CATEGORIZATION OF UNRELIABLE AIRSPEED EVENTS USING RASMUSSEN'S HUMAN PERFORMANCE MODEL

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Abstract

Recent cases indicate that inappropriate crew response to unreliable airspeed continues to be a problem despite technological advancement of the flight deck. The purpose of this analysis is to categorize a subset of reported unreliable airspeed events in order to uncover common themes to determine where the breakdown in crew response occurs. Thirty-one accidents and serious incidents were categorized based on Rasmussen's Human Performance Model [HPM]. Data were gathered capturing the crew's detection of an airspeed anomaly, understanding of the unreliable airspeed, action selection in reaction to the erroneous information, any deviation from the plan, and execution of the plan. Results suggest that despite high instance of detection of an airspeed anomaly, crews show a lack of understanding of the problem in roughly 30% of the total detected cases. One possible reason for this gap between detection and understanding is the potential for apparently conflicting alerts in the cockpit and multiple warnings annunciated as a consequence of unreliable airspeed leading to crew confusion. Cases where the crew exhibited proper response in all five phases of Rasmussen's model led to a successful completion of the flight with no instance of flight outside of the aircraft envelope. The analysis indicates that the largest breakdown in human performance occurs in the understanding stage, suggesting that mitigation strategies for undesirable outcome of unreliable airspeed events should be targeted to this phase of the HPM. This analysis may serve to focus future development in flight deck indications, non-normal checklists, and flight crew training.

1 Introduction

Accidents and serious incidents where improper crew reaction to unreliable airspeed indications is a primary cause has common occurrence throughout aviation history. Recent cases indicate that crew response to unreliable airspeed continues to be a problem despite technological advancement of the flight deck.

1.1 Airspeed Calculation

Before analyzing unreliable airspeed, it is important to understand how airspeed is calculated and displayed to the crew. Airspeed is calculated using the difference in total pressure (measured by a pitot probe) and static pressure (measured by a static port or a combined pitot-static probe).

In transport category aircraft, these two measurements are typically sent to an air data computer (ADC) or air data module (ADM) which interfaces to the flight deck instruments. There are usually two redundant systems with independent pitot and static sources for each flight crewmember. Many aircraft also incorporate standby or backup pitot sources, static sources, and ADC's in the event of failure of the primary system. These redundant systems vary by aircraft model. Figure 1 is a notional pitot-static system depicting the general flow of information for airspeed calculation and depiction to the crew.

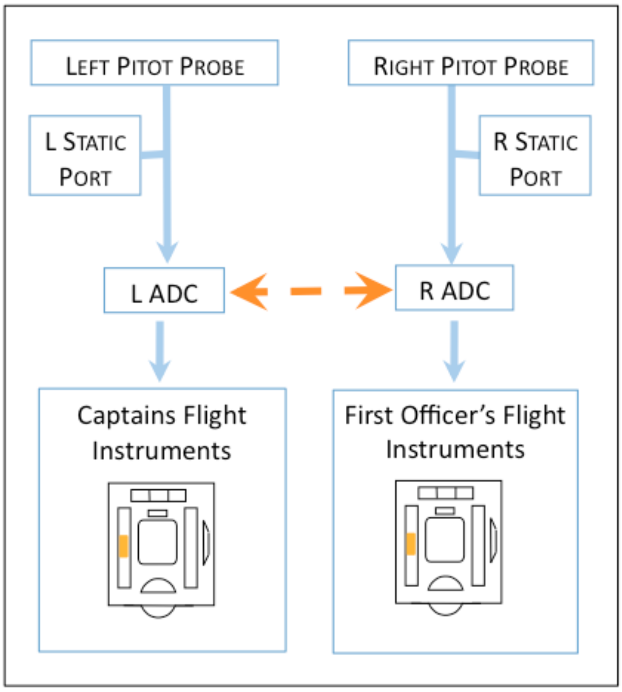

Fig. 1. Diagram of typical airspeed measurement and depiction to crew.

1.2 Rasmussen's Human Performance Model

Rasmussen defined the Step Ladder Model, a symbolic processing model derived from his Human Performance Model. It defines a sequence of mental activities that are used between initiation of a response and the manual action. This sequence is based on rational, causal reasoning that connects "states of knowledge." Rasmussen originally defined these states as activation, observation, identification, interpretation, task definition, procedure formulation, and execution [1].

There have been a number of applications of this Step Ladder Model. One of which is the nuclear power industry's derivation of the model into a "Cognitive Demands Checklist" to model the cognitive demands imposed on control room operators who would be most involved in selection and execution of severe accident control actions [2, 3].

Fucke et. al. used the basis of the "Cognitive Demands Checklist" to develop a Cockpit-Operations Reliability Evaluation Worksheet (CREW) Tool for aviation that systematically analyzes flight crew support in performing necessary recovery actions from in-flight anomalies. Fucke et. al. breaks decision making and action into six phases: Detection, Understanding, Prioritization, Action Selection, Intentional Deviation, and Execution [4].

The analysis described in this paper stems from Rasmussen's Step Ladder Model and derives the "States of Knowledge" from the previous work of Fucke et. al.

- **Detection:** Indication that the crew recognized an airspeed anomaly
- **Understanding:** Indication that the crew understood the implications and limitations resulting from an unreliable airspeed
- **Prioritization:** Indication that the crew properly prioritized the unreliable airspeed reaction in lieu of other failure indications
- **Appropriate Action Selection:** Indication of the crew taking the correct measures to counter the unreliable airspeed
- **Execution:** Indication that the crew executed the action plan properly

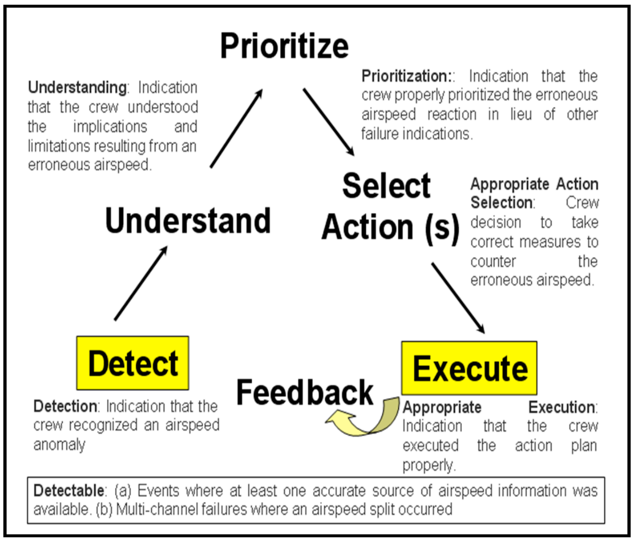

Fig. 2. Rasmussen's Human Performance Model applied to unreliable airspeed analysis.

2 Method

A qualitative analysis was completed on thirty-one accidents and serious incidents involving an unreliable airspeed indication. These events were categorized based on Rasmussen's Human Performance Model (Figure 2). Data were gathered capturing the crew's detection of an airspeed anomaly, understanding of the unreliable airspeed, action selection in reaction to the erroneous information, any deviation from the plan, and execution of the plan. The information extracted from each event related to general conditions, alerting, crew detection, crew understanding, plan formation, and execution.

General information for each event included:

- **Flight Conditions**
  Time of event indicating day or night was noted as well as the meteorological conditions at the time of the event.
- **Phase of Flight**
  Two phases of flight were noted for each event. The first reflected the time of recognition of the airspeed anomaly. The second reflected the phase of flight where loss of control occurred (if applicable).
- **Manifestation of Unreliable Airspeed**
  It was recorded whether the event was a single channel failure, multi-channel failure, or total loss of instruments. Single channel failure refers to an unreliable airspeed indication affecting only one airspeed indicator. A multi channel failure refers to an indication affecting 2 or more indicators. A total loss of instruments refers to all indicators failing to show any airspeed information.
- **Affected Indicators**
  It was recorded whether the captain, first officer, and/or backup airspeed indicators were reflecting the anomalous airspeed.
- **Source of Failure**
  Where there was sufficient information regarding the source of unreliable airspeed, the source was recorded and categorized as aircraft, environmental, or human.
- **System Affected**
  The source of failure was further narrowed into which system was affected. These were categorized into pitot system, static system, Air Data Computer, and indicator.
- **Type of Obstruction (if applicable)**
  Where the cause of the unreliable airspeed was pinned to an obstructed pitot or static probe, the type of obstruction was recorded. These range from icing to insects.
- **Loss of Control**
  Whether a loss of control occurred and the method of LOC was recorded and categorized into stall or overspeed conditions.
- **Time from Recognition to Loss of Control**
  Time between recognition of airspeed anomaly and loss of control was recorded. Also recorded was time from loss of control to recovery if applicable.

In terms of alerting, a number of parameters were collected.

- **Indication Type**
  Whether the crew received an alert for the unreliable airspeed and whether the indication was direct or indirect. Direct indications may include "AIRSPEED UNRELIABLE" messages while an indirect annunciation may be a "MACH/SPD TRM" message which is annunciated due to unreliable airspeed input.
- **Indication**
  The indication received by the crew is also recorded. These could include messages or events such as autopilot disconnects.
- **Overspeed and Stall Warning**
  Annunciation and validity of any stall and overspeed warnings was recorded. It was also noted whether any of the indications were temporary.

- **Reversion to Non-Normal Flight Control Modes**
  It was noted whether the aircraft ever reverted to alternate flight control modes during the event.

In terms of detection, it was first analyzed whether the failure was detectable to the crew. In certain failure cases, all airspeed indicators on the plane could deteriorate at the same time providing no cue to the pilot that a problem exists.

- **Detected**
  Assuming an event was detectable, it was then noted whether the crew recognized the airspeed anomaly.
- **Crew Crosscheck of Instruments**
  Where the information was available, it was noted whether the crew cross-checked the other airspeed indications in the cockpit.

In terms of flight crew understanding of the airspeed anomaly, actions were observed and inference made about the state of understanding of the flight crew.

- **Pilot Flying and Exchange of Flight Controls**
  It was recorded who was pilot flying at the time of recognition of the airspeed anomaly and whether an exchange of flight controls was performed. It was also recorded whether the exchange of flight controls was appropriate.
- **Activation of Autopilot for Recovery**
  Any attempt to activate the autopilot for recovery signified a lack of understanding of the unreliable airspeed and its effect on the autoflight system. Any indications of autoflight mode confusion were also recorded.

Plan formation was tied to checklists and procedures utilized by the crew. It was noted whether the crew identified, began, and/or completed any checklists. It was also identified whether the crew selected the appropriate procedure and performed it correctly.

Execution of the plan was tied to the response of the crew.

- **Crew Resource Management (CRM)**
  CRM was assessed and any deficiencies in CRM were noted. It was also noted whether an authority gradient inhibited the crew from executing the proper plan.
- **End of Flight**
  Outcome of the flight was noted in terms of whether the crew decided to perform a rejected takeoff, air turn back, diversion, or continue and it was assessed whether the decision was appropriate. It was also noted whether any of these resulted in an accident.
- **Pitot Heat Deployment (if applicable)**
  If the cause of the unreliable airspeed was determined to be pitot icing, it was noted whether the crew deployed the pitot heat.
- **Alternate Data Source Switch**
  It was noted whether the crew attempted to switch to an alternate air data source (if applicable).

Using the extracted data tabulated for each of the events, trends were sought in terms of where the crew breakdown in response occurs with respect to Rasmussen's Human Performance Model.

3 Results

3.1 General Trends

Results paint a varied picture as to the general environment and causes of unreliable airspeed (Figure 3). A majority of events occurred in instrument meteorological conditions (IMC). All seven accidents occurred when the crew had no external visual cues either in IMC or visual meteorological conditions (VMC) over water.

With regards to the manifestation of unreliable airspeed, the events were relatively evenly distributed between single channel and multi-channel failures. The events that involved a loss of control were also distributed between single and multi-channel, despite the crew having a good source of airspeed information in the single channel cases. The two total loss cases did not include a loss of control.

The source of failure was 29% aircraft, 48% environmental, and 13% human related. The systems affected include pitot (52%), static (16%), Air Data Computer (19%), and indicator (3%).

The crew was alerted to an airspeed malfunction in 80% of the cases analyzed. The majority of these alerts were indirect.

3.2 Human Performance Model

Results suggest that despite high instance of detection of an airspeed anomaly, crews show a lack of understanding of the problem in roughly 30% of the total detected cases (Figure 4). One possible reason for this gap between detection and understanding is the potential for apparently conflicting alerts in the cockpit and multiple warnings annunciated as a consequence of unreliable airspeed leading to crew confusion. It can also be seen in Figure 4 that all fatal accidents analyzed were associated with breakdowns earlier in the model in the detection and understanding phases. The less severe accidents and incidents were associated with breakdowns later in the model. Cases where the crew exhibited proper response in all five phases of Rasmussen's model led to a successful completion of the flight with no instance of flight outside of the aircraft envelope.

Further analysis was done probing the apparent barriers between detection and understanding. These cases fell into two main categories.

- Systems Knowledge or Training Deficiency
- Cognitive Tunneling or Confirmation Bias

Of the eight cases exhibiting appropriate detection and inappropriate understanding, five were identified as having systems knowledge or training deficiency.

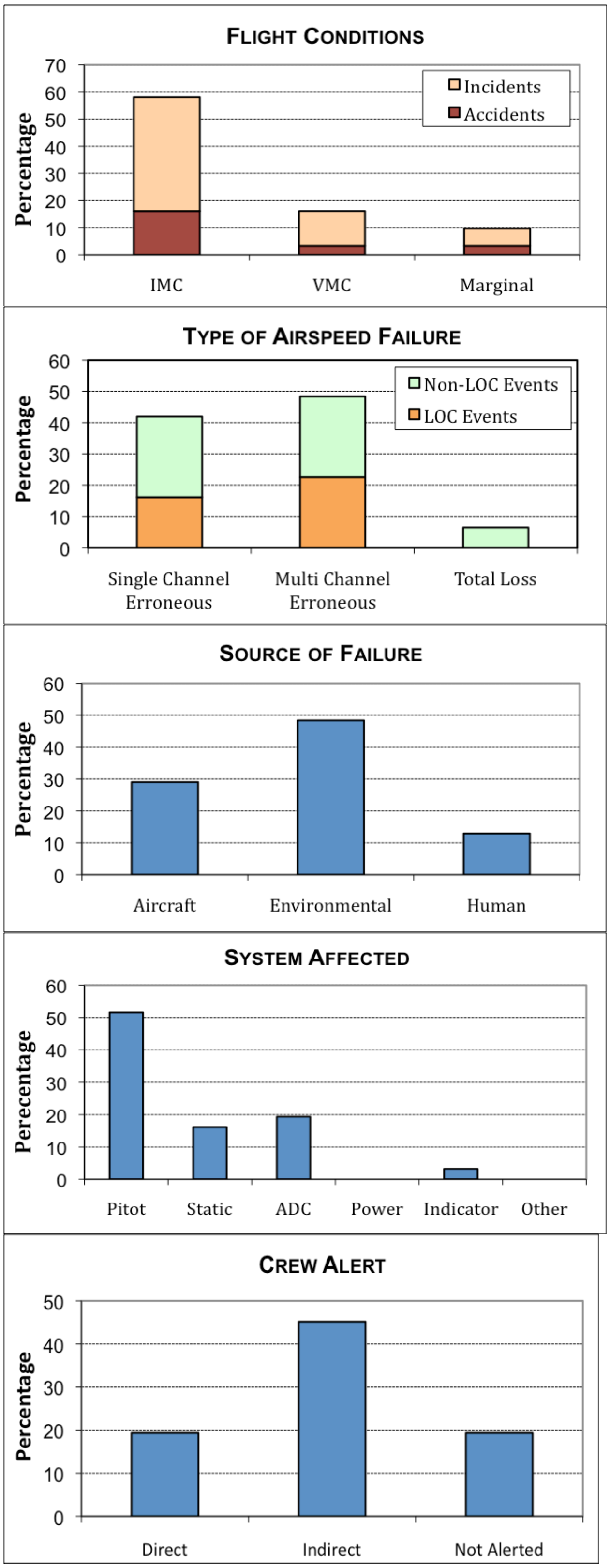

Fig. 3. General trends in analyzed events.

- Three crews were unaware of autopilot limitations
- One crew relied on air traffic control altitude readouts fed by their airplane's erroneous transponder signals
- One crew failed to exhibit stall recognition or recovery skills

Three out of the eight cases were identified as exhibiting cognitive tunneling or confirmation bias.

- Two crews did not put trust in the valid airspeed indicator
- One crew believed their circumstance was due to turbulence.

Using this type of information, mitigation strategies can be targeted for the understanding phase of the Human Performance Model.

3.1 Opposing Alerts

Nine of the thirty-one events analyzed (29%) involved simultaneous annunciation of overspeed and stall warnings. Six of these flights resulted in flight outside the normal flight envelope of the aircraft (Figure 5).

Further analysis was done breaking down the individual warnings for all the events into valid and invalid warnings (Figure 6). Over all of the events analyzed, both the overspeed and stall warnings were valid in half of the cases. Looking only at the accidents, the stall warning was valid in all the cases while the overspeed warning was invalid for most of the cases. For the incidents analyzed, there were more invalid stall warnings cases compared to the overspeed warning cases.

Depending upon the cause and subsequent flight dynamics, an unreliable airspeed event may exhibit combinations of valid and invalid warnings for both overspeed and stall. Typically, the overspeed warning is driven by airspeed sensed by the pitot-static system. An erroneously low airspeed arising from a blocked or leaking pitot-static system may not trigger the overspeed warning in the presence of an actual overspeed. The stall warning is driven by angle of attack (AOA)

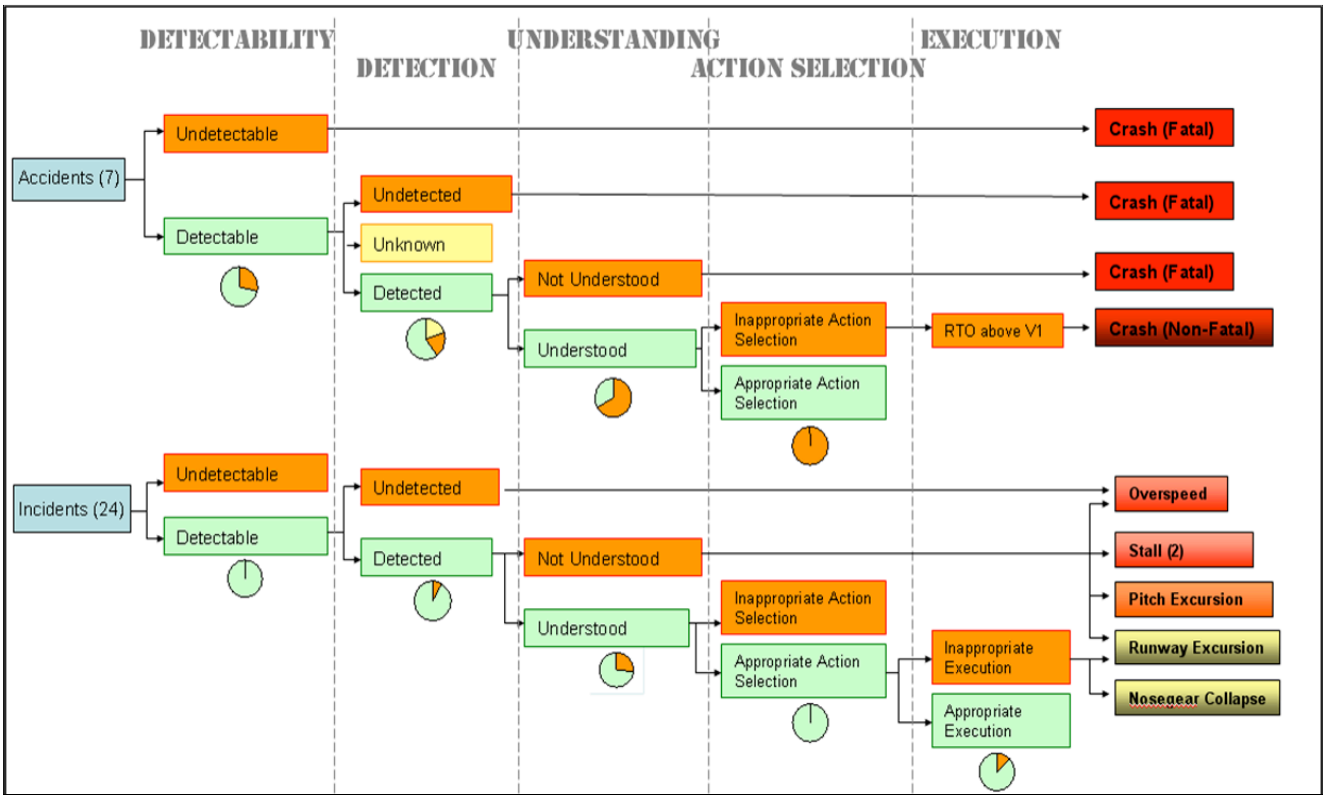

Fig. 4. Breakdown of unreliable airspeed events into Rasmussen's Human Performance Model.

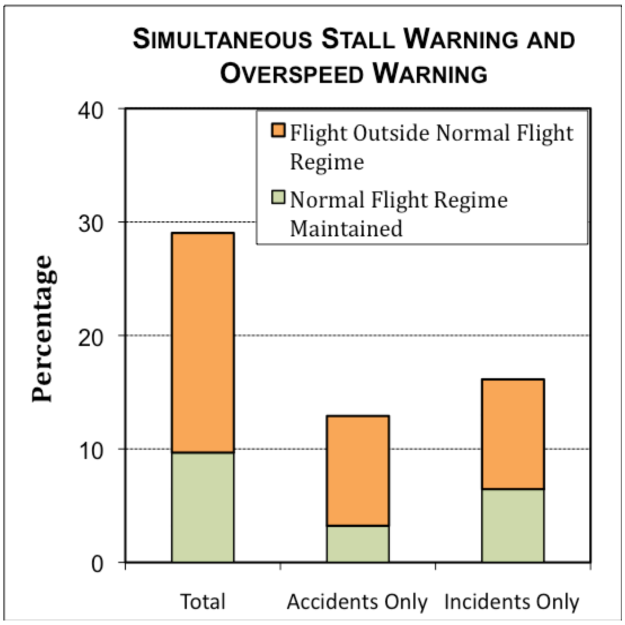

Fig. 5. Simultaneous stall and overspeed warning relation to flight outside normal flight regime.

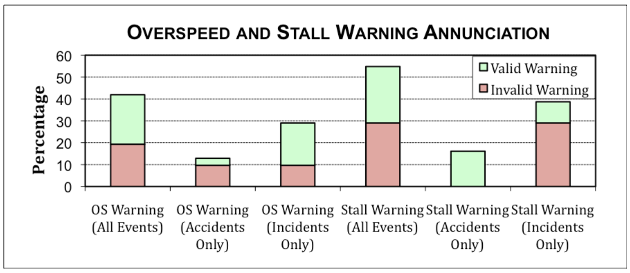

Fig. 6. Overspeed and stall warning annunciation.

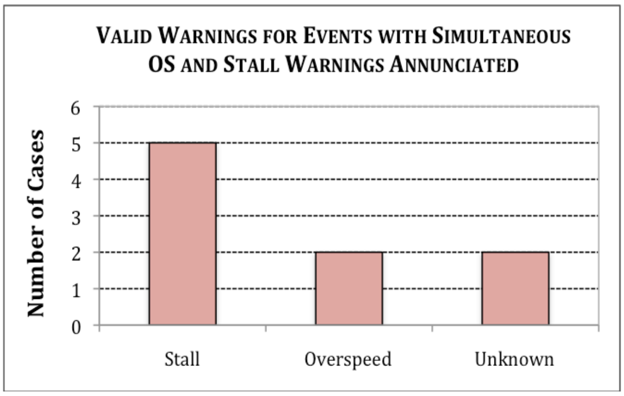

Fig. 7. Valid warnings for simultaneous overspeed and stall warning annunciation

sensed by vanes. To avoid nuisance warnings caused by dynamic inertial and aerodynamic effects on the AOA sensors on the ground, stall warning systems may be inhibited at low airspeed (e.g., 60 knots). In some airplane implementations, a valid stall warning may be inhibited in flight because the sensed airspeed is less than the low airspeed threshold for valid AOA.

For all the valid warnings for events with simultaneous overspeed and stall warnings annunciated, the number of cases for each was tabulated. Five out of nine were valid stall warnings while two out of nine were valid overspeed warnings. The remaining two events did not have enough information recorded for the investigator to determine which was the valid warning.

4 Conclusions

The more severe accidents and incidents were associated with breakdowns earlier in Rasmussen's Model. Detection of an airspeed anomaly was prevalent in most accidents and incidents analyzed. The analysis indicates that the largest breakdown in human performance occurs in the understanding stage, suggesting that mitigation strategies for undesirable outcome of unreliable airspeed events should be targeted to this phase of the Human Performance Model. This analysis may serve to focus future development in flight deck indications, non-normal checklists, and flight crew training.

General observations from the analysis identify a number of underlying issues needing attention to meet commercial aviation safety goals. Enhanced automation in the flight deck has been shown to increase the reliability and safety of commercial aviation, however along with this progress introduces problems such as deterioration of manual flying skills, desensitization to normal operating envelopes, unfamiliarity with operation in degraded modes of flight control, as well as excessive annunciation of nuisance alerts. Without careful consideration of these issues, advancement in terms of automation safety may be hindered.

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