Trajectory Prediction and Alerting for Aircraft Mode and Energy State Awareness

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This paper describes the implementation and evaluation of technologies that predict and assess the future aircraft energy state and autoflight configuration, and provide appropriate alerting to better inform pilots of the effect of problematic autoflight inputs or conditions. Prediction algorithms are used to extrapolate the current state of the aircraft based on flight management, autopilot and autothrottle system control laws and knowledge of mode transition logic. The resulting predicted trajectory represents the future four-dimensional flight path of the aircraft if the current course of action is continued. Probabilistic methods are used to estimate the trim envelope through high-fidelity model-based computation of attainable equilibrium sets. The corresponding maneuverability limitations of the aircraft are determined through a robust reachability analysis (relative to the trim envelope) through an optimal control formulation. The combination of prediction and assessment technologies are used to trigger timely alerts to avoid loss of control situations. The maneuvering envelope limits are also indicated on the primary flight display, and the predicted trajectory is displayed on navigation and vertical situation displays. The display features and alerts were evaluated in the Advanced Concepts Flight Simulator at NASA Ames Research Center, where commercial airline crews flew multiple problematic approach and landings scenarios to investigate the impact on current and future aircraft energy state awareness. Results show that the display features and alerts have the potential to improve situational awareness of what the automation is doing now and what it will do in the future.
I. Introduction

Loss of control (LOC) in flight has been the leading cause of fatal aircraft accidents for many years. In a recent study of LOC accidents and incidents, the Commercial Aviation Safety Team (CAST) identified a growing trend in loss of Airplane State Awareness (ASA) by the flight crew. This has led to recommended safety enhancements that include flight deck technologies with the potential of enhancing flight crew awareness of airplane energy state (SE 207). One of the objectives in this area is to develop systems that predict the future energy state and/or autoflight configuration if the current action is continued and provide appropriate alerting (Output 3).

While automation has contributed substantially to the sustained improvement in air carrier safety, vulnerabilities have been identified in the area of flight crew management of automation and situational awareness. Another CAST team specifically identified concerns regarding mode confusion aspects of human-automation interaction: “Flight crews can lose situational awareness of the automation mode under which the aircraft is operating or may not understand the interaction between a mode of automation and a particular phase of flight or pilot input. These and other examples of mode confusion often lead to mismanaging the energy state of the aircraft or to the aircraft’s deviating from the intended flight path for other reasons.”

The Next Generation Air Transportation System, or NextGen, will increase capacity and efficiency with the transition from clearance-based operations to Trajectory-Based Operations (TBO). The basis for TBO is that each aircraft’s expected flight profile and time (or airspeed) information will be specified by a four-dimensional (4D) trajectory. This will dramatically reduce the uncertainty of an aircraft’s future flight path to enable the assessment and negotiation of fuel-efficient trajectories, including Optimized Profile Descents (OPDs). OPDs will allow aircraft to fly a continuous descent approach to the runway at idle or near idle thrust without level flight segments. While NextGen related procedural and technological advancements could significantly increase capacity and efficiency, they also have the potential of increasing flight crew dependency on the use of automation during day-to-day operations.

Aircraft can automatically fly these 4D trajectories using a combination of the Flight Management System (FMS), autopilot system (APS), and autothrottle system (ATS). Pilots enter a flight plan into the FMS consisting of a sequence of waypoints along with associated constraints. These constraints can be expressed in terms of speed and/or altitude crossing restrictions at the waypoints. The FMS then generates the corresponding four-dimensional (4D) reference trajectory that optimizes performance while complying with constraints. Pilots interact with the FMS, APS, and ATS through Control Display Units (CDUs), the Mode Control Panel (MCP), and (in some cases) direct manipulation of the throttles. The behavior of these coupled systems are complex and have raised a number of human factors related concerns with cockpit automation.

This paper provides an overview of the implementation and evaluation of technologies that predict the future state of the aircraft, assess this future state relative to a safe flight envelope, and provide appropriate alerting. These tools seek to make the behavior of the automation more transparent to the flight crew, while enhancing their energy state awareness, and alerting pilots of problematic autoflight inputs or conditions. These features and alerts were evaluated in the Advanced Concepts Flight Simulator (ACFS) at NASA Ames Research Center.

II. Technical Approach

The goal of this research is to develop predictive, assessment, and alerting technologies to provide flight crews with displays that depict the current and future state of the aircraft, and alerts that provide notification of impending dangerous situations. Prediction algorithms extrapolate the current state of the aircraft based on the behavior of control laws and knowledge of mode transition logic design (for the FMS, APS and ATS). The resulting 4D trajectory represents the future flight path of the aircraft if the current course of action is continued. The predicted trajectory is displayed on navigation and vertical situation displays. Probabilistic envelope estimation methods are used to conduct near real-time system identification to estimate the trim envelope through high-fidelity model-based computation of attainable equilibrium sets (i.e. achievable trim points). The corresponding maneuverability limitations of the aircraft are determined through a robust reachability analysis relative to the trim envelope through an optimal control formulation, while making use of time scale separation and taking into account uncertainties in the aerodynamic derivatives. The resulting maneuvering envelope limits (e.g. airspeed, vertical speed, bank angle) are displayed on the Primary Flight Display (PFD). The predicted trajectory is assessed relative to safe flight envelope conditions to notify pilots when impending dangerous energy state conditions are anticipated. These trajectory prediction, maneuvering envelope assessment, and predictive alerting technologies are described in detail in the following sections.
A. Trajectory Prediction

The objective of trajectory prediction is to rapidly predict the 4D flight path that the automation will fly. This is accomplished using a fast-time simulation method that models the behavior of the (FMS, APS and ATS) guidance, navigation, and control functions. Trajectory prediction is first initialized with the aircraft state, flight plan and trajectory intent information, and the current (FMS, APS and ATS) modes and targets. The navigation prediction function then computes navigation signals relative to the reference trajectory, which is used by the guidance prediction function to determine when mode transitions will occur. The control prediction function computes the control commands based on the predicted mode of the aircraft. Finally, these control commands are used by the aircraft modeling function to update the predicted aircraft state. Aircraft states are modeled as following commands (such as bank angle, flight path angle, and thrust) as a first order system with a rate limit. The states are then propagated forward in time to predict the orientation, velocity, and position of the aircraft. Drag is continually estimated to account for changes in aircraft configuration (speed brakes, flaps, gear, etc). This process is illustrated in Figure 1 below. Reference 9 contains an in-depth discussion of these methods (for the FMS). For this study, the prediction algorithms were expanded to include all APS and ATS modes.

![Trajectory prediction method](image)

The predicted trajectory is incorporated into the navigation and vertical situation displays (ND and VSD). Figure 2 provides an example of the ND and VSD used in this experiment. On both the ND and VSD, the reference trajectory (programmed into the FMS) is shown in magenta, with waypoints denoted by text. The vertical axis of the VSD represents altitude, and the horizontal axis represents the along-track distance of the lateral path. Altitude constraints are represented on the VSD as triangles, and speed constraints are listed numerically below. A white trend vector extending from the aircraft symbol displays a propagation of the current vertical speed (for the next 90 seconds). Also, the MCP altitude is shown as a white horizontal line (e.g., displayed as “70” for 7000 feet in Fig. 2).

The predicted trajectory is shown as a green line on both the ND and VSD. Predicted mode transitions are denoted by small circles with corresponding text on the displays (e.g., “VNAV ALT” in Fig. 2). Because of active drag estimation, the predicted trajectory provides dynamic feedback to pilot changes in the aircraft’s configuration (e.g., speed brakes, throttle position, and flaps). For this study, the trajectory was predicted for the next 5 minutes with a one second timestep (for a total of 300 points), at an update rate of 30 Hz.
B. Maneuvering Envelope

Up-to-date maneuvering envelope limits are estimated in a three-step process (Fig. 3). These methods rely on a nonlinear aircraft model that takes advantage of time scale separation, focusing on the slower aircraft dynamics.
First, a probabilistic Bayesian update method is used to estimate the aerodynamic derivatives and their uncertainties. This online approach runs in the background while the aircraft is flying, and produces adequate estimates provided there is sufficient input excitation to cover the dynamic response of the aircraft.\textsuperscript{10,11} However, for the purpose of this experiment, each scenario was pre-trained since testing the performance of the system identification algorithm was not the focus of this study.

Next, the trim envelope is calculated using the same aircraft model. This step involves a sweep over a grid of allowable input values and a check for stability.\textsuperscript{10,11} In this experiment, the coarse trim envelope estimate was calculated over a grid of allowable airspeeds and flight path angles with a spacing of 2.5 knots and 1 degree, respectively. From the trim envelope, airspeed and flight path angle boundaries were estimated and further refined in resolution to 0.1562 knots for airspeed and 0.0625 degrees for flight path angle.\textsuperscript{12}

Lastly, the maneuverability envelope is estimated. The algorithm performs a robust reachability analysis through an optimal control formulation while making use of time scale separation and taking into account uncertainties in the aerodynamic derivatives computed in the system identification step. The safe maneuvering envelope is defined as the cross section between the forward reachable and backward reachable sets, which have been calculated starting from the stable trim envelope.\textsuperscript{13,14}

The trim and maneuvering envelopes are used to provide pilots with additional energy state information on the PFD. Most conventional flight decks only display airspeed limits and pitch limit indicators that are based on predefined tables. However, this new technology provides dynamically computed (1) airspeed, (2) bank angle, (3) pitch, and (4) vertical speed limit indications (Fig. 4). The upper red barber pole on the airspeed tape indicates the maximum airspeed, corresponding to both the structural limits and the computed control saturation limits of the aircraft. The lower red barber pole on the airspeed tape indicates the minimum airspeed (corresponding to the stall speed). The top amber bracket on the airspeed tape denotes the maximum airspeed at the next flap setting. The lower amber bracket indicates airspeeds with reduced bank maneuverability. This is also reflected in the red bank limit indicators (2). The pitch limit indicator (3) is shown by the amber bar (with whiskers). The amber region on the vertical speed display indicates the minimum and maximum vertical speeds at which the aircraft can no longer maintain its current airspeed. The red region on the vertical speed display indicates the vertical speeds at which the aircraft will require more than 5 seconds to return to a trim condition. Reference 12 contains a detailed explanation of how the envelope is mapped to the limits on the PFD.

![Figure 4. Primary Flight Display (PFD) with new maneuvering envelope information: (1) airspeed limits, (2) bank angle limits, (3) pitch limit indicator, and (4) vertical speed limits](image-url)
C. Predictive Alerting

Predictive alerts notify pilots of impending dangerous energy state conditions, by evaluating the predicted trajectory relative to the estimated trim envelope. An alert is issued if the predicted state of the aircraft exceeds the envelope within a specified time horizon. Based on how soon the unsafe conditions are predicted to occur, the level of the alert is elevated from an advisory, to a caution, to warning (with auditory cues drawing more attention to impending events). A list of all alerts and the associated timing is shown in Table 1.

<table>
<thead>
<tr>
<th>Alert</th>
<th>Advisory time horizon [s]</th>
<th>Caution time horizon [s]</th>
<th>Warning time horizon [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bank Limit</td>
<td>45</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Control Authority</td>
<td>45</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Overspeed</td>
<td>45</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Stall</td>
<td>45</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Unstable Approach</td>
<td>120</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Vertical Speed Limit</td>
<td>45</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Safe envelope limits are checked for bank, control authority (control surface saturation), overspeed (maximum airspeed), stall (minimum airspeed or maximum angle-of-attack), vertical speed, and unstable approach. The unstable approach criteria tests whether the flight path deviation is within 1 dot of the glideslope and localizer, that the airspeed is between the reference velocity ($V_{ref}$) and 20 knots above the reference (for the current flaps setting), and that the sink rate is no more than 1000 feet/min. These criteria are only checked below 1000 feet when the approach mode is armed or engaged. For this study, filters were added in an effort to prevent flickering and false alerts.

The alerts are annunciated on the Engine Indication and Crew Alerting System (EICAS) and displayed on the ND and VSD, which provides a temporal indication of when the unsafe condition is predicted to occur. Figure 5 shows an example stall advisory. On the ND and VSD, the beginning of the alert is noted with a cyan circle and text (to avoid overlap with the white waypoint text), and the predicted trajectory is displayed in cyan instead of green for the predicted duration. As the aircraft approaches the unsafe state, the alert elevates to a caution. A caution is accompanied with an auditory chime, and the EICAS, ND, and VSD messages and predicted unsafe trajectories turn amber. At the highest level, if the aircraft is currently in the unsafe state, the alert would be elevated to a warning. A warning is accompanied by a siren, and the EICAS, ND, and VSD messages and the predicted unsafe trajectories turn red. If the unsafe condition begins beyond the advisory time horizon, no alert will be issued. Note that unstable approach and vertical speed alerts are not raised to a warning, as these are less critical events.

Figure 5, 6, and 7 walk through an impending stall alerting example, as the aircraft approaches the dangerous energy state. As can be seen in Fig. 5, the PFD shows that the airspeed has been dialed to 135 knots, well below the lower safe airspeed limit of 150 knots, indicated by the top of the red barber pole. A stall is predicted within 45 seconds and an advisory is issued, as can be seen on predicted trajectory (Fig. 5). As the aircraft slows into the amber band, bank limits are restricted, and when stall is predicted within 10 seconds, the alert is elevated to a caution (Fig. 6). When the airspeed is below the lower limit, a warning is sounded and the predicted trajectory turns red (Fig. 7).
Figure 5. Stall advisory alert, displayed on the ND (top right), VSD (bottom right), EICAS (bottom left)

Figure 6. Predicted stall caution
III. Experiment Overview

The predictive, assessment, and alerting technologies were evaluated in the ACFS at the Crew-Vehicle Systems Research Facility at NASA Ames Research Center. The study focused on the descent phase of flight, where commercial airline crews flew four different scenarios, both with and without the new technologies, for a total of 80 OPDs. In runs without the new technologies, crews were presented with standard navigation displays, including a vertical situation display (VSD). In runs with the new technologies, trajectory predictions were added to both the ND and the VSD, updated maneuvering limits were displayed on the PFD, and (if triggered) predictive alerts were displayed on the EICAS, ND, and VSD. Scenarios were specifically constructed to induce high and low energy situations, as well as to imitate failures and other off-nominal conditions based on previous accidents and incidents.

A. Simulator Description

The ACFS simulator (Fig. 8) is equipped with a six degree-of-freedom motion system, programmable FMS and flight displays, digital sound and aural cueing system, and a 180-degree field of view visual system. The simulated aircraft is representative of a mid-size two-engine jet transport with general characteristics similar to a Boeing 757 aircraft.

B. Participants

Twenty commercial airline pilots (from three different carriers) participated as ten two-person crews, with each crew consisting of pilots from the same carrier. All participants were current or within one year of retirement, and had previous experience on B757/767 aircraft. Prior to the experiment, pilots were briefed on the new technologies and flew multiple training runs. Pilots were also informed that there would be failures in some of the scenarios, and (in the event of a failure) they would not be able to correct the issue.

Several forms of feedback were collected from the crews. During each run, participants were asked to respond to a real-time workload prompt to assess their current level of workload, using an ATWIT-based procedure. Following each run, the participants completed a questionnaire that included questions about their workload and situational awareness. At the end of the study, participants completed a longer questionnaire asking more general questions about the effectiveness of the displays and alerts.

C. Routes and Airspace

Each crew flew eight OPDs into Memphis, along two arrival routes (Fig. 9). These routes were adapted, from existing standard arrival
procedures (STARs) and approaches/ transitions, to construct NextGen-oriented area navigation (RNAV) routes (without vector segments). The BRBBQ route consisted of the BRBBQ2 STAR (ending at SKEEZ), followed by the approach transition (from SKEEZ to BLEWS) to the approach (from BLEWS to Runway 18 Right). The BLUZZ route consisted of the BLUZZ2 STAR (ending at HEXIN), followed by the approach transition (from HEXIN to REISE) to the approach (from REISE to Runway 18 Left).

**Figure 9. Routes flown into Memphis airspace**

### D. Scenarios

The study consisted of four scenarios, designed to evaluate different aspects of mode and energy state awareness. Each scenario was flown twice: once with the new display and alerting technologies, and once without. The order in which scenarios were flown was semi-randomized between crews. In an attempt to limit the impact of scenario learning, allowances were made to balance the number of times each scenario was flown for the first time with and without the new technologies. The simulator was initialized in descent prior to the BLUZZ (or BRBBQ) waypoint. The scenarios were defined by scripted clearances that were issued by a confederate controller at specific locations along the route. A pseudo pilot controlled traffic in the vicinity for realism. In general, flight crews were given an initial clearance to “descend via the BLUZZ2 (or BRBBQ2) arrival, HEXIN (or SKEEZ) transition, expect Runway 18 Left (or Right) approach.” This cleared the aircraft to descend along the STAR to the lowest altitude constraint in the STAR (4000 feet for the BRBBQ2 arrival and 3000 feet for the BLUZZ2 arrival), while complying with altitude and speed constraints specified along the STAR. A description of each scenario is given below.

1. **Low Energy**

   The low energy scenario was designed to evaluate the impact of the predicted trajectory (displayed on the ND and VSD) during low potential and kinetic energy management conditions, and to assess the impact of predicted stall alerts. This descent scenario was flown along the BLUZZ2 arrival. The aircraft was initialized 2000 feet low prior to BLUZZ at 290 knots, with an initial descent rate that paralleled the reference trajectory. The automation was initialized in VNAV SPD mode, where pitch is used to fly the aircraft at the target speed and thrust is used to manipulate the rate of descent. Shortly after passing OPEN, crews received a (20 knots) slower speed clearance to “maintain 210 knots”. Additionally, the radar altimeter of the Pilot Not Flying (PNF) was failed and displayed zero feet above the ground. This caused the ATS to command idle thrust upon glideslope capture, as the system assumed the aircraft was going to flare, which can result in a stall condition if the crew does not intervene.

2. **High Energy**

   The high energy scenario was designed to evaluate the impact of the predicted trajectory (displayed on the ND and VSD) during high potential and kinetic energy management conditions, and to assess the impact of predicted unstable approach alerts (during a high potential energy approach). This descent scenario was flown along the BRBBQ2 arrival. The aircraft was initialized 2000 feet high prior to BRBBQ at 290 knots, with an initial descent rate that parallels the reference trajectory. The automation was initialized in VNAV SPD mode. Shortly after passing...
JAMLA, crews received a “descend and maintain 5000” feet clearance and a (10 knots) faster speed clearance to “maintain 240 knots.” At SKEEZ, crews were vectored into ELVIS with a clearance to “turn right heading 150” degrees and to “maintain 170 knots.” This resulted in the aircraft being laterally offset from the reference trajectory. While “on present heading,” crews were instructed to “intercept localizer at or above 3000 (feet), cleared ILS Runway 18 Right approach.” Since crews had to wait until capturing the localizer before being cleared to land, this resulted in the aircraft being high on final approach and having to capture the glideslope from above (in what crews refer to as a ‘slam dunk’ situation).

3. Icing

The icing scenario was designed to evaluate the impact of maneuvering envelope information (displayed on the PFD) during conditions where the minimum safe airspeed was higher than normal, and to assess the impact of predicted stall alerts. This descent scenario was flown along the BLUZZ2 arrival. The aircraft was initialized 1000 feet below the path just after BLUZZ at 230 knots, with an initial descent rate that paralleled the reference trajectory. The automation was initialized in VNAV SPD mode. An EICAS message informed the crew of icing built up on the wing of the aircraft. The icing was modeled by increasing drag, decreasing lift, and reducing the maximum angle-of-attack. As a result, the aircraft will stall at significantly faster than normal speeds.

4. Stabilizer Failure

The stabilizer failure scenario was designed to evaluate the impact of maneuvering envelope information (displayed on the PFD) during conditions where maximum safe airspeed was lower than normal, and to assess the impact of predicted overspeed and control authority alerts. This descent scenario was flown along the BRBBQ2 arrival. The aircraft was initialized on the reference trajectory just after BRBBQ at 230 knots, with one degree of flaps. The automation was initialized in VNAV PTH mode, where pitch is used to fly the aircraft along the vertical path and thrust is used to control the airspeed. An EICAS message informed the crew that an unexpected stabilizer anomaly had occurred, resulting in the stabilizer being stuck at an eight degrees nose-up condition. This restricted the maximum airspeeds and climb rates that the aircraft could fly before reaching elevator control saturation. On the approach, the landing clearance was cancelled due to traffic on the runway, and crews were instructed to go-around.

IV. Results

The results were analyzed based on specific areas of interest for each scenario, as well as overall impact to energy state awareness and pilot workload. In general, pilots said the new technologies increased their awareness; however some expressed concerns on potentially placing too much reliance on automation or information overload. Pilots commented that the tools “either confirmed my plan of action, or they alerted me to some situations that needed attention” and that they were “very useful in energy management and flight path planning.”

A. Low Energy Scenario

The low energy scenario began with the aircraft in descent 2000 feet below the reference trajectory. Crews had to manage this low potential energy situation while meeting the (280 knots) speed constraint at BLUZZ and the (230 knots and 10000 feet) speed and altitude constraints at COPEN. This type of off-path operation has a tendency to decrease situational awareness and increase workload, since pilots must now predict the flight path of the aircraft in order to manage energy tradeoffs while ensuring constraint compliance. While all of the crews satisfied the speed and altitude constraints, there were some variations in energy management strategies when flying under current verses new technology conditions. Crews flying with new technology tended to be less aggressive in applying thrust to shallow the aircraft’s rate of descent. One possible explanation is that the predicted trajectory provided some reassurance of altitude constraint satisfaction in the future. Crews with current technology tended to apply more thrust to recapture the path sooner. While flying higher and on-path is generally more efficient, this did not materialize in fuel savings, since speed brakes were often required to compensate for overshooting the speed target when capturing the path from below. Figure 10 displays the altitude and speed brake usage (verses along track distance) from the beginning of the scenario to COPEN. Blue lines represent runs with current technology and green lines represent runs with new technology. Solid lines represent mean values and dashed lines represent mean values plus or minus one standard deviation.
The low energy scenario continued with a slower (20 knots) speed clearance after COPEN. Crews had to manage this low energy situation while meeting the (3000 feet) altitude constraint at HEXIN. While all crews satisfied the altitude constraint at HEXIN, there were some variations in energy management strategies. However, these strategies did not significantly differ when flying under current verses new technology conditions. In a few cases, crews entered the new speed into the FMS. This caused the reference trajectory to be recomputed and allowed the automation to stay in VNAV PTH mode. In the majority of cases, crews entered the new speed into the MCP, which caused the aircraft to depart (approximately 400 feet) above the reference trajectory (in VNAV SPD) when decelerating to the slower speed. In some of these cases, crews applied little-to-no speed brakes or flaps, and allowed the aircraft to fly (a couple of hundred feet) above the reference trajectory before intercepting the path near VNSSA (Fig. 1). In other cases, crews applied speed brakes to catch up to the reference trajectory and then manipulated throttles to follow the path (within approximately 100 feet). In a few cases, crews applied and maintained speed brakes until flying below the reference trajectory before leveling off (at 3000 feet) to meet the altitude constraint at HEXIN.

The low energy scenario finished with a simulated radar altimeter failure, which caused the ATS to incorrectly command the throttles to idle after glideslope capture. However, this behavior can be masked when the aircraft is decelerating (e.g., to the final approach speed). Crews had to recognize and respond to this low kinetic energy situation during the approach. For this study, it was assumed that the guidance prediction logic would be capable of predicting this behavior. As a result, under the new technology condition, crews would receive an alert indicating a predicted stall following glideslope capture (Fig. 12).
When flying under the new technology condition, almost all of the crews commented on the predicted stall alert. However, most crews dismissed the alert since there did not appear to be a reason for the stall prediction. Even though the alerts were generally dismissed, their presence did appear to have an effect on the recognition and response times of the crews. Once the ATS failure became unmasked (i.e., when the airspeed dropped below the MCP commanded speed), the response time was determined by the amount of time it took for the Pilot Flying (PF) to make a corrective action (e.g., applying thrust by overriding the ATS). The resulting speed loss was determined by how much the airspeed had dropped (below the MCP commanded speed) at the time of the corrective action. Both the mean response time and resulting speed loss were significantly lower under the new technology condition when compared to the current technology condition (Fig. 13).

**B. High Energy Scenario**

The high energy scenario began with the aircraft in descent 2000 feet above the reference trajectory. Crews had to manage this high potential energy situation while meeting the (280 knots) speed constraint at BRBBQ and the (230 knots and 10000 feet) speed and altitude constraints at JAMLA. This type of off-path operation has a tendency to decrease situational awareness and increase workload, since pilots lose the benefits of flying a reference trajectory that optimizes performance while ensuring constraint compliance. All of the crews satisfied the altitude constraint (at JAMLA). However, two speed constraints were violated when using current technology, and one speed constraint was violated when using new technology. In general, when using new technology, crews tended to use slightly less speed brakes and thrust. This resulted in a 6.5% fuel savings from the beginning of the scenario to JAMLA (Fig. 14).
One possible explanation is that the predicted trajectory provides dynamic feedback when extending speed brakes, since active drag estimation will cause the predicted trajectory to move as speed brakes are adjusted. Figure 15 shows an example of the predicted trajectory with partial speed brake extension. While the (white) trend vector shows that the projected vertical speed will intercept the reference trajectory at BRBBQ, the (green) predicted trajectory shows that the descent rate will decrease prior to BRBBQ (in order to meet the 280 knots speed constraint) and then recapture the reference trajectory (in VNAV PTH mode) prior to JAMLA.

The high energy scenario continued with a faster (10 knots) speed clearance after JAMLA. In almost all of the cases, crews entered the new speed into the MCP, which caused the aircraft to depart below the reference trajectory (in VNAV SPD) when accelerating to the faster speed. However, since this clearance coincided with a “descend and maintain” altitude clearance, many of these crews continued to expedite the descent to 5000 feet (well below the reference trajectory). In some of the cases, crews manipulated throttles to follow the reference trajectory. Only in a few cases, did crews apply additional thrust to fly above the reference trajectory before increasing the descent rate later on to recapture the path (presumably for fuel efficiency).

The high energy scenario finished with a ‘slam dunk’ to capture the glideslope from above. One of the purposes of this portion of the scenario was to assess the impact of the predicted unstable approach alerts. However, an implementation problem resulted in the predicted unstable approach alerts being intermittent. As a result, crews disregarded these alerts. While all of the crews achieved a stable approach by 1000 feet Above Ground Level (AGL) using current technology, one crew did not achieve a stable approach until 880 feet AGL using new technology. The mean workload assessment of the pilots was also higher for the new technology condition during the final approach (i.e., after capturing the localizer).
The primary reason for the increased workload is that a significant number of crews violated the landing clearance when using current technology (Fig. 16, 17). The clearance instructed crews to stay at or above 3000 feet (since they were not cleared to land) until capturing the localizer. Under the current technology condition, 6 out of the 10 crews dialed the MCP altitude below 3000 feet before intercepting the localizer, and 3 of those crews also descended below 3000 feet before intercepting the localizer. Under the new technology condition, only 1 out of the 10 crews dialed the MCP altitude below 3000 feet before intercepting the localizer, but that crew intercepted the localizer before descending below 3000 feet. Aircraft with the MCP altitude set at 3000 feet (in compliance with the landing clearance) often encountered a mode transition as the aircraft began capturing 3000 feet prior to intercepting the localizer. These crews had to recognize this mode transition, dial down the MCP altitude (upon intercepting the localizer), and then had to revert back to a descent mode. As a result, these crews had to compensate for the disrupted descent while attempting to capture the glideslope from above during the final approach. One possible explanation for the reduced number of landing clearance violations with new technology, is that the predicted trajectory provided enhanced awareness (in regards to when the localizer would be captured) and increased confidence that the ‘slam dunk’ could be achieved (albeit with higher workload).

C. Icing Scenario

The icing scenario began with the aircraft in descent 1000 feet below the reference trajectory. The aircraft was initialized in an icing condition, which significantly increases the stall speed. Furthermore, the increased drag causes the aircraft to experience larger than expected airspeed overshoots during deceleration segments. Crews had to manage airspeed and flap schedules to maintain safe maneuvering speed margins, while flying the published profile along the BLUZZ2 arrival (unless they declared an emergency). Figure 18 provides an example of the airspeed limits that are displayed on the PFD in a clean configuration (i.e., with no flaps) for (a) the current technology condition and (b) the new technology condition. While the current technology displays the nominal minimum maneuvering speed (~182 knots) and stall speed (~157 knots), the new technology displays the computed minimum maneuvering speed (~209 knots) and stall speed (~189 knots). In general, crews with new technology tended to apply more flaps than crews with current technology.13
After passing VNSSA at 210 knots, the commanded speed automatically decreased to 170 knots when entering the deceleration segment prior to HEXIN. Aircraft with flaps deployed less than five degrees would be in danger of flying slower than the safe maneuvering speed of ~209 knots, and would be in danger of stalling if the crew did not apply flaps before reaching ~189 knots. Average flap deployment between VNSSA and HEXIN (at 29 and 37 nm respectively, seen in Fig 19) shows that crews with technology respond with more flaps earlier, both due to the new envelope limits and as a response to the alerts. While all of the crews applied flaps before decelerating to the stall speed, four of the crews using current technology decelerated below the safe maneuvering speed before applying flaps. While all of the crews using new technology applied flaps before reaching the deceleration segment, four of those crews only had one degree of flaps until receiving a predicted stall alert (Fig. 20). All four crews noticed the predicted stall alert and immediately applied more flaps.

Figure 18. Airspeed limits displayed on the PFD

Figure 19. Mean and standard deviation of flaps between VNSSA and HEXIN

Figure 20. Example of predicted stall advisory due to icing (on the VSD)
D. Stabilizer Failure Scenario

The stabilizer failure scenario began with the aircraft in descent on the reference trajectory. The aircraft was initialized with the stabilizer stuck at eight degrees nose-up trim, which significantly reduces maximum airspeeds and climb rates. Otherwise the elevator will saturate, resulting in an uncontrollable pitch-up moment. Crews had to manage airspeed, climb rate, throttles and flap schedules to prevent elevator control saturation (particularly during the go-around maneuver). Figure 21 displays the airspeed, altitude, throttle and flap settings during the go-around maneuver. Blue lines represent runs with current technology and green lines represent runs with new technology. Solid lines represent mean values and dashed lines represent mean values plus or minus one standard deviation. During the initial phase of the go-around maneuver, there is very little variation between crew procedures for both the current technology and new technology conditions. Crews apply thrust to establish a positive rate of climb and then start adjusting the climb rate to control airspeed while retracting flaps. However, at approximately 60 nm, crews with new technology started to reduce thrust (apparently) to hold airspeed (at approximately 165 knots) while maintaining the present rate of climb. One possible explanation is that crews were reacting to the maximum airspeed limit displayed on the PFD and/or predicted overspeed and control authority alerts. Throughout the remainder of the go-around maneuver, crews with new technology tended to keep airspeeds and climb rates lower (than crews with current technology), while also retracting flaps at a slower rate.

![Figure 21](image)

**Figure 21.** Mean and standard deviation of airspeed, altitude, throttles and flaps during go-around

E. Pilot Ratings

Pilots rated their overall energy state awareness as “very high,” both with and without the new technologies. Pilots assessed the predicted trajectory displays as “very helpful,” and commented that they were “very useful in energy management and flight path planning.” While pilots felt confident they could determine the limits of the envelope, both with and without the maneuvering envelope displays, they said that the displays positively affected their flying strategies. The helpfulness of the predict alerts tended to vary by scenario (Fig. 22). The predicted stall
alert was the more helpful during the icing scenario (than the low energy scenario), since the reason for the predicted alert was more transparent. The predicted alerts for the high energy and stabilizer failure scenarios were also not as helpful, since they were intermittent. While the predicted unstable approach alert (during the high energy scenario) was intermittent because of an implementation problem, the predicted overspeed and control authority alerts (during the stabilizer failure scenario) appeared to be intermittent because of the dynamic nature of the go-around maneuver. Several pilots also commented that “it was a little overwhelming at first but after a few tries it was easier to understand the predictive warnings thus they became helpful to avoid a bad situation.”

![Figure 22. Helpfulness of the predictive alerts](image)

In general, the overall mental demand was rated higher using new technology for most of the scenarios (Fig. 23). The low energy scenario was the one exception, where the mental demand was rated slightly lower using new technology. The increased mental demand during the high energy scenario coincides with the higher mean workload assessment (Fig. 16), which was a result of increased landing clearance compliance rates, when using new technology. The increased mental demands during icing and stabilizer failure scenarios reflect the processing of additional envelope information in order to maintain safe maneuvering limits during off-nominal conditions.

![Figure 23. Mental demand](image)
V. Conclusion

Trajectory prediction and maneuvering envelope estimation can rapidly assess the safety of the future state of the aircraft and be combined to provide predictive alerts to flight crews. The 4D flight path prediction of the aircraft is accomplished using a fast-time simulation method that models the underlying behavior of the APS, ATS, and FMS guidance, navigation, and control functions. System identification, trim envelope estimation and a reachability analysis can be performed online, determining a set of safe airspeeds and flight path angles for the current aircraft configuration and observed flight dynamics. Alerts are issued, comparing the predicted state to this safe envelope. The new prediction and assessment technologies were incorporated into the primary flight, navigational, and vertical situation displays and evaluated in piloted simulations.

Results for the low and high energy scenarios show potentially better aircraft energy management with trajectory prediction. When significantly (2000 ft) off-path, crews with new technologies were less aggressive in re-capturing the path and potentially more efficient (i.e., less speedbrakes in the low energy scenario and better fuel efficiency in the high energy scenario). Also, during the “slam dunk” at the end of the high energy scenario, while crews with new technology reported a higher workload, significantly fewer crews violated the landing clearance. A possible explanation of these trends is that the predicted trajectory provided some reassurance of reaching the desired altitudes. However, when varying speed clearances only took crews only slightly off-path, strategies did not significantly differ when flying under current versus new technology conditions.

The icing and stabilizer scenarios show the benefits of updated safe envelope limits. Increased workloads reflect the processing of additional envelope information. With the new technology in the icing scenario, flaps were deployed at higher speeds, increasing the safety margin to the lower airspeed boundary. Also, in the unscheduled stabilizer trim scenario, the average airspeeds, climb rates, and flap retraction rates were lower for the majority of the go-around, increasing the safety margin to the upper airspeed boundary and control authority limits.

Timely responses to stall alerts in the low energy (due to a radar altimeter failure) and icing scenarios indicate some advantages of predictive alerting. While crews may have initially had confusion over the source of the alert in the low energy scenario, they were quicker to respond once the airspeed drops and it is observed that the throttles are not behaving properly. In the icing scenario, with the new airspeed limit displayed, pilots can see and understand clearly in advance that pre-programmed speed changes may result in unsafe situations and react to the predicted alerts.

These technologies show potential in enhancing automation and energy state awareness, but there are still limitations and much room for improvement. The fidelity of the algorithms will need to be increased (e.g., to account for winds). While the predicted trajectory lets pilots see that altitude constraints can be achieved, the displays could be enhanced to give pilots predicted speed information as well. Issues with inconsistencies in alerting must be addressed (as seen with the unstable approach and overspeed alerts). While additional filtering and better-tuned time horizons may alleviate some of these alerting issues, there will always be some limitations in predicting pilot intent. Alerts leading up to expected configuration changes may be seen as an annoyance. In cases where pilots did not understand the underlying reason for the alert -- as seen occasionally in the stabilizer failure scenario -- they are more likely to disregard it as erroneous. Having more information available to the pilots as to the source of the alert, such as through a synoptic display, could potentially alleviate this confusion. Alerts may also go unnoticed in high workload situations -- as suggested by the lack of direct response to alerts during the go-around -- suggesting the need for a more comprehensive solution once in an unsafe state. While the alerts seem to be useful for stall avoidance, stall recovery guidance would be needed to assist in correcting this dangerous condition. These additional enhancements may have the potential to further improve energy management and situational awareness of what the automation is doing now and what it will do in the future.

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