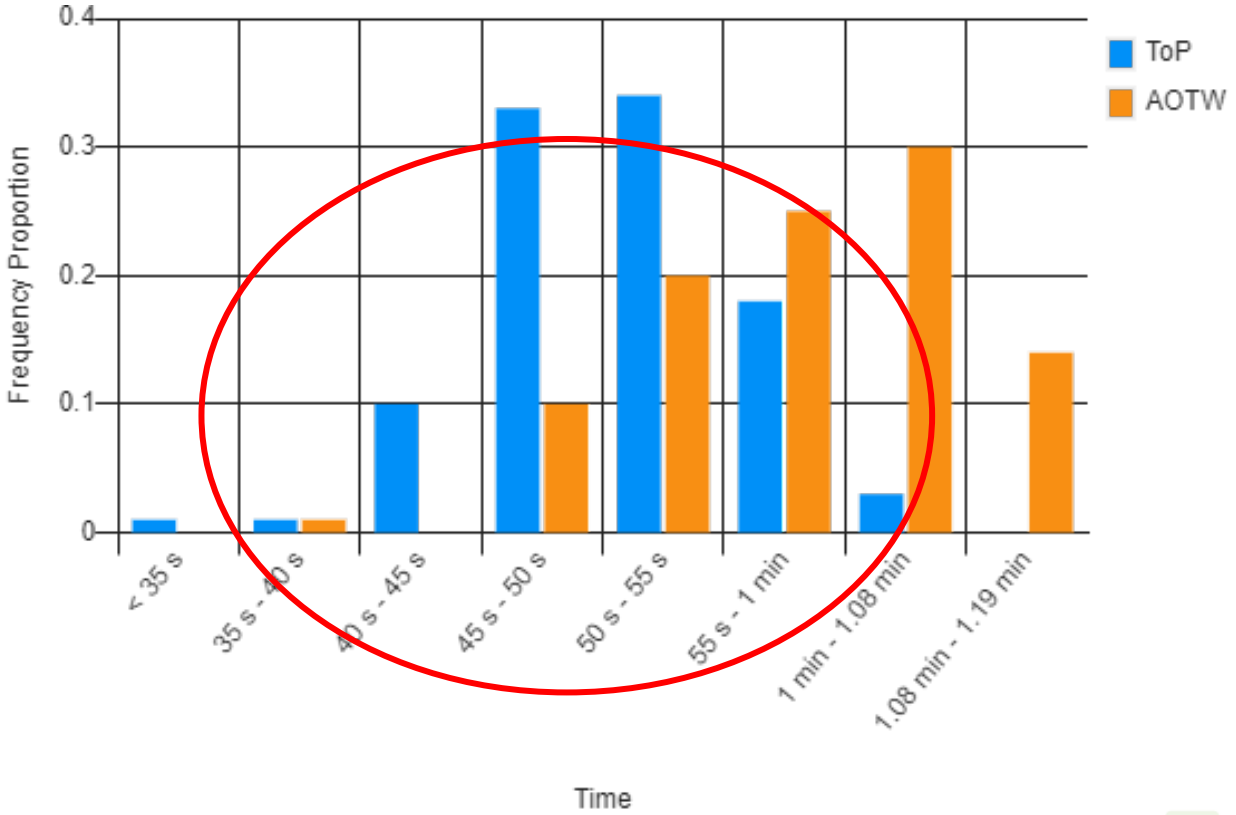
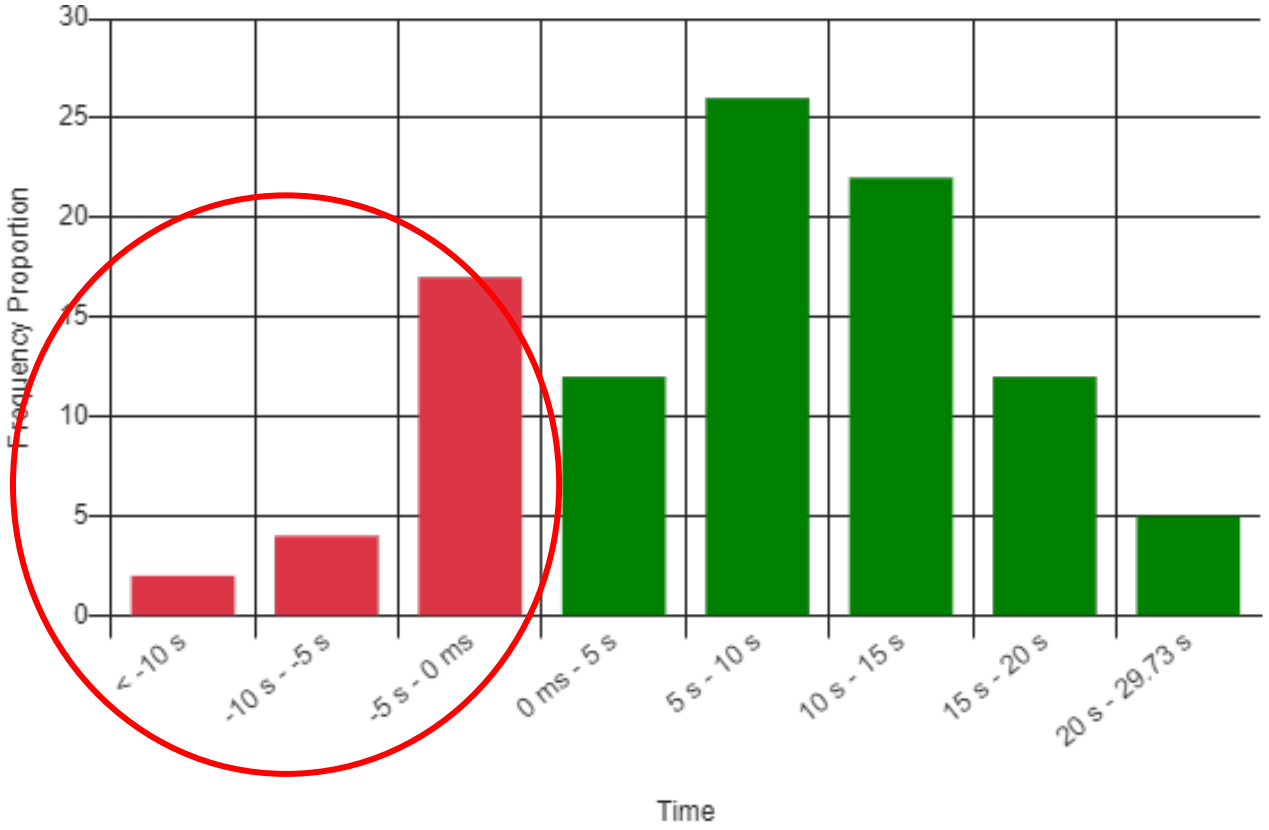


Distributions of AOTW and ToP:
Intersection: Runs where ToP > AOTW

Overview of Metrics for Measuring SOP Performance



-Time on Procedure (ToP): The time to complete all actions of the SOP.
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Distribution of PBT
PBT = AOTW – ToP
PFtC: Left tail of PBT Dist.

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  - Modelling and Simulation of SOPs
  - Categorizing accidents
- Results
  - Taxonomy of SOP Issues Leading to Aviation Accidents
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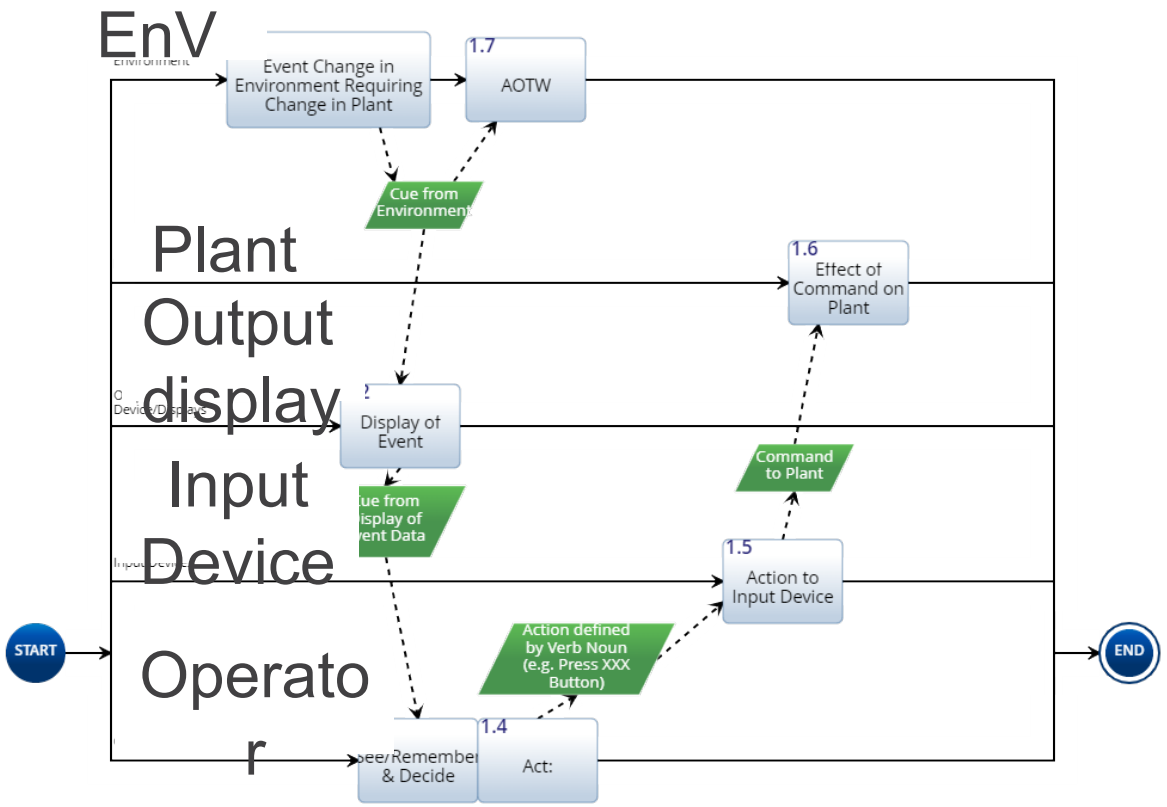
Method to Analyze SOPs' Role in Aviation Accidents

- 2000-2020 Statistics:
  - 614 accidents/incidents [A4A]
  - 61 accidents reviewed required crew intervention in the accident scenario
  - Accident reports cited failure of crew to perform intervention in a timely manner
- 12 randomly sampled accidents were further analyzed
  - Identify SOP used in intervention
  - The AOTW calculated by examining the timeline of events from the first cue of the triggering event until the hazardous event.
  - The SOP was modeled in Sopatra and simulated to obtain an estimated Time to Complete (ToP)

Modelling and Simulation of Standard Operating Procedures

- Bashatah, Jomana, Lance Sherry, 2021, A Model-Based Approach for the Qualification of Standard Operating Procedures, IEEE, pp. 1-10.
- Bashatah, Jomana, Lance Sherry, Steve Dam, Lauren Flenniken, Patrick Hartmann, and Tom Harold, 2021, Analyzing Standard Operating Procedures Using Model-Based Systems Engineering Diagrams, Wiley, pp. 1130-1144.

- Dynamics of procedure can be captured using SOP Action Diagrams
  - SOP Action Diagrams contain:
    - Actions
    - Branches
    - Input/Output (I/Os)
- Actions: actions are shown as squares on AD.
- Branches: Actors that perform SOP actions are depicted as branches. Each action is performed by the branch (actor) where the action sits.
- I/Os: Information flow between actions. Depicted as parallelograms.
  - I/Os must be present between two actions not performed by the same actor.
- SOP Action Diagrams are then simulated in a Model-Based Systems Engineering (MBSE) tool
  - Sopatra: An extension of Innoslate
  - Cameo
  - Core

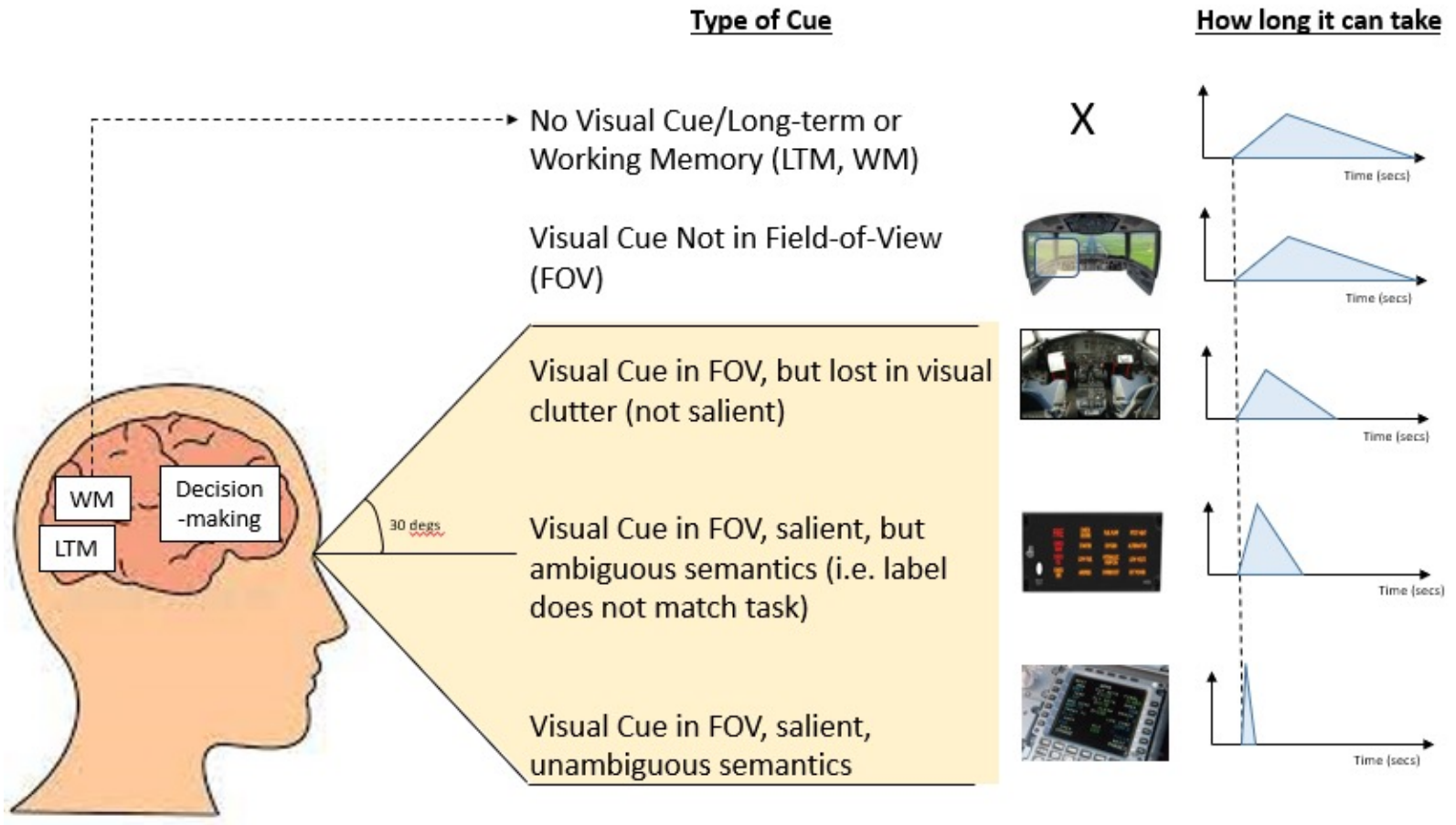


Modeling an SOP – Cue Evaluation and Frequency

- SOP Actions:
  - See & Decide (cognitive/perceptual)
  - Execution (motor)
- All Operator cognitive/perceptual actions are triggered by *cues*
  - Cue Evaluation Properties:
    - No cue (Long Term Memory item)
    - Cue, but Outside of Field-of-View (FOV)
    - Cue, in FOV, but lost in clutter
    - Cue, in FOV, no clutter, ambiguous label semantics
    - Cue, in FOV, no clutter, no ambiguity in label semantics
  - Frequency
    - Rare
    - Infrequent
    - Frequent
    - Always

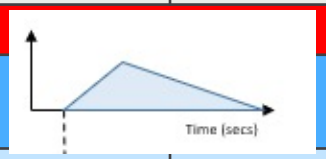
- Kourdali, Houda Kerkoub, Lance Sherry, 2016, A Systems Engineering Method and Simulation of Standard Operating Procedures.

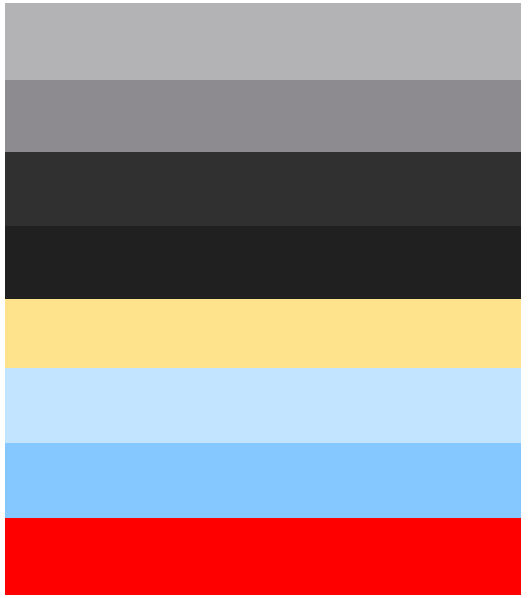
Simulating an SOP – Operator Performance



Simulating an SOP – Operator Performance

Cue Properties	Frequency			
	Always	Frequent	Infrequent	Rare
No cue at all				
Cue not in Field-of-View				
Cue in Field-of-View, but not salient (lost in clutter)				
Cue in FOV and salient, but not a sematic match with the task				
Cue in FOV, salient and semantic match				





Short Right Tail

Long Right Tail

Time Distributions Based on simulations and empirical data

Categorizing Accidents

- The accidents were categorized using the following rules:
  - Insufficient AOTW: If the simulated ToP was in excess of the AOTW when the SOP was performed in an efficient manner according to the time distributions.
  - Excessive ToP: If the AOTW was in excess of the ToP and the SOP was performed in an inefficient manner according to the time distributions

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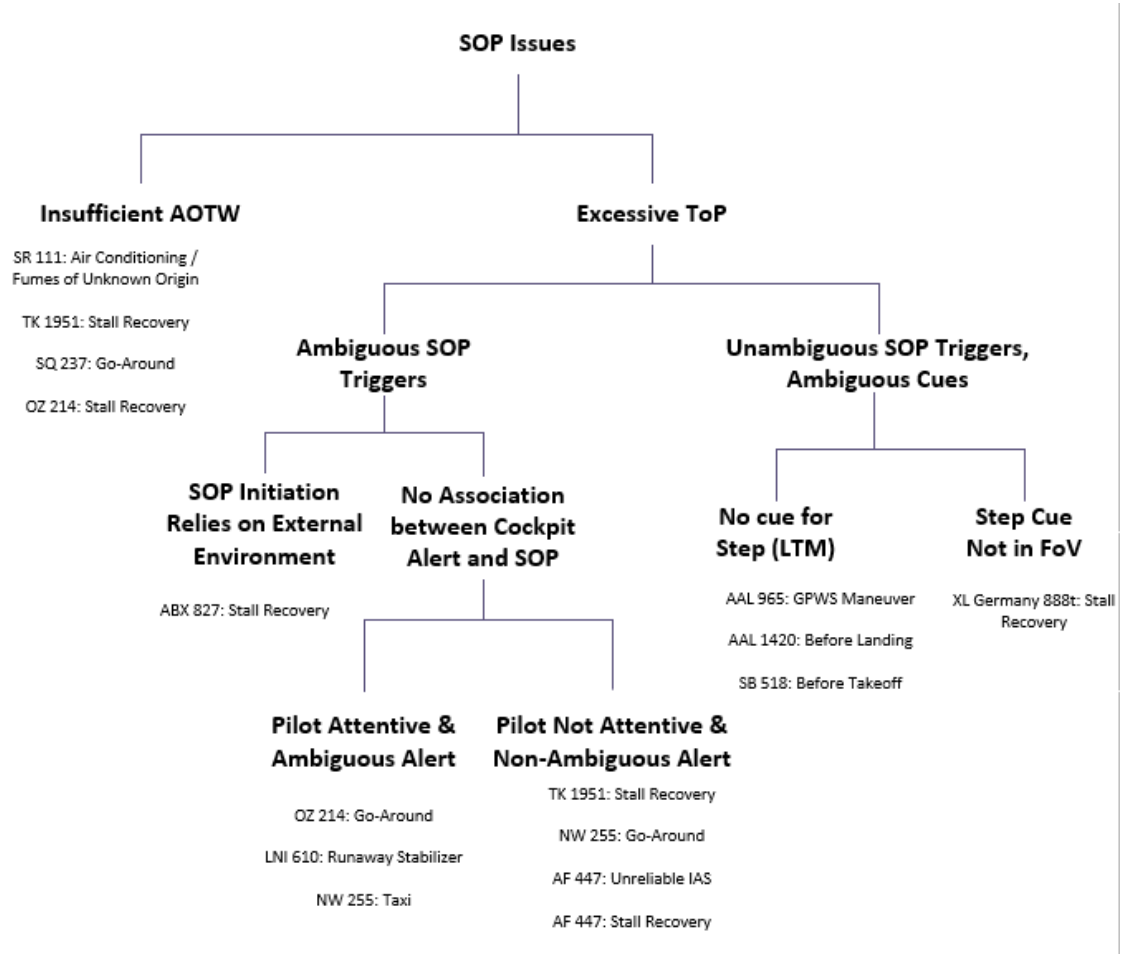
Results

- Analysis found a number of SOP issues
- Two main categories:
  - Insufficient time to complete an SOP
  - Excessive time when completing the SOP

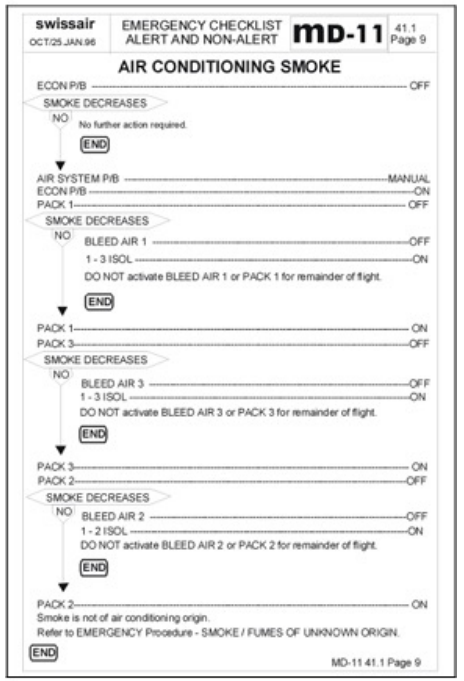


Insufficient Time to Complete SOP

- Occurs when there is not enough time to complete SOP before a hazardous event.
- A phenomenon dictated by environmental conditions, e.g. fire.
- Results from SOP creep
  - Adding more steps to the procedure over time.

Insufficient Time to Complete SOP

- Swiss Air 111
  - Triggering Event: smoke in the cockpit
  - Crew initiated Smoke/Fire in the cockpit SOPs
  - Completing both SOPs “could take 20 to 30 minutes to complete” (Transportation Safety Board 2002, p.255)
  - Crew had 18 minutes before aircraft struck water


swissair EMERGENCY CHECKLIST ALERT AND NON-ALERT MD-11 41.1 Page 9
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AIR CONDITIONING SMOKE

ECON P/B ..... OFF
SMOKE DECREASES
NO
No further action required.
END

AIR SYSTEM P/B ..... MANUAL
ECON P/B ..... ON
PACK 1 ..... OFF
SMOKE DECREASES
NO
BLEED AIR 1 ..... OFF
1 - 3 ISOL ..... ON
DO NOT activate BLEED AIR 1 or PACK 1 for remainder of flight.
END

PACK 1 ..... ON
PACK 3 ..... OFF
SMOKE DECREASES
NO
BLEED AIR 3 ..... OFF
1 - 3 ISOL ..... ON
DO NOT activate BLEED AIR 3 or PACK 3 for remainder of flight.
END

PACK 3 ..... ON
PACK 2 ..... OFF
SMOKE DECREASES
NO
BLEED AIR 2 ..... OFF
1 - 2 ISOL ..... ON
DO NOT activate BLEED AIR 2 or PACK 2 for remainder of flight.
END

PACK 2 ..... ON
Smoke is not of air conditioning origin.
Refer to EMERGENCY Procedure - SMOKE / FUMES OF UNKNOWN ORIGIN.
END

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SMOKE / FUMES OF UNKNOWN ORIGIN

CAB BUS P/B ..... OFF
Pause long enough for cabin crew to evaluate whether smoke or fumes decrease.
SMOKE / FUMES DECREASE
NO
Continue with cabin bus inoperative.
END

CAB BUS P/B ..... ON
SMOKE ELEC/AIR Selector ..... PUSH AND ROTATE
Rotate SMOKE ELEC/AIR Selector clockwise, pausing at each position long enough to evaluate whether smoke or fumes decrease. When a decrease is noted, leave selector in that position for rest of flight.
Continue with that generator channel and air system inoperative and **observe associated consequences.**

NOTE: - When rotating the SMOKE ELEC/AIR Selector, the autothrottle will disengage and be unusable. The autopilot may disengage but then use another autopilot.
- Nuisance stick shaker may occur.
(Stick shaker CBs on overhead panel: Captain E-1, F/O E-31)
- Following essential systems are inoperative or off in accordance with SMOKE ELEC/AIR Selector Pos:

SMOKE Selector Pos. 3/1 OFF:
only Captains VHF 1 and interphone available.
- DU 4, 5, 6; MCDU 2; FMS 2; IRS 2 (after 15 min).
- Radar 2; All Nav aids 2.
- BLEED AIR 1; PACK 1; ECON system; WING anti-ice.
- F/O pitot heat.
- Auto slat extension.
- Landing gear aural warning.
- Autobrakes.
FOR APPROACH:
- Set FLAP LIMIT Selector to OVRD 1.
- Go-around mode is not available.

SMOKE Selector Pos. 2/3 OFF:
-BLEED AIR 3; PACK 3; WING anti-ice.
-Aux pitot heat.
-Fuel dump low level.
-HORIZONTAL STABILIZER TRIM Switches on control column.
-Engine 2 reverser.

SMOKE Selector Pos. 1/2 OFF:
only VHF 2 and 3 available.
- DU 1, 2, 3; MCDU 1; FMS 1.
- IRS 1 and AUX IRS after 15 min, (AP no longer available).
- Radar 1; All Nav aids 1.
- BLEED AIR 2; PACK 2; WING and TAIL anti-ice.
- Captain pitot heat.
- GPWS, GPWS BELOW G/S lights.
- Auto ground spoilers.
- Engine reversers 1 and 3.
FOR APPROACH:
- Set FLAP LIMIT Selector to OVRD 2.
- On CAPT SISP push FD P/B to OFF.
- Go-around mode is not available.

If smoke/fumes are not eliminated, land at nearest suitable airport.
END

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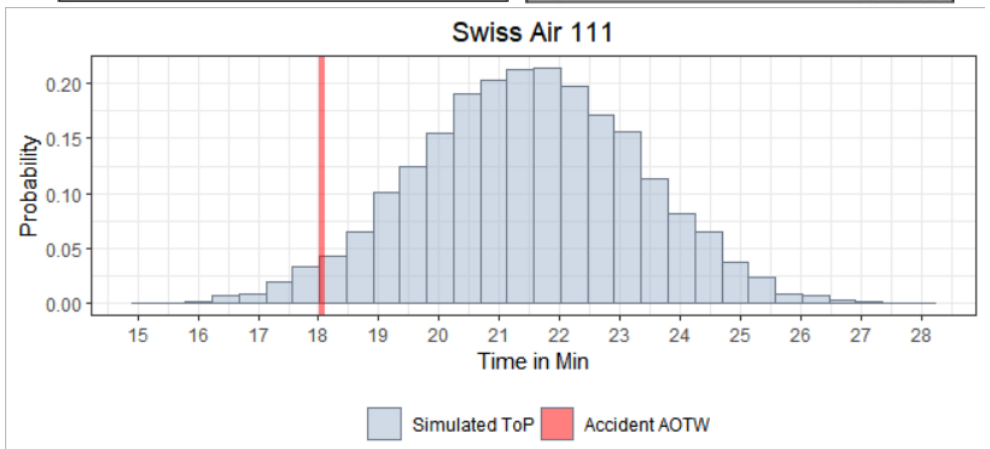
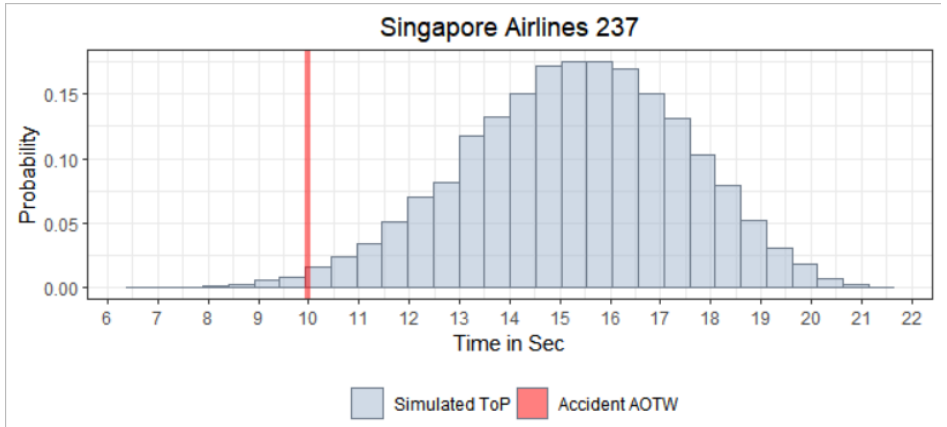


Insufficient Time to Complete SOP

- Singapore Airlines 237
  - 50 feet above the runway, aircraft banked to the left
  - Once noticed, crew tried to initiate Go-Around
  - Go-Around button was deactivated since aircraft had already touched down on left main landing gear.
  - Crew only had 10 seconds from aircraft bank to touchdown

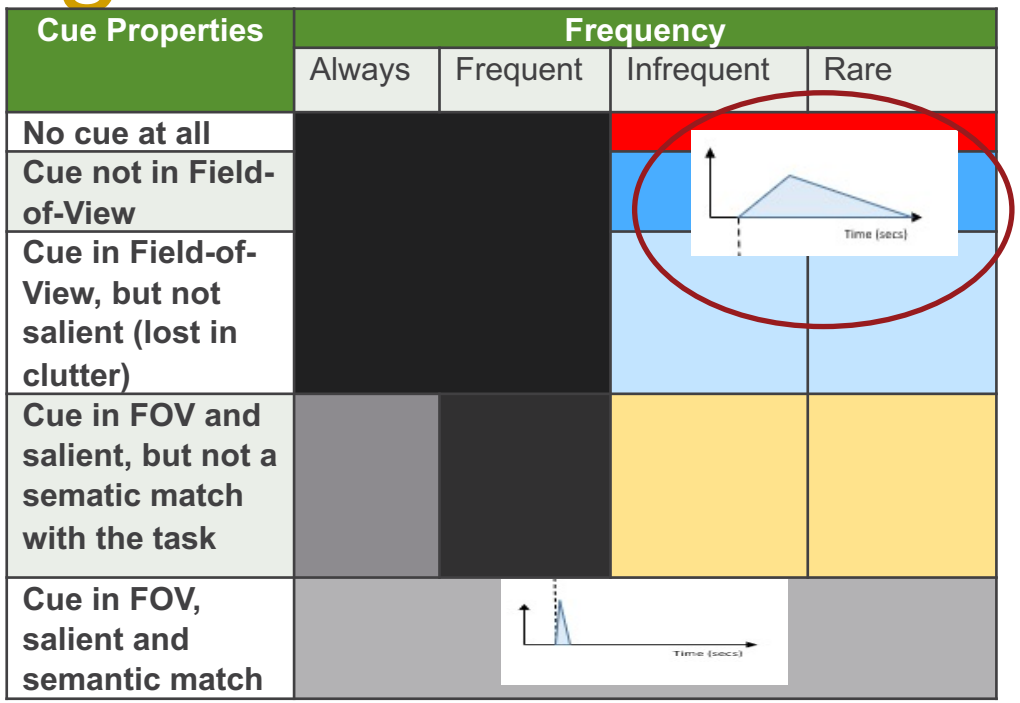


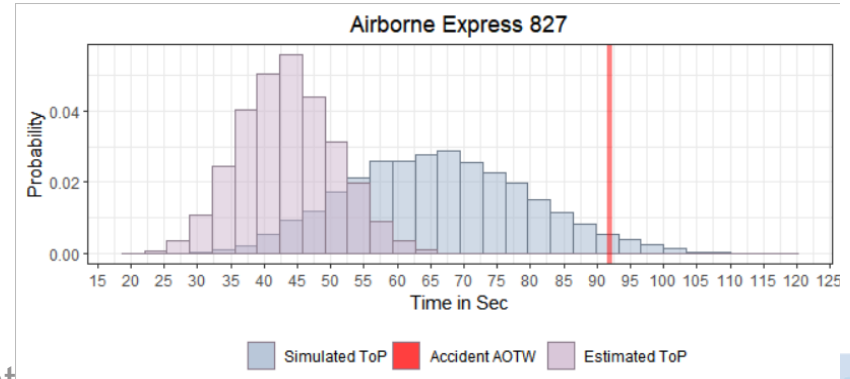
Excessive Time when Completing SOP

- Occurs when crew took abnormally long time to complete (ToP) SOP.
- Reasons behind long ToP:
  - Ambiguous SOP triggering event
    - SOP triggering event is based on external environmental cues. E.g. turbulence due to onset of stall
    - No/Weak association between the triggering event and SOP initiating event. i.e. the triggering alert was not associated with a procedure
  - Unambiguous SOP triggering event
    - Ambiguous/not salient cues for SOP steps
    - Missing triggers for SOP steps i.e. LTM items

Ambiguous SOP Triggering Event

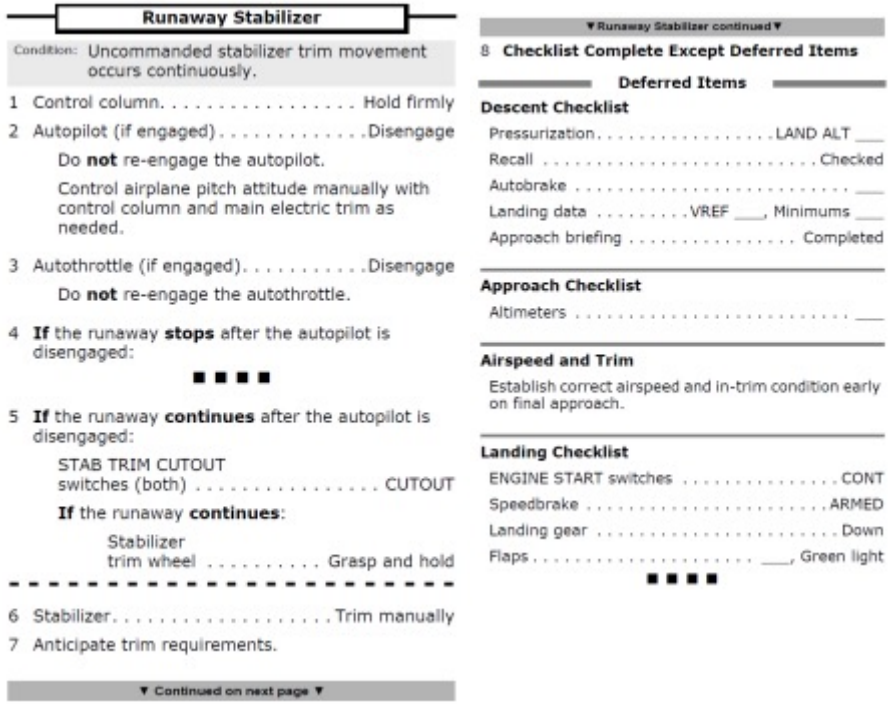
- SOP Initiation Relies on External Environment.
- Airborne Express 827
  - Took off as a Functional Evaluation Flight (FEF) for a series of test
  - Aircraft was deliberately entered into a stall to test stall protection system
  - There was a sense of buffet followed by a rattling sound at a speed higher than the calculated speed
  - Aircraft had entered into a real stall, stick shaker never activated
  - Stall recovery maneuver was initiated (took a longer time to start because of the stall occurring earlier than expected)





Ambiguous SOP Triggering Event

- Ambiguous Alert
- Lion Air 610
  - Uncalibrated Angle of Attack (AOA) sensor giving the aircraft the sense that it was stalling.
  - Aircraft's Maneuvering Characteristics Augmentation System (MCAS) responded by trimming the aircraft suing nose-down commands.
    - aircraft entered a series of nose dives (26 automatic trim commands)
    - Crew fought back with 34 manual trim inputs.
  - To offset MCAS command, crew must recognize that trim wheel was moving erroneously, and initiate "RUNAWAY STABILIZER" procedure.
    - "RUNAWAY STABILIZER" procedure's initial condition: continuous trim wheel movement.
    - Not the case in LNI 610 since trim wheel was performing a series of movements (i.e. not one continuous movement)
    - Abnormal trim wheel movement was never recognized = procedure never initiated



Runaway Stabilizer

Condition: Uncommanded stabilizer trim movement occurs continuously.

1 Control column. . . . . Hold firmly

2 Autopilot (if engaged) . . . . . Disengage

Do **not** re-engage the autopilot.

Control airplane pitch attitude manually with control column and main electric trim as needed.

3 Autothrottle (if engaged) . . . . . Disengage

Do **not** re-engage the autothrottle.

4 **If** the runaway **stops** after the autopilot is disengaged:

■ ■ ■ ■

5 **If** the runaway **continues** after the autopilot is disengaged:

STAB TRIM CUTOUT switches (both) . . . . . CUTOUT

If the runaway **continues**:

Stabilizer trim wheel . . . . . Grasp and hold

6 Stabilizer. . . . . Trim manually

7 Anticipate trim requirements.

▼ Continued on next page ▼

▼ Runaway Stabilizer continued ▼

8 **Checklist Complete Except Deferred Items**

Deferred Items

Descent Checklist

Pressurization. . . . . LAND ALT ___

Recall . . . . . Checked

Autobrake . . . . . ___

Landing data . . . . . VREF ___, Minimums ___

Approach briefing . . . . . Completed

Approach Checklist

Altimeters . . . . . ___

Airspeed and Trim

Establish correct airspeed and in-trim condition early on final approach.

Landing Checklist

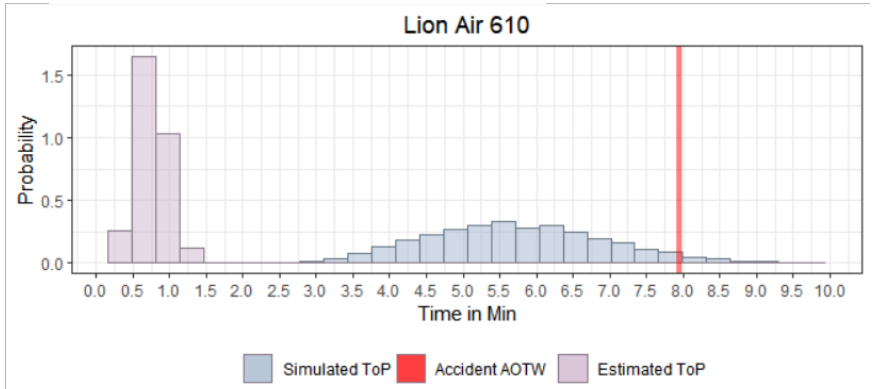
ENGINE START switches . . . . . CONT

Speedbrake . . . . . ARMED

Landing gear . . . . . Down

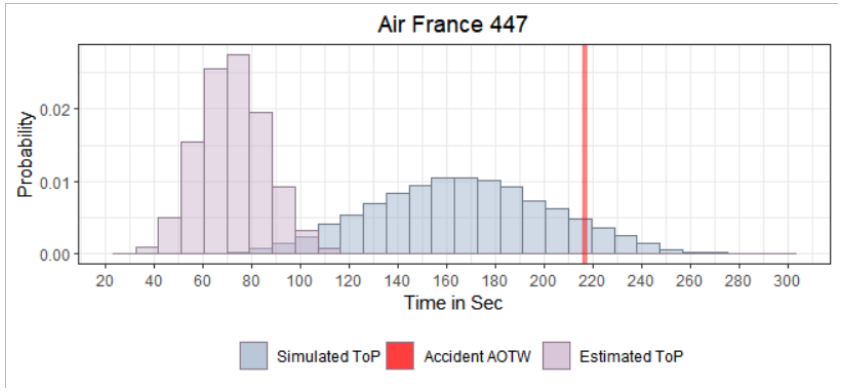
Flaps . . . . . ___, Green light

■ ■ ■ ■



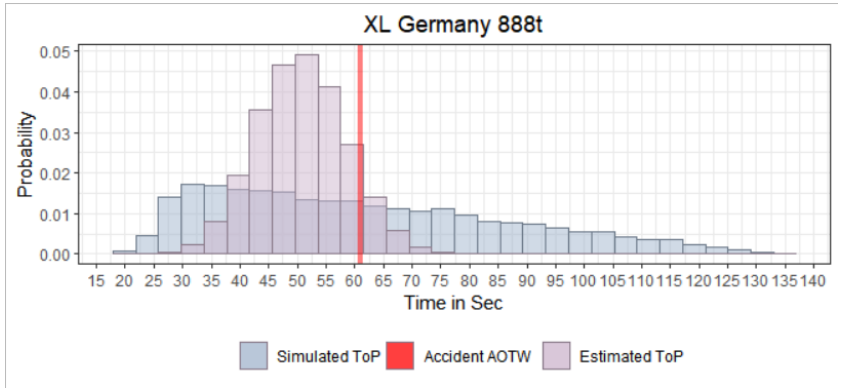
Ambiguous SOP Triggering Event

- Non-Ambiguous Alert
- Air France 447
  - Crew reduced speed in anticipation of turbulence.
  - A/P & A/T disengaged as a result of pitot tubes freezing
  - Pilot took command of aircraft, and made a nose-up input in an attempt to maintain speed.
  - Nose-up input with low speed resulted in a stall
  - Stall warning sounded 75 times



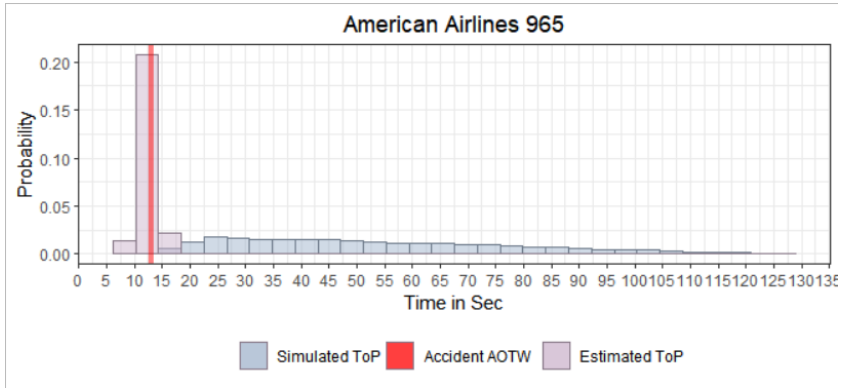
Unambiguous SOP Triggering Event

- Ambiguous/Not Salient cues for SOP Step
- XL Germany 888t
  - Aircraft took off as an acceptance flight to return leased aircraft to owner
  - Testing stall protection systems on board
    - Initiated only 4000 feet above ground
  - Aircraft entered a stall
  - Crew initiated stall recovery maneuver
  - Masked from the crew was the fact that flight control system passed into direct law.
  - Auto-trim function was disabled, and nose-down inputs were not enough to trim aircraft
  - ”the manual use of pitch trim, which is not included as a reminder in the approach-to-stall procedures, only occurs very rarely in operation and occasionally in training” (BEA 2010, p. 101).



Unambiguous SOP Triggering Event

- Missing steps i.e. LTM items
- American Airlines 965
  - After a heading misconfiguration, aircraft began veering off-course
  - Not knowing that heading was wring, crew flew into the mountains
  - Before impact, aircraft sounded Ground Proximity Warning System (GPWS)
  - Crew reacted immediately with GPWS maneuver
  - GPWS maneuver did not include the crucial step of “making sure spoilers were retracted”.
  - there was an assumption that “the flightcrew should have recognized that the spoilers were still extended during the attempt to avoid the terrain and should have retracted them early in the escape maneuver” (Colombian Civil Aviation Authority 1996, p. 47).



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Conclusions

- Testing human performance is crucial to ensure safe and efficient operations of the aircraft
  - Special emphasis on off-nominal and emergency situations.
- Analysis of 12 aviation accidents
  - Insufficient time to complete even a one step procedure
    - Factors unrelated to design of SOP
  - Excessive time to complete the procedure.
    - Design of the SOP played a role in increasing time to complete the procedure
    - Initiation condition of the SOP was ambiguous
    - SOP missed some steps and assumed crew would remember
- Results highlight the importance of testing the SOP accounting for all combinations of human performance and environmental conditions.
  - Designers could catch SOP designs leading to a high failure percentage

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