

# Design of a Primary Flight Display (PFD) to Avoid Controlled Flight into Stall

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## Abstract

Analysis of recent airliner accidents and incidents identified a class of events in which structurally, mechanically, and electronically sound aircraft decelerated through the minimum safe operating speed ( $1.3 V_{Stall}$ ) to the stick-shaker stall speed. Each of these Controlled Flight into Stall (CFIS) events involved a unique sequence that lead to an inappropriate automation response as the aircraft decelerated to a stall. The inappropriate automation responses were “hidden” such that it was very difficult for the flight crew to intervene in a timely manner. Despite the differences in scenarios, a subset of the incidents and accidents had one thing in common – for different reasons, the automation was *no longer actively controlling to the airspeed target*. This paper describes the accident scenarios and defines a modification to enhance the airspeed tape on the Primary Flight Display (PFD) to explicitly annunciate the absence of active speed control. An experiment to evaluate the efficacy of the enhanced airspeed tape and the implications of these results for design and certification of flight deck automation are discussed.

## Introduction

In several recent accidents and incidents a structurally, mechanically, and electronically sound commercial airliner decelerated through the minimum safe operating speed ( $1.3 V_{Stall}$ ) to the stick-shaker stall speed. Each of these “Controlled Flight into Stall (CFIS)” accidents and incidents followed a unique sequence of events [1]. However, the sequence of events exhibited a general pattern in which: (1) a triggering event (e.g., sensor failure, and/or erroneous flight crew entry) resulted in (2) a mode change or

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change in automation engagement status, that led to (3) an inappropriate automation command that in turn, (4) resulted in a speed envelope violation.

In each of these cases, the flight crew was *not* able to intervene in a timely manner because 1) the changes in the automation states were not explicitly annunciated on the flight deck and 2) the deceleration resulting from the inappropriate automation commands was masked by an appropriate deceleration.

The displays on the flight deck, such as the Primary Flight Display (PFD), that could have been used to identify the triggering events and their effects on automation modes and engagement status failed to provide the flight crews with the information that they needed in a sufficiently explicit manner. In some cases, the mode labels displayed on the Flight Mode Annunciator (FMA) were overloaded; that is, the same label had two different meanings. In other cases, the displayed data could not be interpreted without relying on memorized rules. To address these issues, researchers have been developing concepts to improve the detection, recognition, and diagnosis of this speed deviation. For example, concepts that would increase the salience of the low speed condition [2], provide additional displays to anticipate the low speed condition [1], manage aircraft energy [3], [4], and eliminate ambiguity in mode labels [5] have been proposed.

This paper describes the CFIS accident and incident scenarios, defines requirements to explicitly annunciate the “no active airspeed control” condition (no matter the reason), and examines the efficacy of an enhancement of the airspeed tape on the Primary Flight Display (PFD) to show this condition. The implications of these results for design and certification of flight deck automation are discussed.

The next section of this paper provides a model of flight deck operations including the roles of modes, targets, and automation engagement status in those operations. The following section describes the CFIS cases and identifies categories of CFIS scenarios based on the flight deck model. The next section analyzes the Human Computer Interaction (HCI) required to intervene in CFIS events. In this section, requirements for the explicit annunciation of information on the flight deck are described together

with an example of a proposed integrated target display that meets those requirements. Finally, the implications for design and certification are discussed in the conclusion.

### **A Model of Flight Deck Operations**

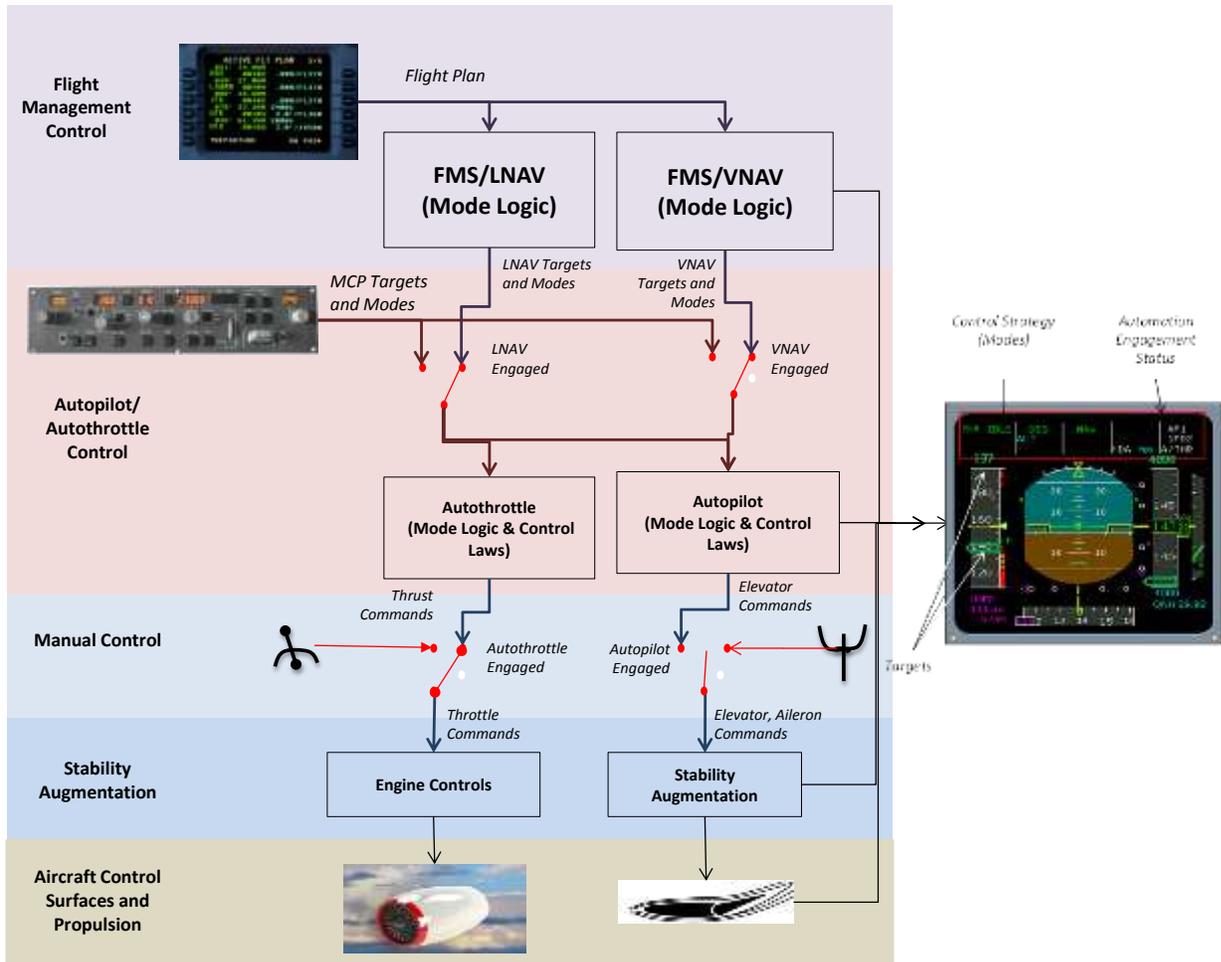
Every airline flight is executed according to a “flight plan” filed with Air Traffic Control (ATC). This flight plan is composed of a sequence of navigation stages or “procedures” (e.g. Departure, Enroute, Standard Arrival, and Approach) that define a four-dimensional flight trajectory for the aircraft. The flight deck system, composed of the flight crew and the flight deck automation, is responsible for the execution of the flight plan. However, the operational environment is dynamic and uncertain. As a consequence, the flight deck responsibilities can be organized into three categories: (1) performing the actions required to execute the flight plan as filed, (2) managing expected (but unplanned) flight plan events that require deviations from the flight plan (e.g., ATC instructions aimed at separating air traffic), and (3) managing unexpected events that require deviations from the flight plan (e.g., wind shear). The flight deck system must be able to detect, recognize and adapt to these changes in the environment. In particular, the flight deck automation and the flight crew must work together to achieve a target level of safety of  $10^{-9}$ .

The capabilities of aircraft automation have grown organically throughout the history of aviation from: (i) stability augmentation for stick, rudder, and throttle inputs, to (ii) direct trajectory control from pilot selected targets and modes (i.e. Autopilot and Autothrottle), to (iii) optimum trajectory derivation and control from a flight plan entered into a Flight Management Computer (i.e. Flight Management Vertical and Lateral Navigation). Modern flight deck automation extends the capabilities of human operators by performing control tasks (e.g. stability augmentation and trajectory control) more accurately than human pilots and for longer periods of time, by rapidly and precisely performing complex calculations for predicting future trajectories (e.g. flight paths, fuel burn), and by performing complex optimizations (e.g. calculating step-climb points and economy speeds). These functions and the associated user interfaces for the flight deck automation on a modern airliner are summarized in Figure 1.

Starting from the top of the diagram, the flight plan can be “programmed” by the flight crew via the Multi-function Control Display (MCDU) into the Flight Management Computer (FMC). The automation’s lateral navigation (LNAV) and vertical navigation (VNAV) functions determine the targets and control modes for each segment of the flight plan. The flight crew may modify the flight plan in flight by transferring flight plan clearances from ATC to the automation via the MCDU and/or the Mode Control Panel (MCP).

The MCP can be used to over-ride the flight plan targets and modes for unplanned tactical modifications to the flight plan including: deviations around traffic or weather, navigation direct to specified points, intermediate level-offs, holding patterns, lateral path offsets, and expedited climbs and descents. Unexpected events are generally managed by flight crew intervention and control of aircraft trajectory via the stick and throttle. This is particularly the case when the flight crew is uncertain of the state and intentions of the automation.

In the event of an expected but unplanned event, or an unexpected event, the flight crew must recognize the situation through a combination of direct observation, communication with ATC, and/or information obtained from the automation user-interface. However, due to the organic growth of the automation, the user-interface may not be designed sufficiently well to support detecting, recognizing and diagnosing many unexpected events.



**FIGURE 1: The flight deck can be configured for 12 combinations of engagement status of LNAV, VNAV, A/P, and A/T.**

### Automation Configuration and Engagement Status

Depending on the task (i.e. coordinating flight plan progress, managing expected but unplanned events, or managing unexpected events), the flight crew must configure the automation to “couple” the correct automation component to the control surfaces and engine. The automation is designed with four conceptual “switches” to configure the automation. These are shown in red in Figure 1. The Autopilot (A/P) and Autothrottle (A/T) switches determine whether manual commands (from stick and throttles) are commanding the aircraft trajectory or whether the commands are from the Autopilot and Autothrottle. The VNAV and LNAV switches determine whether the targets and control strategies are flight crew selected (on the MCP) or from the flight plan programmed into the FMC.

When the flight is progressing along the flight plan programmed into the FMC, the VNAV and LNAV switches are closed as are the A/P and A/T switches. This allows the automation to set the targets and modes to command the flight trajectory according to the flight plan. VNAV, LNAV, the A/P and A/T are said to be “engaged.” In this configuration, the flight crew is responsible for monitoring the automation for inappropriate behavior.

In the event of an unplanned, but expected event, the flight crew may use the MCDU to change the flight plan programmed into the FMC and allow VNAV and LNAV to remain engaged. If the event cannot be addressed by amending the flight plan (or the flight crew determines that reprogramming the FMC would be too difficult or time consuming), then VNAV and/or LNAV are disengaged, and the procedure is conducted by flight crew selection of targets and modes on the MCP. If the flight plan programmed into the FMC cannot be easily amended and the trajectory cannot be easily achieved in a timely fashion through selection of control strategies (i.e. modes) and targets on the MCP, the A/P and/or A/T will be disengaged and manual control (i.e. stick and throttle) exerted.

This automation architecture enables combinations of engagement status. For example, LNAV can be engaged to provide automated FMC control of the lateral flight plan, while VNAV is not engaged allowing the flight crew to select altitude, airspeed, and rate of climb/descent targets and control strategies. Another configuration may have LNAV and VNAV engaged with the A/P engaged and the A/T not engaged. In this way the flight crew would be manually adjusting thrust while both lateral and vertical trajectories are commanded by the automation to follow the flight plan.

All told, there are twelve (12) combinations of LNAV, VNAV, A/P and A/T engagement status that can be selected by the flight crew when the automation is controlling at least one parameter.

### **Control Modes and Targets**

As noted above, the flight plan is composed of a sequence of stages or “procedures.” These require the execution of a sequence of maneuvers. Each maneuver involves a change in the energy-state of the aircraft. When the automation is engaged, control of the energy states is achieved by applying a

combination of control strategies, instantiated in automation “modes” (e.g., using elevator or thrust to control speed or altitude, and aileron/rudder to control heading), that are directed towards achieving specified targets for airspeed, altitude, rate-of-climb/descent, and course/heading. The flight crew and the flight deck automation determine the trajectory of the aircraft by generating the appropriate sequence of targets and modes. When engaged, the automation computes the associated elevator, aileron, and thrust commands to achieve the targets according to the control strategy of the mode.

To maintain a safe energy state, the trajectory is restricted during each maneuver by the current energy state of the aircraft and the aircraft’s performance limits. Managing expected (but unplanned) events, and managing unexpected deceleration events can require rapid transitions in energy states that reduce safety margins [6]. Unlike the lateral trajectory that has a single parameter to control (roll), the vertical trajectory requires the coordination of both pitch and thrust. There are several maneuvers in which *airspeed is the indirect outcome of control to a flight path using a fixed thrust setting*. When the flight path is computed correctly, taking into account the thrust setting, the airspeed will achieve the correct value. However, if the flight path is not consistent with the performance of the aircraft (e.g. too steep or too shallow), the desired airspeed will not be achieved.

The choice of control strategies and targets is a complex decision-making activity. It requires consideration of a large number of inputs including actual aircraft state parameters (e.g. barometric altitude, calibrated airspeed, etc.), flight plan parameters (e.g. active leg altitude, speed, time constraints), traffic data, and terrain data. Due to the complex nature of the environment in which the flight deck system operates, there are a myriad of rare events that require managing *unexpected* events. In some cases (e.g. inaccurate sensor data or erroneous flight crew entries in support of ATC instructions), the automation may select targets and/or modes that command a trajectory that is not commensurate with the flight plan. In these cases, the flight crew must reconfigure the automation (using the A/P, A/T, LNAV and VNAV switches) to ensure that the appropriate modes and targets are used or exert manual control.

To do so, the flight crew must be able to monitor the control modes and targets for rare events and intervene in a timely manner.

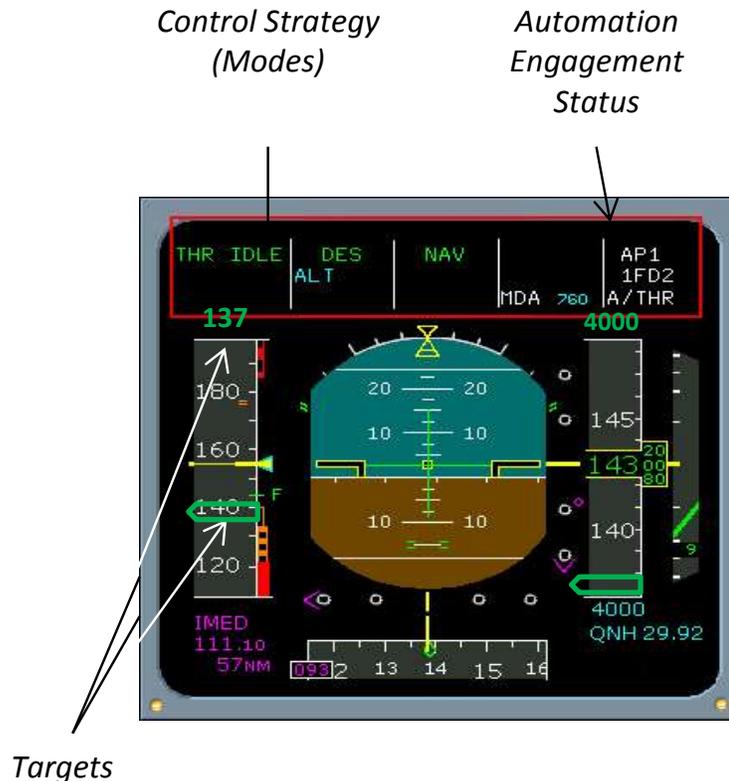
### **Monitoring Engagement Status, Control Modes, and Targets**

For the flight crew, the primary source of information on engagement status, target, mode, and aircraft energy-state is the Primary Flight Display (PFD). The modern “glass” PFD is an integrated version of the federated “steam gauge” displays used in older aircraft that used one gauge for each parameter. Many of the features of the PFD were designed prior to the evolution of the automation and were *not explicitly designed to support tasks associated with monitoring complex automation for inappropriate commands*.

The PFD (Figure 2) is organized as follows. The center section of the display is an attitude indicator (AI). The top of the AI has a bank indicator. To the left of the AI is an airspeed tape. To the right of the AI is the altitude tape and vertical speed indicator. Below the AI is a partial compass rose that displays the aircraft heading. Above the AI is the Flight Mode Annunciator (FMA).

The actual airspeed, altitude, and vertical speed are displayed along with their associated targets. In addition, the airspeed tape displays information on the speed envelope. “Barber poles” --striped bars -- indicate regions outside of the safe energy state for the aircraft. On the low end of the speed envelope, the safe operating speed is set at 30% above the stall speed, creating a buffer zone. The  $1.3V_{Stall}$  zone is represented by a yellow barber pole. The unsafe  $V_{Stall}$  is represented by a red barber pole.

The numerical altitude and speed targets are shown above the tapes. When a target is within the scaling of the tape, it is represented on the tape by a target icon. The values indicating the present state of the aircraft are centered on the airspeed and altitude tapes. When the present state is at the target, the target icon coincides with the present state value.



**FIGURE 2: Primary Flight Display (PFD) was designed prior to evolution of flight crew tasks to “monitor” the automation.**

However, the PFD does not explicitly display whether the automation is controlling to the targets and the labels displayed on the FMA are sometimes ambiguous. These issues may have contributed to several CFIS incidents and accidents.

### Analysis of CFIS Accidents

Twenty-two CFIS accidents and incidents were analyzed [1]. These accidents and incidents were all characterized by a structurally, mechanically, and electronically sound commercial airliner that decelerated through the minimum safe operating speed ( $1.3 V_{Stall}$ ) to the stick-shaker stall speed. Although each accident or incident involved a unique sequence of events, the sequence of events followed a basic pattern:

1. a triggering event (e.g., sensor discrepancy and/or flight crew entry), led to
2. a mode change or change in automation engagement status, that led to
3. an inappropriate command which resulted in

#### 4. a speed envelope violation

In each of these cases, the flight crew was *not* able to intervene in a timely manner. In all of these events, the aircraft trajectory associated with the inappropriate automation commands (e.g., inappropriate deceleration) was not detected or recognized by the flight crew because it was masked by an appropriate trajectory leading up to the speed envelope violation. Furthermore, the cues identifying the triggering events and their effect on automation modes and engagement status did not lead to detection, recognition, or diagnosis because they were not explicitly annunciated. In some cases, interpreting the available data required inferences based on memorized rules. In other cases, mode labels had multiple meanings.

A further detailed analysis of a subset of the CFIS accidents not related to changes in aerodynamic properties of the aircraft (e.g. icing) or errors in computation of the aircraft airspeed envelope (e.g. angle of attack discrepancy), revealed a set of accidents in which **the automation was no longer actively controlling to the airspeed target**. Specifically, (1) the automation was no longer engaged for airspeed control (i.e. the automation was no longer coupled to the control surface and/or engines), or (2) the automation was engaged, but transitioned to a control mode that does not control to the airspeed target.

**TABLE 1: CFIS accidents when the automation was no longer actively controlling airspeed**

<b>Accidents and Incidents</b>	<b>Maneuver</b>	<b>Effects of Triggering Events on Automation</b>
<b>AAL 903</b>	Decelerating entering a holding pattern at FL160	Automation no longer engaged for speed control
<b>ThomsonFly, Bournemouth ThompsonFly, Belfast ThomsonFly, not specified</b>	Decelerating on approach	Automation no longer engaged for speed control
<b>Midwest 490</b>	Climb	Automation no longer engaged for speed control
<b>JetStar 248</b>	Decelerating on approach	Automation no longer engaged for speed control
<b>Air France 447</b>	Cruise (Coffin Corner)	Automation no longer engaged for speed control
<b>AirAsia 8501</b>	Cruise (coffin Corner)	Automation no longer engaged for speed control
<b>OZ 214 (dormant mode)</b>	Decelerating on approach	Automation engaged, but no active speed control. A/T in “dormant” mode
<b>TK 1951 (fixed thrust mode)</b>	Decelerating on approach	Automation engaged, but speed not actively controlled. A/T transitions to “fixed thrust” mode.
<b>Provincial Airlines</b>	Climb	Incompatible mode for energy management

### **Automation Not Engaged**

In several cases, the automation autonomously disengaged, no longer coupling the automation commands to the control surfaces and engines (Table 1). The American Airlines (AAL) 903 incident is an example of this scenario. AAL 903 was instructed to hold at 16,000’ due to a weather cell on the arrival procedure. The aircraft decelerated and leveled-off as it made the turn into the holding pattern. During this period, with the A/T commanding idle thrust, the A/T disengaged. Without the A/T coupled to the engines, and the thrust at idle, the aircraft decelerated well below the minimum safe operating speed ( $1.3 V_{Stall}$ ).

### **Automation Engaged, but Control Mode does not Actively Control Speed (Inappropriate Mode)**

In several cases, the effect on the automation of the triggering events was to cause a transition to a control mode combination that did not directly control airspeed (Table 1).

The Turkish Airlines (TK) 1951 accident is an example of this situation. The aircraft was vectored for an instrument approach that resulted in a late localizer capture and subsequent clearance to descend. This left the aircraft fast and above the glideslope. After receiving a clearance to land, the flight crew instructed the automation to descend to recapture the glideslope from above *and* to decelerate to the landing speed. When the aircraft reached 2000' above the ground, a malfunctioning radio altimeter indicated to the aircraft automation that the aircraft had landed. This caused the Autothrottle to transition to the RETARD mode. In this mode, the throttles are locked at the idle position and *do not control airspeed*. In this configuration, the aircraft decelerated well below the minimum safe operating speed ( $1.3 V_{Stall}$ ). The incorrect radio altimeter value was shown on the Captain's display. However, the First Officer was flying the approach and his radio altimeter was functioning properly and displaying the correct altitude, which agreed with the barometric altimeter.

Another example is the Asiana Air 214 (OZ 214) accident. This flight was vectored for a visual approach at 14 nm to the runway at an altitude that left the aircraft above the desired three-degree glideslope. At 5nm to the runway, the aircraft remained well above the desired glide path. In an attempt to increase the airplane's descent rate and capture the desired glide path, the flight crew selected an autopilot mode (flight level change speed [FLCH SPD]) that instead, resulted in the autoflight system initiating a climb because the airplane was below the previously selected Go Around altitude. The flight crew disconnected the A/P and moved the thrust levers to idle. This action signaled the A/T to transition to a "dormant mode" in which the A/T does *not directly control airspeed*, but allows the flight crew to manually adjust the flight trajectory by setting the thrust. In this configuration, the aircraft decelerated well below the minimum safe operating speed ( $1.3 V_{Stall}$ ).

To intervene in these scenarios, the flight crew must detect, recognize and diagnose the CFIS situation by obtaining data from a variety of sources, integrating the data into a coherent whole, and

relying on memorized rules to extract meaning from the result. The information required to detect, recognize and diagnose the two scenarios described above is distributed across the PFD.

### **Human Computer Interaction Required for CFIS Intervention**

To diagnose a CFIS scenario, the pilots must first determine if the automation is controlling the airspeed. If the automation is not controlling the airspeed, then the pilots must determine why and take appropriate actions to regain control of the airspeed whether by using the automation (re-engage, or change mode) or exerting manual control. The information required to detect, recognize and diagnose the two scenarios described above is distributed across the PFD and summarized the table in Figure 4.

#### **Is Airspeed Control Active?**

The PFD does *not* explicitly display whether the automation is controlling airspeed. The aircraft automation can control airspeed by pitch using the A/P or by thrust using the A/T. To determine whether the A/P and/or A/T are engaged, the pilot must read the FMA (see Figure 3). Typically, when the A/P or A/T is engaged, the corresponding mode annunciation on the FMA will be displayed in green. When the A/P or A/T is engaged, some FMA's will also display "A/P" and/or "A/T" in green. If the A/P or A/T is armed or engaged, the respective buttons on the MCP may be lit. When the A/P or A/T disengage, an aural alert is generated and the Altitude|Heading or Speed labels are briefly surrounded by rectangles (not shown in Figure 3).

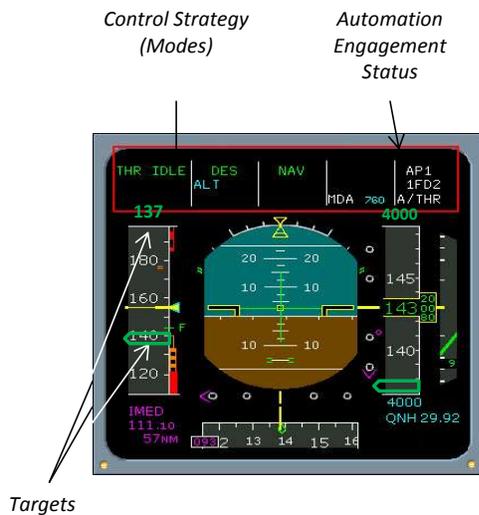
However, the automation may be engaged but engaged in a mode that does not control to the displayed target.

#### **What is the Control Strategy (i.e. mode)?**

The selected mode is displayed on the FMA (Figure 3). The center FMA label identifies the mode selected to control the lateral path (i.e. course, heading, VOR, localizer). The left and right labels identify the modes controlling the vertical axis. There are two designs for the labels. One design indicates which control surface is controlling airspeed or altitude. For example, speed can be controlled by PITCH or by

THRUST. The other design indicates what parameter is controlled by the thrust and pitch. For example, pitch can control SPEED, ALTITUDE, Vertical Speed (VS), or the vertical PATH.

The labeling of the modes is critical to the recognition and interpretation of the mode. The meaning of the labels is not always clear. For example, in the Asiana accident the A/T was engaged in a mode indicated by “HOLD” on the FMA. In this mode, the A/T does not “hold” the airspeed. “HOLD” indicates that the A/T is “on hold” waiting for instructions while the pilot is exerting manual control. Furthermore, the airspeed target is displayed on the PFD but not controlled. There is no single display component that reliably indicates to the pilot whether airspeed is or is not being controlled. In this case, the pilot must recall from memory that airspeed is not being controlled when the A/T is engaged in the “HOLD” mode despite the other cues that suggest that airspeed is being controlled. In the TK 1951 accident, the “RETARD” label on the FMA indicated that the automation had entered the “landing flare” mode in which the automation was programmed to assume that any movement of the thrust levels was meant to be a temporary adjustment and hence the thrust should be returned to idle. In this case, the pilot must recall from memory that in the RETARD mode, the AT is locked at idle and will actively return the thrust to idle.



Information	Location on Traditional PFD	Memorized Rules to Interpret
Airspeed Control Active?	FMA	Label interpretation Location of A/P and A/T Labels and presence/absence of A/P and A/T Label. Color of FMA and Targets
Engagement Status?	Below FMA for A/P and A/T FMA and Targets for VNAV and LNAV	Location of A/P and A/T Labels and presence/absence of A/P and A/T Label. Color of FMA and Targets
Mode selected?	FMA	Label interpretation
Target selected	Tape	None
Actual	Tape	None

**FIGURE 3: Summary of location on PFD for information required to detect, recognize, and diagnose CFIS scenarios.**

Although the FMA is the only place in the cockpit where the automation mode is displayed, it is not the only way in which pilots can determine the likely state of the automation. Because the automation usually controls the aircraft as expected, pilots frequently infer the state of the automation from the behavior of the aircraft. As a result, flight crews do not value the FMA information as much as might be expected [7]. For example, using eye-tracking technology, Mumaw et al. [8] observed that pilots spend relatively little time (less than 5%) fixating on the FMA. Only 53% of the pilots inspected the FMA within 10 seconds of manually induced transitions; only 45% inspected the FMA within 10 seconds after expected automation-induced transitions (e.g. capture altitude), and only 62% inspected the FMA within 10 seconds after an unexpected of automation-induced transition. Thus, the information that is available is frequently not perceived. By increasing the salience of critical information, the likelihood that it will be noticed and used can be greatly increased.

### **Enhanced PFD Airspeed Tape**

By increasing the salience of critical airspeed information, the ability the flight crew to detect, recognize, and diagnose the CFIS scenario prior to a speed deviation may be enhanced. The display should explicitly indicate in a salient and unambiguous manner, without the need for memorized rules, whether 1) airspeed is being controlled and 2) if so, to what target.

The standard integrated airspeed tape display has three graphic icons whose shapes and colors are manipulated: (1) the numerical airspeed target, (2) the target pointer, known as the “bug”, and (3) the current airspeed display. When the target is within the range of the tape display, the target pointer slides with the tape as the airspeed changes. When the target is not within the range of the display, it is parked at the top or bottom of the tape.

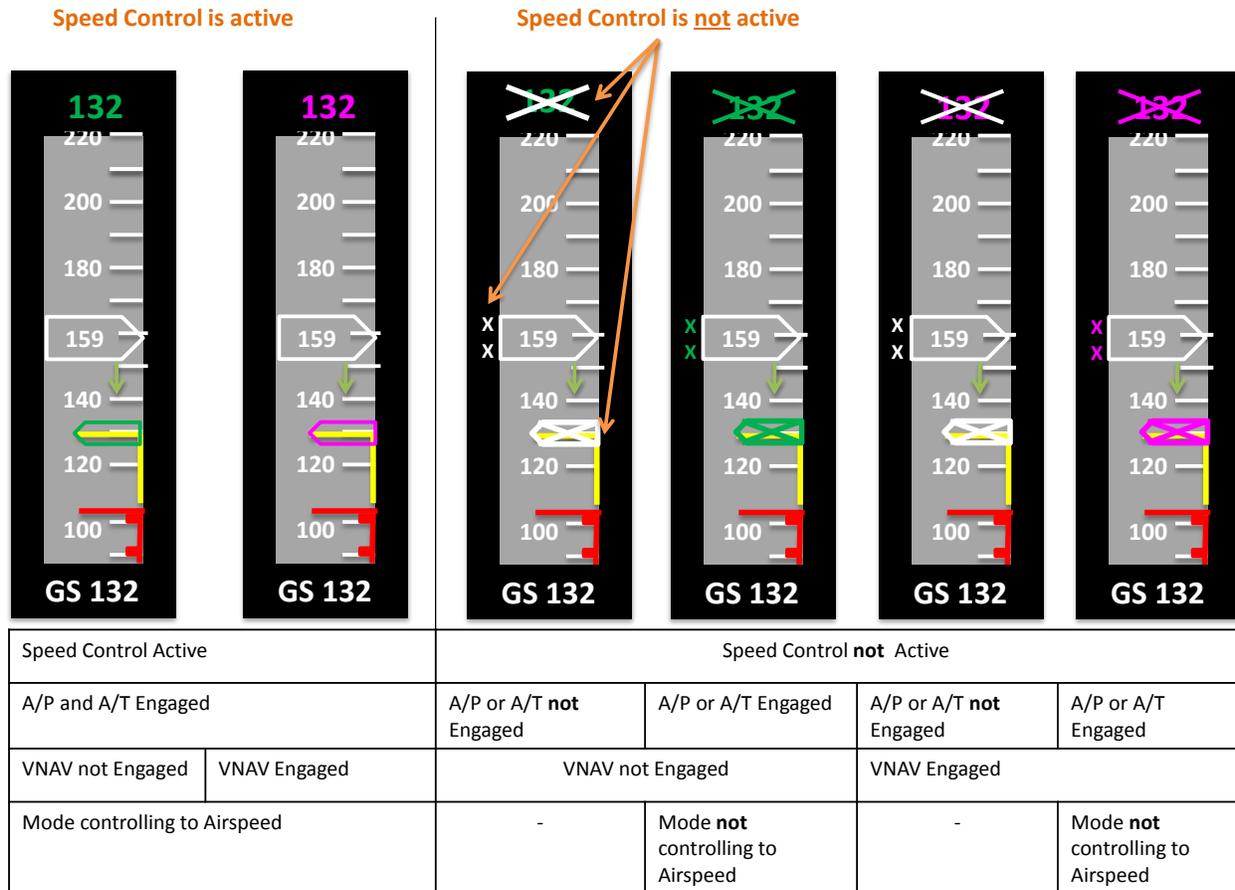
An enhanced airspeed tape display is proposed to provide this information in one location without requiring the use of memorized rules. The following description provides one example of a display that would meet these requirements. Of course, alternate symbology, color schemes, etc. could be used. The

design for the enhanced PFD airspeed tape is summarized in Table 2 and illustrated in Figure 4. In normal operation, with the targets generated from the MCP, with the Autopilot and/or Autothrottle engaged, and the selected control mode actively controlling airspeed, the numerical target and bug are green. With the same situation with targets generated from VNAV, the numerical targets and bug are magenta.

When airspeed is not actively being controlled, the numeric target and the bug are displayed with attention grabbing crosses indicating the target is not being controlled. The reason for the absence of airspeed control is explained by the color of the crosses. White crosses indicate that the Autopilot and/or the Autothrottle are no longer engaged. When the Autopilot and/or the Autothrottle are engaged, but the selected control mode is not actively controlling airspeed (e.g. “dormant” mode, “land” mode), the crosses are green for MCP targets and magenta for VNAV targets.

**TABLE 2: Design of a PFD Airspeed Tape to Identify CFIS Scenarios**

<b>Automation Configuration and Control Mode</b>						
	<i>Scenario: Normal Ops</i>		<i>Scenario: A/P or A/T disconnect</i>		<i>Scenario: Control Mode does not Control Airspeed</i>	
<b>Airspeed Target Source</b>	MCP	VNAV	MCP	VNAV	MCP	VNAV
<b>A/P and/or A/T Engaged</b>	Engaged	Engaged	No Longer Engaged	No Longer Engaged	Engaged	Engaged
<b>Control Mode controls speed</b>	Control Mode selected does control Airspeed		Airspeed not controlled.		Control Mode selected does <u>not</u> control airspeed	
<b>PFD Speed Tape</b>						
<b>Numerical Airspeed Target</b>	Green	Magenta	Green with White X	Magenta with White X	Green with Green X	Magenta with Magenta X
<b>Target Pointer</b>	Green	Magenta	Green with White X	Magenta with White X	Green with Green X	Magenta with Magenta X



**FIGURE 4: Enhanced PFD Airspeed tape with explicit indication of the absence of airspeed due to engagement status or control model**

With this proposed design, the flight crew can answer the three CFIS questions with a single glance at the airspeed tape.

Mauro & Trippe [9] designed and ran a human-in-the-loop experiment to evaluate this design. Airline pilots currently flying Boeing aircraft were recruited to participate in an online study comparing a traditional PFD design (used in the Boeing 777) and a modified PFD designed to alert the pilot when airspeed or altitude was not being controlled by the autoflight system.

**Method**

Participating pilots were shown a series of flight scenarios composed of a set of still frame “slides” on their computer screens. For each flight scenario, they were first shown a brief written description of the scenario along with ATC-like instructions in italics that described what would happen in the

upcoming slides. For example, “Inbound to KJFK RWY 31R; maintain 1900 feet; heading 285 to intercept the localizer; cleared ILS RWY 31R.” If the scenario placed the pilot’s aircraft on an approach, the participants were also shown an approach plate with the approximate vertical and lateral position of the aircraft indicated.

After the description slide, there were 3 or 4 slides depicting the aircraft’s PFD at advancing time points in the flight. As soon as the final PFD slide in the scenario appeared the pilots were instructed to indicate whether or not there was a deviation from the intended airspeed and/or flight path by pressing the "y" key for “yes, there is a problem” or the "n" key for “no, there is no problem” as fast as possible without making mistakes. The pilot’s reaction time from the time that the last slide was presented until a key was pressed was recorded. Twelve scenarios depicted a normal operation and 12 scenarios depicted a problem. Reaction time was used to determine whether the enhancements to the PFD would have any effects because reaction times are more sensitive measures of performance than error rates. Half of the scenarios depicted a traditional PFD and half depicted an enhanced PFD. The scenarios that were presented on each type of PFD were counterbalanced across the participants. The order of presentation, traditional PFD first or enhanced PFD first, was also counterbalanced.

## **Results**

Thirty-one pilots participated in the experiment. As might be expected given the design and the experience level of the pilots, the pilots made very few errors. There were no differences in the proportion of correct responses due to the type of PFD.

For 17 experiment scenarios there were no differences in the speed of responses due to the type of PFD. One scenario was incorrectly presented. For 6 scenarios there was a statistically significant difference. In all of these cases, pilots were faster to respond when the scenario was presented using the enhanced PFD.

## Discussion

In this study, there was no attempt to load the pilots or to distract them with mechanical failures or operational issues of the sorts that populate accident reports. All that the pilots were required to do was to view the PFD and determine whether the display indicated that there was a deviation from the expected altitude or airspeed target. As would be expected, the participants, all of whom were experienced pilots, made very few errors reading their PFDs. Had many errors been observed, the fidelity of the study would have to be questioned. Experienced pilots do not make many errors on such routine tasks. Indeed, on most scenarios, the participants were equally fast at responding to the scenarios on either type of PFD. However, whenever there was a statistically reliable difference in speed of response, pilots were faster to respond correctly when they were using the enhanced PFD whether or not there was a problem. This pattern of results indicates that the enhancements had no unintended consequences and caused a measurable increase in performance.

## Conclusion

This paper describes the results of an analysis of CFIS events and the associated Human-Computer Interaction for the flight crew task of intervention in the CFIS scenarios. The analysis determined that in many CFIS events the automation failed *to actively control to the airspeed target*. There were two causes: (1) the automation was not coupled, and (2) the control strategy (mode) for speed control did not directly control airspeed.

The analysis of the flight deck cues needed for the flight crew to detect, recognize and diagnose these scenarios revealed that the data needed to determine if airspeed control to the target is active is **not** explicitly annunciated. Further, the information required to diagnose the causes is located in different locations on the PFD, and memorized rules are required to interpret these data. In this way, the PFD is *not* designed to explicitly support the flight crew in performing this task.

Requirements for a flight deck display to support the CFIS intervention task without memorized rules were derived. An example of a new enhanced airspeed tape to explicitly identify whether airspeed

control is active, the control strategy (mode), and the automation configuration is described. An experiment to evaluate the efficacy of the enhanced PFD demonstrated that the enhanced display was superior to the traditional display in every situation in which a difference was observed.

### **Problem of Evolving Functionality without Evolving Displays**

The modern “glass” PFD is an integrated version of the federated “steam gauge” displays. Data on the gauges for airspeed, horizontal situation, bank, altitude, rate-of-climb/descent, and heading were consolidated onto a single digital display. This was supplemented by adding flight mode annunciation, localizer and glideslope deviation displays, tuned nav aids, and radio altimeter information. In this way the “glass” PFD is designed to support the flight crew tasks that were performed by the steam gauges and other federated displays.

The features of the PFD were, however, designed prior to the evolution of the automation and may not adequately support new tasks required by the automation including monitoring of automation for rare unexpected events.

### **Designing a “Safety Barrier” to Controlled Flight into Stall**

The unique sequence of events that lead to CFIS accidents and incidents indicate that it may not be feasible to *a priori* design automation in which speed control is always active. A catch-all approach is to assess the changed role of the flight crew monitoring the automation and performing intervention tasks.

During the design, the safety analyses (e.g. Fault Tree Analyses (FTA) and Failure Mode Effects Analysis (FMEA)) should explicitly address conditions related to situations when *airspeed is intentionally not actively controlled*. These situations are not always failure conditions. In the case of CFIS accidents and incidents a structurally, mechanically, and electronically sound aircraft decelerated through the minimum safe operating speed ( $1.3 V_{\text{Stall}}$ ) to the stick-shaker stall speed.

Certification checklists for new functions could be supplemented with the following checks of intended function and displays. In particular to ensure that the *not active control* state does not occur, and if it does occur, that it is unambiguously annunciated.

### Intended Function

- (1) Does the new function include modes that control aircraft trajectory?
- (2) If yes, do any of these modes (or mode combinations) result in a situation where energy-state, lateral trajectory, or vertical trajectory is *not actively controlled*?
- (3) If yes, can it be shown that for the finite set of combinations of conditions that may occur, that the automation does not result in a situation where energy-state, lateral trajectory, or vertical trajectory is not actively controlled?

### Displays

- (1) Do the displays explicitly annunciate an automation mode selection that does not actively control aircraft trajectory resulting in any of the following hazards: loss of safe energy-state, collision with terrain or obstacles, or collision with traffic?
- (2) Do the displays explicitly annunciate the causes of not actively control aircraft trajectory (coupling, mode, target, command) resulting in any of the following hazards: loss of safe energy-state, collision with terrain or obstacles, or collision with traffic?

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