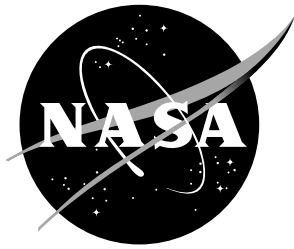# Vertical Motion Simulator Experiment on Stall Recovery Guidance

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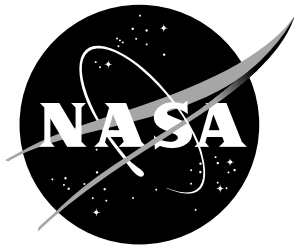- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

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Abstract

A stall recovery guidance system was designed to help pilots improve their stall recovery performance when the current aircraft state may be unrecognized under various complicating operational factors. Candidate guidance algorithms were connected to the split-cue pitch and roll flight directors that are standard on large transport commercial aircraft. A new thrust guidance algorithm and cue was also developed to help pilots prevent the combination of excessive thrust and nose-up stabilizer trim. The overall system was designed to reinforce the current FAA recommended stall recovery procedure. A general transport aircraft model, similar to a Boeing 757, with an extended aerodynamic database for improved stall dynamics simulation fidelity was integrated into the Vertical Motion Simulator at NASA Ames Research Center. A detailed study of the guidance system was then conducted across four stall scenarios with 30 commercial and 10 research test pilots, and the results are reported.

Advisory Committee

A committee of experts independently advised the design of the recovery guidance technology, and the experiment detailed in this report. Members of this committee provided impactful feedback on the experiment plan, and recommendations after flying fixed-base simulations at various points in time throughout the experiment development process. Any good idea in this report likely sprang from their feedback, and credit should be extended to them. We are sincerely grateful for their diligence and support.

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Executive Summary

Despite stall warning systems in most all commercial aircraft, full stalls do still sometimes occur. In several such cases, the pilots applied control in a direction opposite to that required to recover the aircraft after it had stalled. After performing a detailed analysis of representative Loss-of-Control accident cases, including some that involved stall, an international Commercial Aviation Safety Team of government and industry experts recommended numerous safety enhancements to address the primary issues identified. Among these was a recommendation to conduct research into algorithms and display strategies to provide guidance for recovery from approach-to-stall and stall.

The study detailed in this report examines one such stall recovery guidance system that has been designed to help pilots improve their stall recovery performance when the current aircraft state may be unrecognized in the presence of complicating operational factors. The focus of the study was on two candidate pitch guidance algorithms, in addition to a new thrust guidance system. The thrust guidance system was developed to help pilots avoid the loss of nose-down elevator authority caused by the application of too much thrust and nose-up stabilizer trim on aircraft with low mounted engines. A basic roll guidance strategy was also implemented to complete the pitch-roll-thrust guidance system. The outputs of the pitch and roll guidance computation were connected to split-cue pitch and roll flight directors that are standard on most large transport commercial aircraft. The overall system was designed to reinforce the current FAA recommended stall recovery procedure, and to potentially provide a benefit to that procedure when justified by the guidance computation.

The objectives of the study were to investigate the degree to which the candidate stall recovery guidance algorithms and displays could improve pilot stall recovery performance criteria in four scenarios: a high altitude stall recovery, a low altitude stall recovery with and without a misaligned stabilizer, and an approach stall recovery. The scenarios were designed specifically for baselining the potential safety benefits of the recovery strategy, computation, and display employed by the guidance system.

In total, 30 commercial and 10 research test pilots flew three runs of each scenario, each with and without guidance, in the Vertical Motion Simulator at NASA Ames Research Center. A general transport aircraft model, similar to a Boeing 757, was implemented for the study. This model contained an important extended aerodynamic database with improved stall dynamics simulation fidelity. The main findings of the study were: (1) that aggressive pitch down guidance was effective at preventing secondary aerodynamic stall during the recovery, especially at high altitude, (2) pitch and thrust guidance helped prevent excessive altitude loss in the low altitude scenario, (3) pitch-up guidance had a minor effect on reducing flap overspeed conditions while recovering with full thrust in the approach scenario, and (4) the addition of thrust guidance was effective at preventing over thrust in combination with excessive nose-up trim, but to the detriment of maintaining margin to secondary aerodynamic stall.

Contents

Nomenclature

α Angle-of-Attack. Angle from the airspeed velocity vector to the fuselage reference line.

α_{SR} Stall reference angle-of-attack. Exceeding of the stall reference angle-of-attack quickly leads to full stall. In this report, α_{SR} is defined as the angle-of-attack that first maximizes C_L.

γ Flight path angle. Angle from the horizon to the airspeed velocity vector.

ρ Air density at the current aircraft altitude.

θ Pitch angle. Angle from the horizon to the fuselage reference line. $\theta = \gamma + \alpha$.

C_D Dimensionless coefficient of drag.

C_L Dimensionless coefficient of lift, depends on α and other factors.

D Force of Drag.

g Acceleration due to gravity.

L Force of Lift.

m Aircraft mass.

n_{LF} Load factor, defined as L/W.

S Net wing surface area.

T Net force of thrust generated by the engines.

V True airspeed, i.e., the speed of the airflow over the wings.

V_{REF} Landing reference speed in knots, see Appendix A.

V_{SW} Stall warning airspeed in knots. Corresponds to α_{SW} and triggers the stick-shaker stall warning alert. See Appendix A.

W Aircraft weight, i.e., mg.

FMPC   Fast Model Predictive Control. One of the two pitch guidance algorithms used in the study.

ADI   Attitude Direction Indicator. Central portion of the PFD with the artificial horizon and flight director cues.

ADS-B   Automatic Dependent Surveillance-Broadcast.

Angle-of-attack   See α.

AoA	Angle-of-attack, see α.
ATC	Air Traffic Control.
CAS	Calibrated Airspeed. Indicated airspeed corrected for position and instrument error.
CAST	Commercial Aviation Safety Team.
CFR	Code of Federal Regulations.
EBA	Energy Based Algorithm. One of the two pitch guidance algorithms used in the study.
EICAS	Engine Indicating and Crew Alerting System.
FAA	Federal Aviation Administration.
FDR	Flight Data Recorder.
Full Stall	An aerodynamic condition where the angle-of-attack exceeds the stall reference angle-of-attack α_{SR}. The FAA provides an operational definition, based on the flight characteristics of stall, see [1, §1-7, pg. 2].
GTM	General Transport Model, the standardized commercial aircraft simulation model used in this study.
IAS	Indicated Airspeed. Airspeed reading on the flight-deck airspeed indicator. In this report, indicated and calibrated airspeed are treated as equivalent.
Load Factor	See n_{LF}.
LOC-I	Loss-of-Control In-flight.
NTSB	National Transportation Safety Board.
PF	Pilot Flying.
PFD	Primary Flight Display.
PIO	Pilot Induced Oscillation.
Pitching Moment	Rotational moment that produces a change in pitch.
PLI	Pitch Limit Indicator.
PM	Pilot Monitoring.
PNF	Pilot Not Flying.
Secondary Stall	Any full stall that occurs after breaking the initial stall in a stall recovery.

SRG	Stall Recovery Guidance.
Stall Buffet	A strong turbulence that sometimes occurs just prior to stall, caused by local regions of pressure- or shock-induced flow separation on the wing.
TAS	True Airspeed. Calibrated airspeed corrected for altitude and non-standard temperature — the speed of the aircraft relative to the airmass in which it is flying.
VMS	Vertical Motion Simulator.

1 Introduction

Aerodynamic stall is a potentially dangerous condition that occurs when an aircraft's angle-of-attack becomes so large that the desired smooth airflow across its wings is disrupted. An aircraft in this state loses the lift required to support its weight and is difficult to control. Stall is a condition most pilots train to avoid, and there are stall warning systems onboard most aircraft to help them prevent stalled flight conditions before they can occur. Unfortunately, stall related accidents and incidents do still occur in spite of the existing pilot training and systems for preventing stall. While the occurrence is rare, the consequences can be dire.

Two accidents in particular, both occurring in 2009, have exemplified the need for new thinking when it comes to preventing and recovering from aerodynamic stall. The first was the Colgan Air Flight 3407 accident in New York. The second was the Air France Flight 447 accident, out of Rio de Janeiro, Brazil. In each case, there was a different cascade of complicating factors that led to the stalled aircraft condition. The most striking observation for many, however, was that once the stall had occurred, the pilots reacted by applying the controls in the direction opposite to what was necessary to recover the aircraft. Although both crews in their most recent training cycle had been taught to minimize altitude loss in approach-to-stall recoveries (a concept now changed in FAA regulations), their in-flight actions made the situation worse.

Stall related accidents and incidents are formally categorized as Loss-Of-Control while In-flight (LOC-I). In decadal surveys, the LOC-I accident category has been, and remains to this day, the most significant *fatal* accident category for commercial jet airplane accidents worldwide [2]. Furthermore, LOC-I accidents are widely recognized by aviation safety experts as characteristically complex. Starting in 1999, the National Aeronautics and Space Administration (NASA) has been highly engaged in national and international efforts to reduce loss-of-control accidents in commercial aircraft [3]. One of the many outcomes of this work, is the recognition that the occurrence of stall is, typically, a final aircraft condition that results from the cascade of multiple safety system failures. The reduction of LOC-I accidents in general, and of stall related accidents in particular, therefore requires addressing the significant failures in the cascade. The focus of this report, however, is on the system of last resort, where a stall has occurred and the aircraft needs to be recovered to a safe flight condition under complex circumstances that have likely caused the pilot to lose aircraft state awareness.

In August 2010, the Commercial Aviation Safety Team (CAST) commissioned a group of government and industry experts to examine LOC-I accident and incident events, where the crew lost awareness of their airplane's state [4].[1] This Airplane State Awareness (ASA) team focused on 18 accident or incident events dating from 1998 to mid 2009. Nine of the 18 events were classified as attitude state awareness related (pitch or bank angle or rate). The other nine events, including 5 specific events where stall occurred, were classified as energy state awareness related (combination of airspeed, altitude, vertical speed, thrust, and airplane configuration). Nearly all

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[1]This CAST activity was a follow-on effort to previous analysis work done on loss-of-control in 2000.

of the incidents involved issues related to lack of external visual references, distraction, and ineffective alerting. Though not all of them were stall related, 12 of the 18 events involved inappropriate control inputs. Overall, the analysis showed again, what has long been known in aviation safety: that LOC-I accidents are complex, and that reducing their frequency requires a spectrum of safety improvements.

As a result of the CAST process, detailed Airplane State Awareness Safety Enhancement (SE) plans, numbered SE192–SE211, were developed to address the significant issued identified in their analysis [5]. The study presented in this report is focused on the pilot control guidance aspect of the research recommended in SE207, output 2, with the stated objective to "develop and refine algorithms and display strategies to provide control guidance for recovery from approach-to-stall or stall [6]."

To address this output, several guidance algorithms were developed around a central idea: that by using sensor measurements on-board the aircraft, and the physics for how aircraft fly, an algorithm can compute the specific trajectory that an aircraft should fly, to either prevent or recover from a stalled aircraft condition. The results of the computation were translated to standard pitch and roll flight directors on the Primary Flight Display (PFD), which the pilots could follow to effect their recovery. In addition, a new thrust director, and underlying thrust guidance computation, was added to the display in an effort to help pilots avoid applying too much thrust in an excessive nose-up trim condition — a condition which has been observed in multiple stall event reports.

The purpose of the experiment was to conduct a baseline study of the proposed new stall recovery guidance system, with two candidate underlying pitch recovery guidance computations. In the experiment, the guidance system was tested by both commercial line pilots, and research test pilots, across four different stall scenarios with aspects similar, but not identical, to those of real commercial aircraft accidents and incidents summarized in Section 1.5. Many of the motivating stall events were taken from the stall related scenarios studied by the CAST Airplane State Awareness team. The NASA developed General Transport Aircraft model, with extended aerodynamic envelope for full stall, was implemented in the Vertical Motion Simulator (VMS) facility at NASA Ames Research Center. A total of 40 pilot participants flew the simulated scenarios over the course of 23 days starting on April 11 and ending on May 19, 2017.

The objectives of this baseline study were three fold: (1) to obtain pilot validation of the stall recovery strategy employed by the guidance computation, (2) to determine if the system creates a benefit without doing harm, and (3) to assess the system usability with almost no training. The third objective is important from a technology development perspective. This is because the system would likely see operational use under adverse piloting conditions, where a stalled aircraft state may be unexpected or unrecognized. The guidance system should be a simple tool to help pilots recognize and completely recover the aircraft from stall with minimal mental workload.

1.1 Literature Survey

The technology research addressing stall prevention and recovery spans multiple themes identified in accidents and incidents. These include a lack of aircraft state awareness due to factors such as poor visibility, sensor failure, automation system confusion, and pilot distraction [4, 6–10]. In addition, research into improved simulator models with stall characteristics, and pilot training for manual stall prevention and recovery were recommended by the CAST [11, 12]. In relation to this overall body of work, the focus of this study is on the development of algorithms and guidance display strategies for helping pilots maximize the effectiveness of their stall training, on the rare occasion that it needs to be used [6].

Extensive prior research has been conducted under the topic of upset prevention and recovery to address loss-of-control [3, 13], which is a multifaceted topic, where the type of stall considered here is often viewed as a simple case. For example, Gandhi et. al., develops a joint human automated recovery system for more generalized loss-of-control scenarios, in part by determining maneuver sequences that optimize loss of altitude subject to load factor and input constraints [14]. In their approach, a commercial nonlinear program solver was used to precompute recovery procedures for storage in a lookup table that is accessed during flight operations. Offline strategies of this nature can suffer if the conditions encountered do not match at runtime, or in some cases, if there is a high computational cost of matching the current condition to a large dictionary of stored conditions. Reinforcement learning strategies for optimal upset recovery were also considered for UAV applications [15]. Here, large batches of simulation runs were used to train optimal recovery strategies for online use. However, the trained optimal recovery strategy is typically not reliable if the current aircraft condition is not well covered by the training data set. As an alternative to the offline training based methods, constrained control approaches to the stall recovery guidance problem have been investigated. One such approach uses Pseudo Control Hedging to adapt the system output commands to prevent control input saturation, for example by reducing the flight path angle to ensure angle-of-attack limits are not saturated [16].

In recent ongoing work, Richards and Ghandhi, et. al., developed an upset detection and recovery system for providing control guidance [17]. The approach included pilot behavior modeling, along with a combination of both on-, and, off-line upset recovery computation — in an effort to reap the benefits of both approaches in a scenario dependent way. In their work, other upset conditions besides stall are also considered, including runaway pitch trim, hard-over rudder and hard-over aileron failures. A distinguishing feature of their work is the computation of control inceptor guidance (e.g., where to put the control wheel and column), as opposed to the fly-to attitude guidance (e.g., the pitch and bank angles to fly) approach that we have taken in our work. The Richards study showed reduced oscillation in the inceptor movement and vehicle response during the recovery maneuver, which may be a characteristic of their inceptor guidance approach. Finally, their system was flight tested on a specialized variable stability Learjet 25B, by a small sample group of 5 pilots with encouraging initial results [18].

In general, much of the prior work in stall recovery does not specifically address

important operational complexities that can arise in real scenarios, such as an excessive nose-up pitching moment when too much thrust is applied, or the potential for a secondary stall to occur due to the coupled dynamics between pitch and the angle-of-attack during the pull-up phase of the recovery. The novel aspect of the approach presented in this report is that it specifically addresses these important operational issues, using fundamental physical principles with well defined operational limits.

1.2 Basic Flight Dynamics of Stall and Stall Recovery

Several flight dynamics concepts are referred to throughout this report. These concepts are important for understanding the key issues addressed by the recovery guidance technology presented in this report. The descriptions here are only detailed enough to impart a basic understanding. Appropriate references should be consulted for more detailed discussion, see for example [19–21].

Aerodynamic Forces

Fundamentally, airplanes fly because their wings generate a net upward force, called lift (L), by bending the passing airflow downward, as shown at the top of Figure 1. The production of lift is controlled by the angle-of-attack (α) that the wing makes with respect to the direction of airflow, shown in Figure 1. Increasing α increases the lift. But this effect only works up to a point. After α exceeds a critical value α_{SR}, the airflow starts to separate from the wing and is no longer adequately deflected downward, as depicted at the bottom of Figure 1.[2] Just prior to the separation of flow, most aircraft experience a pre-stall buffet that may feel like a strong oscillatory shaking or turbulence.[3] After the separation of flow, the lift generated by the wing diminishes with further increase in the angle-of-attack. As the lift becomes insufficient to counteract the downward pull of gravity, the aircraft begins to lose altitude in a manner that is not typically intended by the pilot. The controllability of the aircraft is also reduced at high angle-of-attack, and small asymmetries in the angular moments can produce large upsets. For more discussion on flight at high angle-of-attack, see [20, §7.4].

Besides the lift, there are three other forces important to our study of stall recovery. Two of these are shown at the top of Figure 1. The first is the force of drag (D) acting in the direction of the airflow across the wing, and opposite to the wind-relative velocity vector of the aircraft. The second force is the weight of the aircraft (W) acting in the direction of gravity, and the third force is the net thrust (T) generated by the engines (not shown in the figure, but primarily acting along the body axis of the aircraft). The lift and drag forces are both proportional to the air density (ρ), net wing surface area (S), and the square of the airspeed over the

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[2]In this study, we set α_{SR} to the angle-of-attack that corresponds to maximum of $C_L(\alpha)$, sometimes denoted as $\alpha_{C_{L_{\max}}}$.

[3]Buffet in the pre-stall region can be heavy enough to make reading the panel instruments or performing precision tracking difficult. Furthermore, differential pressure- or shock-induced flow separation across the wings can lead to wing drop or wing rock [20, §7.4, pg. 750].
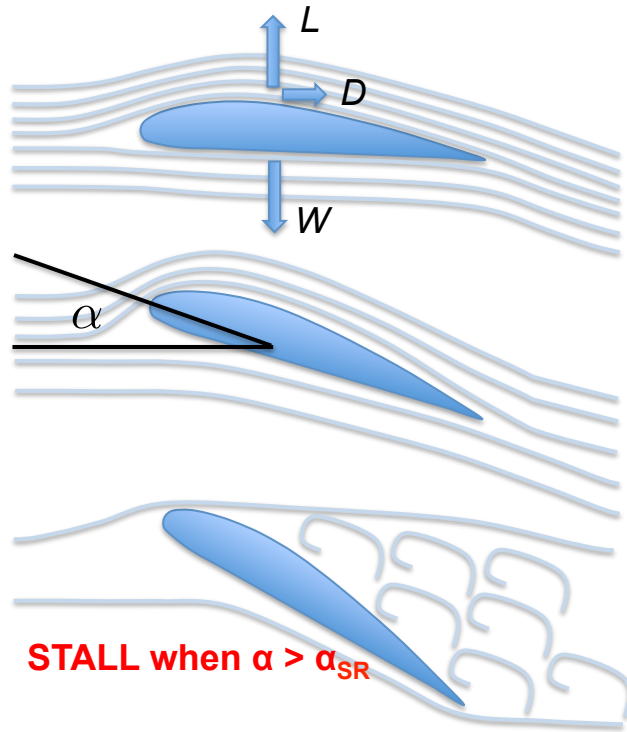
Figure 1. Notional airflow over a wing vs. angle-of-attack (α).

wing (V).[4] Therefore, the lift and drag forces are described by the equations

$$
\begin{aligned}
L &= \rho S V^2 C_L(\alpha)/2 & (1)\\
D &= \rho S V^2 C_D(\alpha)/2 & (2)
\end{aligned}
$$

where the dimensionless coefficients of lift and drag, $C_L(\alpha)$ and $C_D(\alpha)$, respectively, are functions that depend on the angle-of-attack, as well as the geometrical design (and orientation) of the aircraft's wings. These coefficients also depend on the aircraft's configuration (e.g., flap, gear, and speed-brake setting), in addition to the Mach number and Reynolds number.

Definition of Stall

In this report we define stall for simplicity, as any aircraft state with an angle-of-attack greater than α_{SR}. We can do this however, only because the underlying aerodynamic model for the simulation is known, and this is where we assume the separation of flow occurs.

On a real aircraft the precise angle-of-attack where the separation of flow occurs is difficult to predict or accurately observe. In fact, the flow separation does not

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[4]The airspeed over the wing V, is also referred to as the true airspeed. With this definition of V, the mean effect of the wind (across the time-scale of interest) is included, and the true airspeed can then be viewed as equal to the aircraft velocity in the mean wind-relative inertial coordinate frame.

occur all at once. Rather, it manifests from localized regions along the wing through time until it includes the whole wing. This is due to a variety of complicating factors beyond the level of detail we can explain here.[5] However, because of the uncertainty in the angle-of-attack where stall might occur, it is more practical to define stall by the aircraft behavior a pilot would observe during stall. From part of the FAA's definition of *Full Stall* "any one, or combination of, the following characteristics are observed: (a) an uncommanded nose-down pitch that cannot be readily arrested, which may be accompanied by an uncommanded rolling motion; (b) buffeting of a magnitude and severity that is a strong and effective deterrent to further increase in AoA; (c) no further increase in pitch occurs when the pitch control is held at the full aft stop for 2 seconds, leading to an inability to arrest descent rate [1, §1-7]." In addition to these, the roll damping is also usually degraded near stall, making the aircraft bank angle more difficult to control just prior to, and after stall.

Load Factor

The load factor (n_{LF}) is defined as the aircraft's lift-to-weight ratio

$$n_{\mathrm{LF}} = \frac{L}{W} = \frac{\rho S V^2 C_L(\alpha)}{2mg}, \tag{3}$$

where m is the current aircraft mass (which changes with fuel usage), and g is the acceleration due to gravity. The load factor is related to the force, and consequent acceleration, experienced by a passengers sitting close to the aircraft's center of mass. For example, when flying straight-and-level, the lift-to-weight ratio is one, and that passenger (along with all the others) experiences a 1 g load factor. If the aircraft accelerates upward to initiate a climb, the passenger experiences a load factor greater than 1 g. If the aircraft accelerates downward fast enough, the passenger may experience the weightless feeling of a 0 g load factor. If the aircraft is accelerated downward even faster, the passenger (who we hope is wearing a seatbelt) may experience a negative load factor. Sustained negative load factors are undesirable because anything not strapped down will strike the aircraft ceiling (think of the drink carts, flight attendants, and toilet water). The aircraft structure itself is also engineered to withstand maximum positive and negative load factors before its integrity is compromised. Typically, for large transport class commercial aircraft the limiting positive load factor is around 2.5 g with a clean aircraft configuration (flaps and gear up), and 2 g otherwise.

The load factor limits come into play during stall recoveries for three reasons. The first reason is that any stall recovery involves pitching the aircraft nose-down to get $\alpha \leq \alpha_{\mathrm{SR}}$. This may require a forward column input, which when applied too abruptly will produce a negative load factor that puts the passengers at risk for injury, as noted above. The second reason is because, once the aircraft has pitched down, the pilot will naturally want to pitch the aircraft nose-up and recover to level or climbing flight. This requires pulling the column aft, but this action must also be taken appropriately. Otherwise, the increased angle-of-attack required to reduce

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[5]Some of these factors include: Mach number, Reynolds number, turbulence, and icing.

the descent rate can cause a secondary aerodynamic stall (any full stall that occurs after the initial stall is broken). The central issue that relates the load factor to stall, is that getting the aircraft to move upwards requires upward force, and therefore, increasing the angle-of-attack, and the load factor to greater than 1 g. Therefore, a stall is produced by attempting to pull more g's than the aircraft can support with an $\alpha < \alpha_{\mathrm{SR}}$, and this can happen at any airspeed. At high altitude, the pull-up maneuver may be further complicated by the significantly reduced air density that degrades the aerodynamic damping and causes a pitch sensitive aircraft response.[6] This makes it easy to inadvertently exceed α_{SR}. Finally, the third reason is that the pull-up maneuver may cause a load factor that exceeds the maximum limit that the aircraft structure was designed to withstand.

Back Side of the Power Curve

In order to hold steady level flight at slower airspeed, an aircraft must fly at higher angle-of-attack. Unfortunately, as the angle-of-attack is increased there comes a point where an associated increase in drag requires more thrust to hold the airspeed constant. When more thrust is required to fly *slower*, the aircraft is said to be on the *back side of the power curve*. Furthermore, in situations at higher altitudes, it is even possible that the thrust required exceeds the maximum thrust available. This means that even with *full throttle*, the aircraft can decelerate and stall if the pilot attempts to hold level flight.

For these reasons, it is important to end up on the *front side* of the power curve at the end of a high altitude stall recovery. This means recovering with sufficient airspeed so that the aircraft can accelerate without the need for additional altitude loss.

Loss of Nose-Down Pitch Authority

For many commercial aircraft, with engines mounted below the wings, there is yet another dynamic effect important to stall recovery. In order to recover from stall, the aircraft has to reduce its angle-of-attack (to get $\alpha < \alpha_{\mathrm{SR}}$) and increase its airspeed, as one might expect from Equation (1). Decreasing the angle-of-attack requires a nose-down pitch input, while increasing airspeed is significantly aided through the application of full engine thrust. However, when the engines are mounted below the wings, the application of full thrust creates an upward pitch tendency, or *pitching moment*, that counteracts the ability of the aircraft to pitch nose-down.

This nose-up pitching moment is significant at lower altitude where, because of the increased air density, the thrust available from the engines is at its greatest. In addition, the effect can be exacerbated by the position of the stabilizer trim, to the point where the pilot no longer has elevator authority to pitch the aircraft nose-down. In this situation, the aircraft pitches nose-up uncontrollably, possibly putting the aircraft into an even deeper stall. This issue appears in a surprising number of

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[6]In addition to reduced pitch damping, $C_L(\alpha_{\mathrm{SR}})$ generally decreases with increasing Mach in the transonic regime. So as the aircraft flies faster, $C_L(\alpha_{\mathrm{SR}})$ is decreased.

stall related accidents and incidents (see Section 1.5), and is well recognized in the current FAA guidance on stall recovery.

At high altitude the engine thrust effect on the pitching moment is significantly diminished. Aircraft still exhibit a more sensitive pitch response at high altitude, but this is primarily caused by the reduced aerodynamic damping that occurs at high altitude. An additional nose-up pitching moment from the engines may make this increased pitch sensitivity feel a little worse to a pilot, but it should have almost no effect on the elevator authority to pitch down.

Summary of Stall Recovery

In summary, a successful stall recovery can be divided into two phases, which are referred to throughout this report. The first phase of the recovery is the *push* phase, where the objective is to push the control column forward to reduce the angle-of-attack and restore smooth airflow across the wings. During this phase of the recovery, a deliberate and smooth pitch down action is required. The goals are to avoid a negative load factor, and to not overcorrect by pitching down so much that it takes more altitude and time to recover to level flight in the second phase of the recovery. The second phase of the maneuver is the *pull-up* phase, where the objective is to level the wings and gently pull-up out of the nose-down condition, usually to re-establish level or climbing flight, while also avoiding secondary aerodynamic stall, and any positive load factor in excess of the aircraft's structural limit.

1.3   A Brief History of Stall Simulator Training

Flight simulators have been used for commercial pilot training and checking since the mid-1950s [22]. Since then, simulation technology has grown significantly to include advanced vision and motion cueing systems that can recreate a realistic in-flight experience and deliver a very high transfer of learning and behavior to the airplane [23]. Furthermore, pilot training by flight simulator is less expensive than in-flight training by almost any measure including pilot and instructor time, safety risk, fuel use, pollution, and noise [23]. However, there is also risk. Simulation beyond appropriate limits can exhibit false aircraft behavior that then causes incorrect or negative training to occur.

In 2002, NASA and The Boeing Company established that current aircraft simulators were generally limited to normal flight conditions not representative of most LOC flight conditions including stall [3, §III.A.1]. One consequence was that the simulation fidelity required to train pilots for full stall recovery was missing [24]. Recent updates to simulator qualification guidelines have acknowledged that the simulators used for pilot training "did not always provide the necessary cues and associated performance degradation needed to train the recognition of an impending stall or techniques needed to recover from a stalled flight condition [25]."

Furthermore, the FAA training regulations at the time only required pilots to train for stall prevention by initiating the recovery at, or prior to, the stall warning, which occurs before full stall [1]. Prior to full aerodynamic stall *at low altitude*, a recovery strategy that prioritizes the minimization of altitude loss is viable, and

this seemed to become a general policy with many air-carriers. An unintended consequence of this policy, however, is a reluctance to pitch the aircraft nose-down in an effort to avoid altitude loss. This reluctance can impede the reduction of angle-of-attack required for a full stall recovery *at any altitude*. At high altitude, a reluctance to pitch down also impedes the recovery from even an approach-to-stall, or stall warning, because significant altitude loss is actually required to recover the aircraft on the front side of the power curve. Furthermore, the lack of pitch damping at high altitude makes it easy to over control the pitch. This makes it easy to exceed the aircraft's angle-of-attack limitations, creating secondary stall warnings, and the potential to fully stall the aircraft again.

Fortunately, extraordinary progress has been made towards solving the pilot stall recovery training issue, world-wide. A recent summary of the advanced vehicle dynamics modeling work for loss-of-control prevention, mitigation, and recovery is presented in [3]. At NASA Langley Research Center, and in collaboration with The Boeing Company, a much needed high angle-of-attack aerodynamic database was fused together from wind tunnel and flight testing for one general commercial transport aircraft type [26]. From this database, proper aerodynamic models were developed for stall related research of large transport aircraft [26]. The International Committee for Aviation Training in Extended Envelopes (ICATEE) has made recommendations to effectively train pilots for stall awareness, recognition, and recovery [27]. Implementation plans developed by the CAST also targeted research into the aerodynamic modeling required to improve pilot performance at stall recovery [12]. In 2014, the International Civil Aviation Organization (ICAO) developed new standards and recommended practices to address LOC-I training concerns [28]. In Europe, the Simulation of Upset Recovery in Aviation (SUPRA) project has investigated the use of enhanced aerodynamic models and motion cueing to conclude that conventional hexapod motion cueing can be improved for the purpose of upset simulation, including stall [29, 30]. Still a careful approach is required, since a follow-on study with 12 airline pilots also showed that improved g-load simulation — beyond typical hexapod-type motion capability — deteriorated pilot recovery performance [31]. Work by the FAA was conducted to delineate simplified approaches for stall simulation specifically for pilot training [32], and the effects on training transfer were explored in [33]. For turbo-prop aircraft, unique stall simulation modeling requirements are identified in [34]. In a collaborative project with the FAA, further reduced cost methods for post-stall modeling from certification flight-test and wind-tunnel data were developed at the University of Toronto [35].

While the research community has supported stall related technology advancement for some time, it was the tragic Colgan 3407 accident that prompted the NTSB to recommend that all pilots in part 121, 135, and 91K operations receive training that incorporates fully developed stalls [36, §4.1]. As a result, the United States congress passed Public Law 111-216 in 2010, which mandated the recommended training for all part 121 air-carriers by March 12, 2019 [1]. The FAA subsequently updated the training requirements to reflect this law (14 CFR §121.423(c) and Appendices E and F). In 2015, the updated Advisory Circular AC120-109A on stall prevention and recovery training was published to emphasize the reduction in angle-of-attack for both stall prevention and stall recovery [1]. Finally, in 2016 the FAA

published changes to the requirements for level C and D simulators to include high angle-of-attack modeling and qualification for full stall maneuvers (see 14 CFR Part 60) [25].

Over just the past couple years, FlightSafety International, and Alaska Airlines have become some of the first training providers to gain FAA National Simulator Program validation for the use of extended stall-capable aerodynamic envelopes in Gulfstream G550, and Boeing 737-800 full-motion simulators [37]. Thanks to all of these efforts, and no-doubt many others, the world-wide aviation community has made important strides towards establishing more effective simulation based training for recovery from approach-to-stall and stall.

1.4   The FAA's Revised Recovery Guidance

Once an aircraft has stalled, a particular recovery procedure is required to restore smooth airflow across the surface of the wings. The FAA recommends a stall recovery procedure to which all pilots should be trained [1]. A slightly abbreviated version of this procedure is reproduced in Table 1. This well considered stall recovery template emphasizes reducing the angle-of-attack at the first indication of stall, while also being general enough to apply in a multitude of operational conditions including complications introduced by autopilot-induced excessive nose-up trim, and the need to avoid secondary stalls in the pull-up phase of the recovery. Though this procedure appears as a sequence of steps, many pilots commented that in practice, they view the steps as a prioritization of tasks to be simultaneously completed.

Within the FAA Stall Recovery Template, there are important aircraft and situational dependent details that could be provided by a computational recovery guidance routine. These include the magnitude of the initial pitch down maneuver, the specific amount of airspeed and thrust needed before pulling out of the recovery dive, as well as the maximum pitch-up rate that can be sustained without causing a secondary stall. An algorithm can also compute the maximum amount of thrust that can be safely added to the system when the aircraft is in an excessive nose-up pitch trim condition. Together, these elements affect how quickly the aircraft is returned to safe flight, and the loss of altitude required by the recovery maneuver. The purpose of the present study was to test candidate recovery guidance algorithms developed to provide these missing details.

1.5   Motivating Accidents and Incidents

To facilitate a better understanding for the context under which aerodynamic stall occurs in commercial aviation, we provide a detailed summary of the primary recent accidents that motivated this work. Appreciation for the complexities inherent to LOC-I accidents is only gained by considering the complicating details in each scenario, which make evident the primary issues: distraction, poor crew resource management, insufficient training, automation confusion, ineffective alerting, invalid source data, and several others [4].

Colgan Air: The accident involving a twin-engine turboprop Bombardier Dash 8 Q400, occurred on February 12, 2009 shortly after the flight was cleared for an

Table 1. Abbreviated FAA Stall Recovery Template

1	**Disconnect autopilot and autothrottle/autothrust**
	Rationale: Leaving the autopilot or autothrottle/autothrust connected may result in inadvertent changes or adjustments that may not be easily recognized or appropriate, especially during high workload situations.
2	**(a) nose-down pitch control until impending stall indications are eliminated.** **(b) nose-down pitch trim as needed.**
	Rationale: Reducing the angle-of-attack is crucial for recovery. This will also address autopilot-induced excessive nose-up trim. If the control column does not provide sufficient response, pitch trim may be necessary.
3	**Bank wings level.**
	Rationale: This orients the lift vector for recovery.
4	**Apply thrust as needed.**
	Rationale: Amount of thrust depends on aircraft configuration and in some cases applying maximum thrust may create a strong nose-up pitching moment if airspeed is low.
5	**Retract speed-brakes/spoilers.**
	Rationale: This will improve lift and stall margin.
6	**Return to the desired flightpath.**
	Rationale: Apply gentle action for recovery to avoid secondary stalls then return to desired flightpath.

instrument landing at Buffalo Niagara International Airport, New York. During the flight, the First Officer reported not feeling well. The flight data recorder (FDR) showed that, during the climb to altitude, the airplane de-icing equipment was turned on. At this time, the captain would have turned the REF SPEEDS SWITCH to the increase position. With the switch in this position, the stall warning system would be triggered at an increased airspeed [36, §2.2.1]. The climb and cruise phase of the flight were otherwise uneventful. Prior to beginning their descent, the first officer briefed a landing reference speed of 118 knots for landing with flaps at 15 degrees. The 118 knot landing reference speed was not appropriate for an airplane configured for flight in icing conditions, and did not account for the position of the REF SPEEDS SWITCH noted earlier. The captain acknowledged the information, and later repeated it in the approach briefing. After descending through 10,000 feet, the Captain and First Officer began a conversation unrelated to their flying duties, violating the sterile cockpit rule. The FDR showed the auto-pilot had applied additional pitch trim in the nose-up direction and that an "ice detected" message appeared on the engine display. Shortly thereafter, a stick-shaker occurred and the autopilot disconnected sounding a horn. The control column was moved aft and thrust was increased to about 75% torque. While engine power was increasing the airplane pitched up, and rolled 45 degrees left wing down. The stick pusher activated as the wings were rolled level. The flaps were fully retracted, and the aircraft vacillated through a series of extreme roll angles. The Captain called for gear up, as the aircraft pitched 25 degrees nose-down before crashing into a home. While the crew observed ice on the windshield and leading edges of the wings during the flight, the NTSB found that: "the minimal aircraft performance degradation resulting from ice accumulation did not affect the flight crew's ability to fly and control the

airplane." During post-accident interviews the NTSB learned that company training instructed pilots to complete the approach-to-stall recovery without deviating more than 100 feet above or below the assigned altitude, and some check airmen indicated any deviation outside that limit would result in a failed check-ride. Other check airmen considered this altitude limitation to be the minimal loss of altitude (which was consistent with practical test standards). [36]

Air France: The accident involving an Airbus A330-203, occurred on June 1, 2009 in route from Rio de Janeiro Galeo and Paris Charles de Gaulle with a 3 person flight crew — two Copilots and a Captain. After flying through some slight turbulence the plane was flying at 35,000 ft, Mach 0.82, at about 2 hours into the flight and the Captain left the cockpit. The pitch attitude was 2.5 degrees. Presumably due to weather, the crew decided to reduce the speed to Mach 0.8 and turn on the engine de-icing system. A few minutes later the autopilot and auto-thrust are disconnected and the pilot-flying (PF) has the controls. The airplane began to roll to the right and the PF made a nose-up and left input. The stall warning triggered briefly twice in a row and the recorded airspeed showed an abrupt change from 275 knots to 65 knots on the primary flight display, and later on the integrated standby instrument system (ISIS).[7] The flight control law reconfigured from normal to alternate mode. The flight directors were not disconnected by the crew, but the crossbars disappeared. The pilot-not-flying (PNF) acknowledges the loss of airspeed and alternate mode, and the PF then made rapid and high amplitude roll control inputs, more or less from stop to stop. He also made a nose-up input that increased the pitch attitude to 11 degrees in ten seconds. After reading the Electronic Centralized Aircraft Monitoring (ECAM) message in a disorganized manner, the PNF called out and turned on the wing anti-icing. The PNF also called out that the aircraft was climbing and repeatedly asked the PF to descend. The PF made several nose-down inputs that resulted in reduced pitch attitude and vertical speed; the plane was now at about 37,000 ft and continued to climb. At 2 hours and 10 minutes into the flight the speed displayed on the left side became valid again (it was incorrect for 29 seconds), showing 223 knots, but the ISIS speed was still erroneous. A few seconds later the thrust controls were pulled back to 85% N1, and the pitch attitude increased to greater than 6 degrees. The angle-of-attack was just under 5 degrees and roll was controlled. The PNF called the Captain back to the cockpit several times, and the stall warning triggered again, in a continuous manner. The thrust levers were positioned to TO/GA (max available) and the PF made nose-up inputs. The AoA was at 6 degrees and increasing. The horizontal stabilizer began trimming from 3 to 13 degrees pitch-up over the course of a minute and remained there. About 15 seconds later all indicated airspeeds became valid, showing 185 knots. The PF continued making nose-up inputs and the plane climbed to its maximum height of 38,000 ft; its pitch attitude and AoA were 16 degrees. The PNF and PF rapidly traded piloting priority without any callout. The Captain entered the cockpit at 2 hours and 11.5 minutes into the flight, and during the following seconds all of the recorded airspeeds became invalid. The stall warning stopped, the altitude was

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[7]The likely cause of this was icing in the pitot-static air-data system.

35,000 ft, the AoA exceeded 40 degrees and the vertical speed was −10,000 ft/min. The airplane's pitch attitude was not in excess of 15 degrees, and the engine N1 was close to 100%. Roll oscillations to the right occurred, sometimes reaching 40 degrees. The PF made a side-stick input to the left stop and nose-up, which lasted 30 seconds. The PF and PNF verbally call out invalid displays and indications. The thrust levers were in the IDLE detent and engine at 55% N1. The PF made pitch down inputs, the AoA decreased, the speeds became valid, and the stall warning triggered again. At one point simultaneous inputs by both pilots on the side-sticks were recorded and the PF said "go ahead you have the controls." When it was valid the AoA always remained above 35 degrees. The flight recordings stopped after 2 hours, 14 minutes, and 28 seconds into the flight. The last recorded values were: vertical speed −10,912 ft/min, ground speed 107 knots, pitch attitude 16.2 degrees nose-up, roll angle 5.3 degrees left, heading 270 degrees. No emergency message was transmitted by the crew. The wreckage was found almost two years later, on April 2, 2011. The only practical simulator stall training available to the two Copilots was for stall warning, and it would have occurred at low altitude (10,000 ft) during their basic training and during their initial A320 type rating. [38]

Icelandair: The incident involving a Boeing 757-200, occurred on October 19, 2002 in route from Orlando, Florida, to Keflavik, Iceland. During takeoff, the Captain (as the non-flying pilot) noticed an approximate 20 knot discrepancy between his airspeed reading and that of the First Officer, which agreed with the standby airspeed indicators. Shortly after takeoff the pilots indicated that the lateral and vertical flight director (FD) bars on the Captain's display, and the lateral FD bar on the First Officer's display disappeared, as well as multiple advisory messages on the Engine Indication and Crew Alerting System (EICAS). The Captain instructed the First Officer to continue the climb with the intent to deal with the EICAS messages later. However, after trimming the airplane and retracting the flaps the messages disappeared and the FD bars returned with all airspeed readings consistent. After climbing through 10,000 feet the airspeed discrepancy (this time a 10 knot discrepancy was noted) and the same EICAS messages appeared and then disappeared a few minutes later. The same event repeated itself again as the airplane reached 33,000 feet. A little over an hour into the flight, air traffic control (ATC) authorized a climb to 37,000 feet, which was made at normal climb power with the auto-throttle and autopilot engaged. During the climb, the Captain's airspeed began increasing to a maximum between 320 and 350 knots, which caused an overspeed warning. The flight management computer used the Captain's (left) air data reading, so it would have provided continuous airplane-nose-up elevator and horizontal stabilizer commands sensing that the airplane was flying faster than the target airspeed — an action that would cause the airplane to decelerate. The First Officer then noticed a decrease from about 250 to 220 knots on both his airspeed indicator and on the standby airspeed indicator. Now doubting his reading, the First Officer transferred control of the plane to the Captain. When asked why control was transferred, despite the acknowledged airspeed anomalies on the Captain's side, the First Officer indicated that he doubted his instruments because the airplane's pitch was unusually high and the airspeed had substantially deceased. These observations, however,

were consistent with the aforementioned autopilot reaction to the erroneous airspeed reading. Soon after the Captain assumed control, the stick-shaker activated and a heavy stall buffet occurred.[8] The Captain stated that he initiated the stall recovery by reducing the power to idle and lowering the nose to about 5 degrees below the horizon. The flight data recorder showed that the control column was maintained aft of the neutral position for approximately 20 seconds after the autopilot was disengaged, and that the stick-shaker continued for about 45 seconds. During the recovery over 7,000, feet would be lost. The First Officer advised ATC that they were unable to maintain altitude and were descending out of their cleared flight level. Immediate clearance was issued, at first to 30,000 feet, and then to 29,000 feet. The Captain noted that during the descent his airspeed indication was 40 to 70 knots lower than the First Officer and the standby airspeed indicators. The First Officer took control of the airplane and reengaged the autopilot. They landed safely at Baltimore-Washington International Airport in Maryland. The cause of the airspeed malfunction was not definitively determined, though blockage debris in the Captain's airspeed system was suspected.[9] In 1996, a B757 crashed under similar circumstances during takeoff from the Dominican Republic including: intermittent erroneous airspeed behavior on the Captain's side (first noted during takeoff), and the same EICAS warning indications. The investigation of that accident determined that the erroneous airspeed indications were consistent with a blocked pitot tube. [39]

Midwest Express: The incident involving a Boeing 717-200, occurred on May 12, 2005, while climbing to cruise altitude over Union Star, Missouri. Prior to takeoff, significant weather was reported and the Captain elected to delay the takeoff until the weather had passed to the east. As the airplane climbed to 27,000 feet under autopilot control, the closest weather cell was about 20 to 25 miles away, and the crew felt that the outside temperature was too warm to require the use of the manually operated anti-icing system. At the location and altitude where the incident occurred, the National Weather Service indicated a 40% probability of severe clear icing conditions. Convective activity present in the area also increased the probability of icing conditions, and night instrument meteorological conditions (IMC) prevailed for the flight. While climbing through about 19,000 feet, the Captain noticed the master caution light was illuminated, and then noted a RUDDER LIM FAIL alert on the engine and alert display unit. While the Captain attempted to deal with the alert, the airplane suddenly pitched down, in excess of 20 degrees. The Captain recalled hearing the aural alert for the autopilot disconnect. The flight data showed that just prior to autopilot disconnect, the Captain and First Officer's computed airspeed values began to diverge and continued to split during phases of the recovery. The data also showed that the autopilot disconnect switch was activated

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[8]The Captain stated that "there was a lot of vibration" during the stall encounter, and both pilots acknowledged that they had never experienced anything like it before. The First Officer indicated that the stall buffet felt a little bit different than what he had experienced during simulator training but that it felt the same in strength.

[9]Dusty particles were expelled when the pitot probe and pressure lines were flushed. The material was not captured. A subsequent pitot-static test on the Captain's airspeed indicator showed that the airspeed was still not indicating correctly.

on one of the control yokes. The Captain was still the pilot flying, but the First Officer was assisting him on the controls. There was apparent confusion as to who was controlling the airplane, as both crew members applied conflicting forces on the control columns.[10] Due to the opposing column forces, a breakout occurred,[11] and the two elevators would have been operated independently of each other. During the recovery the Captain recalled that the flight controls felt very heavy, with little response from the elevator controls inputs that would rapidly become "a lot" of response — unlike any training scenario or airplane flight characteristics he had previously experienced. The airplane went through a series of altitude excursions over the next 8 minutes, during which the airspeed values fluctuated between 52 knots and 460 knots, though, the recorded values may have been inaccurate do to the nature of the event. The altitudes during the pitch up and pitch down cycles varied between a minimum altitude of 10,600 feet and 23,300 feet. The Captain ultimately relinquished control to the First Officer, who then recovered the airplane. After declaring an emergency, the crew safely diverted to Kirksville Regional Airport (IRK), Kirksville, Missouri. [40]

Provincial Airlines: The incident involving a de Havilland Canada DCH-8, occurred on May 27, 2005, while climbing after takeoff from St. John's, Newfoundland, Canada. Shortly after takeoff, the Captain engaged the autopilot to hold the rate of climb at 1,190 ft/min. During this time, the airspeed fluctuated slowly between 160 and 170 knots. At around 7,000 ft, the crew selected the engine anti-ice systems ON, but they elected to leave the pneumatic manually operated de-ice system OFF.[12] The outside temperature was 5 degrees Celsius and decreasing to below freezing at about 11,000 ft. After crossing about 8,000 ft, the aircraft began decelerating from 170 knots for a period of 5 minutes. During this time, the aircraft continued to climb at 1190 ft/min. The First Officer noticed the decreased airspeed and notified the Captain, who subsequently, rotated the pitch control wheel on the flight guidance controller in the nose-down direction. While attempting the adjustment, at 14,800 ft and 104 knots, the Captain saw the stall warning stick-shaker activate causing the autopilot to disengage. Within the next second, the aircraft began to roll right and pitch down. Ice was then observed on the left engine inlet. The roll angle increased to 64 degrees while the pitch angle decreased from 15 to 5 degrees nose-up. The aircraft's vertical acceleration dropped to about 0.5 g. The aircraft pitch then increased to 30 degrees nose-up, and then to 40 degrees nose-down. These were all indications that the aircraft wing had stalled. The flight data showed that the aircraft underwent three distinct stalls during the event. The control column position cycled rapidly back and forth as the stall developed, but was moved generally aft,

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[10]During post-incident interviews, both pilots stated that there was no formal transfer of control during the event.

[11]A post-incident test of the column breakout mechanism showed that a disconnect occurred when pulling the Captain's control column aft, from neutral, with 124 pounds of force, and when pushing forward, from neutral, with 110 pounds of force.

[12]The aircraft was not equipped with an electronic ice detector. Crews detect ice visually, looking for evidence of ice accumulation on the wing leading edges and on an ice probe located in front of the cockpit window. The Flight Safety Canada standard operating procedure advises that, even if ice is not detected visually, ice may be present on portions of the aircraft that cannot be seen.

and remained aft during all three stalls. The power remained unchanged, and the control column was pulled aft of its pre-stall position for about 22 seconds. There were significant aileron and rudder pedal movements during the recovery, but they were ineffective in recovering control. During the recovery, there was severe buffeting, and heavy control column forces. The aircraft descended rapidly and lost 4200 ft. The maximum airspeed reached 240 knots, and the load factor peaked at 2.24 g. The minimum airspeed recored was 0 knots, which likely occurred during phases of high angle-of-attack and sideslip that would have disrupted the airflow over the pitot tubes. Only after recovering control did the crew observe that ice had built up on the aircraft fuselage, which likely caused the aircraft to stall at higher than expected airspeed. The stall airspeed for the aircraft condition and weight was 94.5 knots, but in this event the stall occurred just after stick-shaker at 103 knots. The de-icing system was switched on and functioned properly. The crew requested a lower altitude to avoid further icing and continued on to Deer Lake. After landing, the pilot only reported a severe turbulence encounter to company personnel. The crew had received the typical stall recovery training, which did not familiarize pilots with natural stall indicators, such as the aerodynamic buffet that occurs just prior to stall (which can be mistaken for turbulence). It also did not allow any practice in recovering from full aerodynamic stall. [41]

Thompson Fly: The incident involving a Boeing 737-300, occurred on September 23, 2007, during a go-around after an unstable approach, at Bournemouth Airport, UK. At 11 nautical miles from the airport, in clear airspace, the airplane was level at 2500 feet, 180 knots, flaps 5, and autothrottle engaged at approximately 60% N1. At 7 nautical miles, the autopilot captured the glideslope and the pilots began working through the landing checklist. The PF selected a lower speed on the mode control panel and, as expected, the auto-throttle retarded to idle to slow the aircraft to the selected speed. After about 20 seconds the autothrottle disconnect warning was triggered and the autothrottle disengaged. The disconnect was not recognized by the flight crew and no manual disconnect was recorded in the flight data. The thrust levers remained at idle throughout the remainder of the approach. The aircraft decelerated at about 1 knot/sec in agreement with the Captain's expectations as flaps were deployed. As the flaps reached the flap 40 position, the aircraft was at 130 knots and decelerating at about 1.5 knots/sec — though 135 knots had been selected on the Mode Control Panel (MCP). As the commander stowed the checklist, he noticed the slow airspeed and called "speed," followed by "I have control." The flight data showed that at 110 knots and an altitude of 1,540 feet, the autothrottle manual disconnect button was pressed and the thrust levers moved forward slightly. Within 1.5 seconds the stick-shaker activated and the thrust levers were advanced to the full forward position. The autopilot mode changed from localizer and glideslope to Control Wheel Steer (CWS) pitch and CWS roll. In this mode the autopilot controls the aircraft in response to manually applied pressure on either control column. The commander moved the control column forward to counteract the expected pitch-up moment from the increased thrust. The stick-shaker operation stopped and the minimum airspeed was 101 knots. Four seconds after the thrust levers reached full forward, with airspeed increasing and N1 increasing through 81%, the TOGA mode

became active. The autopilot disengaged. The pitch attitude began increasing and the stick-shaker activated again. A corrective roll input brought the wings level. With the control column full forward, the aircraft pitched nose-up to 22 degrees and appeared to stabilize. The First Officer then selected flaps 15 (from flaps 40). As the flaps retracted through the flap 25 position, the nose of the aircraft began to pitch up through 27 degrees with a roll now increasing through 7 degrees. The stick-shaker reactivated. The pilots continued to apply full nose-down elevator while the airspeed further decayed. As the pitch increased above 36 degrees nose-up, the TOGA mode disengaged. A small sharp right rudder input recovered the roll from a maximum of 22 degrees left wing down, to wings level. The aircraft stalled with a peak pitch of 44 degrees nose-up. With no change in elevator position, the pitch rate reversed from positive to negative, but the angle-of-attack continued to increase while the airspeed decreased for another 5 seconds. The airspeed reached its minimum recorded value of 82 knots, with a 33 degree nose-up pitch attitude. Five seconds after the minimum recorded speed, the thrust was reduced to 86%. The pitch down rate then increased and the pitch was quickly reduced (within 2 seconds) to 5 degrees nose-up. The airspeed increased and the commander regained control of the aircraft, ultimately landing it safely at Bournemouth Airport. Both pilots were current on training for recovery from approach-to-stall and unusual attitudes. The operator's Quick Reference Handbook (QRH) for approach-to-stall recovery referenced a drill that required the pilot to select maximum thrust, but not to change configuration (flaps or landing gear). The drill did not mention the use of pitch trim. [42]

West Caribbean: The accident involving an MD-82, occurred on August 16, 2005, during cruise over Venezuela, while flying through weather en-route to Martinique International Airport. As the aircraft reached 31,000 feet, the Engine Pressure Ratio (EPR) indicated that both the airfoil and engine anti-ice systems were probably in operation. To avoid a storm formation, the crew requested clearance to 33,000 feet. As the aircraft began its climb, the Mach speed started dropping from 0.75. The climb was interrupted twice, and the autopilot was switched to vertical speed mode to maintain a constant rate of climb. The auto-throttle mode was switched to MACH EPR LIMIT a mode where the speed would have been limited to a lower airspeed than the one selected. The aircraft had also reached the maximum permissible thrust that guaranteed the protection of the engines. The Captain asked the First Officer to disconnect the engine anti-ice system, and an increase in EPR was recorded. The aircraft reached 33,000 feet and accelerated to the target speed of Mach 0.75 with an angle-of-attack of 2.6 degrees. During this time the Captain stated twice, that he could not accelerate. A few seconds later, the auto-throttle reduced thrust and changed mode to maintain Mach speed. Variation in the EPR at this point suggested that the anti-ice system was switched back on. The aircraft was unable to maintain Mach 0.75 at 33,000 feet. The speed continued to decrease while the autopilot compensated with the stabilizer trim to maintain altitude. After 7 minutes and some discussion regarding the airfoil anti-ice system, the airspeed had decelerated to Mach 0.62. The Copilot requested clearance to 31,000 feet, the Captain disengaged the auto-pilot as the speed reached Mach 0.6 with an angle-of-attack of 7.7 degrees and horizontal stab position of −4.05 degrees. An aural warning sounded indicating

the selected airspeed was not being maintained, and the aircraft descended to 31,700 feet. The engine EPR fell sharply from about 2 to 1.8. The stall warning system (stick-shaker and aural alerts) activated, and stayed activated for the remainder of the flight. The aircraft was losing altitude at 2500 feet/min. The stab trim was gradually trimmed nose-up to the maximum limit. At the current angle-of-attack, the wings disrupted airflow to the engines. At the request of the Captain, the First Officer informed air traffic control that the crew was continuing the descent to 29,000 feet. The aircraft's rate of descent was approaching 5,000 feet/min at Mach 0.5. The EPR values dropped sharply again, this time to 1.06. Without reporting an emergency the Copilot told the air traffic controller that they were continuing the descent to 24,000 feet. Air traffic control asked the crew if there was any problem on board, and the Copilot, at the request of the Captain, replied that they had suffered a flame-out in both engines. At this point, the rate of descent was approaching 7,000 feet/min with engine EPR between 1.04 and 1.1. As the rate of descent further increased through 12,000 feet/min the Copilot (at the request of the Captain) asked the air traffic controller for the minimum en-route altitude. Over the course of about 40 seconds, the auto-throttle system was disengaged, and the EPR rapidly increased to 1.8. At the request of the Captain, the Copilot reported that the aircraft was out of control with an altitude of 12,400 feet. The position of the elevator trim increased through 12.5 degrees nose-up as the ground proximity warning system engaged "SINK RATE, WHOOP WHOOP, PULL-UP." Shortly thereafter, the recordings stopped as the aircraft crashed into the ground. The crew training provided by West Caribbean did not cover recognition of stall buffeting, or procedures for recovering an MD-80 aircraft from stall at high altitude. [43]

1.6 The Benefit of Stall Recovery Guidance

The stall related accidents and incidents summarized above should make one thing clear: that aerodynamic stall in commercial flight is typically proceeded by a series of complicating issues, starting with distraction (caused by automation system confusion, sensor issues producing mismatches in airspeed readings, etc.), poor communication and crew resource management, and typically, ending with inappropriate control action. While each of these factors can be treated individually through improvements to training, it is perhaps more difficult to adequately train for their compounding effects and rare occurrence in operational practice. Pilots that get into aerodynamic stall often seem to be operating with a momentary incorrect mental model for the expected aircraft behavior — one that is brought on by a failure to recognize the stall. In addition to improvements to training, guidance cues might also help remedy these conditions by aiding the stall recovery process in two important ways: first, by providing a simple, easy to execute, method for effecting a recovery, and second, by contradicting an incorrect mental model for the aircraft behavior if it exists. In other words, recovery guidance can help pilots in the execution of the correct procedure while operating under high workload. While it is imperative that pilots train stall recognition and recovery without guidance, having a guidance system in a complex real-world stall event may reduce the likelihood of a catastrophic result. Furthermore, stall recovery guidance may also serve as a

useful support tool for pilot training, for example, by enabling the definition of pilot performance metrics relative to the guidance computation.

Recovery guidance can also provide a benefit that goes beyond what pilots might be easily trained to accomplish on their own. This benefit is the specific computation of the scenario and aircraft configuration dependent recovery objectives. For example, how far to pitch the nose of the aircraft over in a high altitude recovery, versus, a low altitude recovery where the engines have more authority to increase airspeed. Another example, studied in the present system, is the maximum amount of throttle a pilot can add before saturating the elevator when an aircraft (with engines mounted below the wings) is operating under an excessive nose-up trim condition. In this case, the guidance computation may enable a pilot to be less cautious, and therefore faster, with the application of thrust than is recommended in the FAA stall recovery template. This information can be critical, especially for low altitude stalls. Yet another example, not examined in this study, is the potential to coordinate with Automatic Dependent Surveillance-Broadcast (ADS-B) information to avoid collision with other aircraft during the recovery maneuver.

1.7   Guidance System Design Criteria

Considering the complex circumstances surrounding the occurrence of stall, it is critical to have a recovery guidance system that is easy to use. For our study, the goal was to maximize the use of existing standard guidance cues, in an effort to minimize any training that would be required to learn new aspects of the system. It was expected that following the guidance system should reduce the recovery workload by focusing pilot attention on guidance cues in the center of the PFD, rather than splitting that attention to monitor the airspeed and rate of climb indicators on opposite sides of the PFD. A primary objective of the stall recovery experiment was to test how readily pilots were able to accept and use the system with no additional training, beyond the initial pilot briefing discussed in Section 5.

The system was also explicitly designed without requiring any prediction or knowledge of pilot intent during the recovery — though we hope the pilot at least intends to recover the aircraft. To deal with the uncertainty inherent to this philosophy, along with the uncertainty inherent to how well any particular pilot follows the guidance, the implementation requires the online re-computation of the recovery action *always from the current aircraft state*. In addition, the recovery guidance should generally agree with the recommended manual recovery procedure that pilots are trained to follow for their particular aircraft.

Feedback from pilot subject matter experts was used to tune the guidance system for appropriate manual tracking characteristics. All tuning and algorithm parameters were fixed prior to beginning the experiment, and no changes were made during the execution of the experiment.

2   Recovery Guidance Algorithms

The recovery guidance system for this study was designed using one of two candidate pitch guidance algorithms, a thrust guidance algorithm, and a simple roll

guidance algorithm. This section provides a detailed summary of the stall recovery strategy, and the underlying computational algorithms used to implement it. The approach is targeted at commercial transport class aircraft with engines mounted below the wings. As such, it does not explicitly consider some aspects of stall that are important for many smaller transport, turbo-prop, general aviation, unmanned aerial system, and military aircraft. In particular stall induced spin [44], and high angle-of-attack maneuvers for T-tail type aircraft are not specifically addressed. In addition, the guidance system we developed for this study would not properly handle sensor faults. The potential for sensor failure is an important aspect that must be addressed prior to any operational use of the system.

2.1 Stall Recovery Strategy

The stall recovery guidance (SRG) implemented for this experiment adopted the following strategy based on the FAA stall recovery template. First, the SRG mode activated when the angle-of-attack exceeded a particular critical value. For the experiment only, the critical angle-of-attack was scenario dependent.[13] During actual operational use, the SRG mode should trigger in concert with the stall warning system. Several pilots commented that the display and operation of the SRG mode was analogous to the wind shear warning systems currently in operational use on commercial aircraft.

When the SRG mode triggered, the autopilot and auto-throttle systems were automatically disconnected, placing the aircraft in manual open-loop control with yaw damper. The horizontal pitch flight director bar provided nose-down guidance, while the vertical roll director bar held the bank angle fixed to the bank angle latched on SRG mode entry. As the nose of the aircraft dropped below the Pitch Limit Indicator (PLI, see Section 3.3), the roll guidance engaged to level the wings, while the pitch guidance continued to control pitch to recover a target airspeed. For the lower altitude scenarios below 30,000 feet, the target airspeed was set to V_{REF} (flap dependent); for the high altitude scenario the target recovery speed was set to 230 knots, in a deliberate effort to recover the aircraft on the front side of the power curve.

At SRG mode entry, the thrust guidance cue was programmed to command the maximum available thrust that would maintain at least some elevator authority to pitch nose-down at the target recovery airspeed and angle-of-attack. The computation of this thrust limit relied on the knowledge of the pitching moment coefficients representative of the aircraft in its current configuration, and on the mapping between throttle position and the force generated by the engines (after transient engine effects).

Based on expert pilot feedback obtained during the guidance system development, we also deliberately chose not to implement an automated SRG mode exit. The rationale was that the system should not automatically transition to another

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[13]For all the lower altitude scenarios, the critical AoA that triggered the SRG mode was $\alpha = 16$ degrees. This value corresponded to aerodynamic stall onset for the particular aircraft model used in the study. For the high altitude stall scenario, the SRG mode triggered at $\alpha = 25$ degrees to force the recovery from a fully developed stall.

mode, since it may take some time for the pilot to recover mentally after surviving an unexpected stall, and an automated mode transition may produce more confusion if the pilot was not yet ready to continue. Therefore, the operational concept was for the pilot to manually transition out of the SRG mode at a safe flight path and airspeed when ready.

Pilot Feedback on the Strategy

The pilots provided informative feedback on the recovery strategy. Many pilots liked the strategy and felt is was consistent with their training. Others felt that the roll and pitch guidance should begin simultaneously, rather than waiting for the pitch to drop below the PLI before rolling wings-level. This roll recovery strategy was adopted to agree with the FAA recovery template shown in Table 1. However, an implication of this strategy, was that the roll guidance would command a roll direction away from wings-level if the pilot attempted to roll wings-level before getting the nose below the PLI. This was a counter-intuitive behavior for those pilots who observed it.

A few of the experiment participants attempted to recover the aircraft using the rudder. These pilots ended up significantly exacerbating the roll upset, and in the process exceeded the simulator's lateral motion limits causing a hard stop before completing the run. The roll upset was caused by a strong coupling between the effect of side-slip on rolling moment with high angle-of-attack [20, §7.4, pg. 748]. Though this effect was realistic for the particular aircraft model, those pilots who attempted recoveries with rudder input felt that the resulting roll upset was an unrealistic characteristic of the simulation. Their rationale was that the rudder is a more reliable control surface when the wings are potentially stalled. In particular, with the airflow disrupted across the wing during stall, an unpredictable aileron response (or roll reversal) may occur. This rationale, however, does not consider that the coupling between side-slip and rolling moment can also be unpredictable, or at least, unexpected at high angle-of-attack. The overuse of rudder can have significant impact on the airplanes stability and control, which can lead to sudden loss of control [45,46]. Excess use of rudder in a recovery attempt can also produce structural loads that exceed the design strength of the associated airframe components [45].

2.2 Pitch Guidance Targets

There were two pitch guidance algorithms studied in this report. Both of them used the aircraft pitch to control the airspeed at the current thrust and roll angle. In this way, the pitch guidance system is decoupled from the roll and throttle guidance systems. The idea is to make the integrated guidance system easier for humans to follow, since with this approach, the guidance system does not require simultaneous coordinated tracking of the three separate cues for pitch, roll, and thrust.

Both of the pitch guidance algorithms employed in this study, drive the aircraft to the same target state. The target state is determined first by selecting a target recovery airspeed. This target airspeed is then used to derive the corresponding targets for angle-of-attack and pitch that would trim the aircraft at the current

thrust setting and bank angle. As noted above, in this study the target airspeed is V_{REF} if the aircraft is below 30,000 feet (so for all of the scenarios except the high altitude scenario), or 230 knots if the aircraft is above 30,000 feet (so for the high altitude scenario). The reason for the altitude discrepancy in the airspeed target, was that at high altitude, the computation for V_{REF} was not on the front side of the power curve for the aircraft. Essentially, this means that at level flight and full thrust, the aircraft would not be able to accelerate to cruise airspeed without losing additional altitude. The computation of V_{REF} is discussed further in Appendix A.

With the recovery airspeed determined, and a basic linearized model for the dependency between angle-of-attack and the coefficient of lift, we solved for the angle-of-attack that achieves a load factor of 1 g at the target airspeed using Equation (3). With this target angle-of-attack, we then solved for the drag required to hold the aircraft at the target airspeed using a quadratic drag model.[14] With the required drag, we then solved for the target flight path angle and corresponding pitch angle at the current thrust and roll setting, simply by balancing the forces in the vertical plane of the aircraft using Newton's second law. At this point, good approximations were obtained for the angle-of-attack, flight path angle, and pitch angle that will trim the aircraft at the target airspeed, and at the current thrust setting and bank angle. Together these values determine the target aircraft state to which the pitch guidance control algorithm will try to recover the aircraft. The underlying model dependencies used for this computation are discussed in Appendix B.

2.3   Fast Model Predictive Control Algorithm

Model predictive control (MPC) is an advanced optimal control method that lends itself to the determination of scenario specific stall recovery guidance. The first step in the approach is to linearize and discretize the aircraft equations of motion around the current aircraft state of interest, defined as the airspeed, angle-of-attack, and pitch. This linear discrete model then approximately predicts the aircraft state trajectory from the current state, given a sequence of pitch rate control inputs. An optimal pitch recovery maneuver that returns the aircraft to the target state, is then found by solving a linearly constrained optimization problem with quadratic cost function (i.e., a quadratic program). In our formulation for stall recovery, the solution to the optimization problem determines the input pitch rate sequence required to recover the aircraft across a 30 second time horizon, discretized to 0.5 second increments.[15] In the classical model predictive control approach, only the most immediate control input from the solution is used, and the entire computation is repeated in the next computational cycle (or simulator frame). To determine the guidance cue input, however, we found that a blended combination of the near-term pitch and pitch-rate error was easier to track, as judged by a test pilot subject

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[14]Both the linear and quadratic models used for the dependency between angle-of-attack and the coefficient of lift and drag, respectively, were fitted to the aircraft's current configuration to pick up the dependencies on flap, gear, and speed-brake setting.

[15]The 30 second time horizon was about the shortest time required to cover the important duration of the push and pull-up phases of the longest stall recoveries at high altitude.

matter expert.

The actual online computation of the maneuver ultimately requires solving a quadratic program, which is accomplished using the Fast Model Predictive Control (FMPC) interior point algorithm developed in [47]. This algorithm has important features that help to ensure fast and reliable convergence of the optimal solutions at relatively low computational cost suitable for online implementations. The more advanced computational details covering the application of the FMPC algorithm to stall recovery guidance are documented in [48].

There are two important features to the FMPC approach. The first is that the optimal recovery input is recomputed from the current aircraft state in each simulator frame (or computational cycle). This means that the pilot is always provided with optimal guidance from the current aircraft state (with respect to the quadratic cost function), independent of how well he or she follows that guidance. The second important feature is that constraints on the state variables (airspeed, angle-of-attack, pitch angle and rate) can be specified directly. In particular, constraints on the pitch rate were used to prevent exceeding load factor limits, while the angle-of-attack corresponding to stall warning was used as the maximum angle-of-attack constraint in the formulation. The optimal solution with the predictive model then intelligently includes consideration for protecting the load factors and angle-of-attack during the full pull-up phase of the recovery maneuver.

Figure 2 illustrates these important features, by showing the predictive guidance maneuvers, as well as the discretized aircraft trajectory flown by one of the pilot participants in the study. In this scenario, the autopilot flies the aircraft into a fully developed aerodynamic stall, at 40,000 feet. At $t = 0$ seconds, the manual piloted recovery begins with the model predictive guidance. The gray trajectories show the computed predictive recoveries at each time step.[16] Initially, while the angle-of-attack exceeds the stall warning angle-of-attack, the default guidance is to pitch the aircraft nose-down at 5 degrees per second — because the linearized model used for the FMPC computation is invalid in the stalled dynamics regime. In the plots, the pilot follows the default pitch guidance below the PLI position, and therefore reduces the angle-of-attack below the stall warning threshold. At this point, around 4 seconds into the recovery the model predictive guidance becomes valid and initially finds a pitch input plan that puts the aircraft pitch to 30 degrees nose-down. The pilot lags the guidance, following it only to about 15 degrees nose-down, at which point the pilot follows the guidance to pull the nose of the aircraft back up. At each time instance, the predictive guidance intelligently re-schedules the pull-up maneuver to efficiently use the full angle-of-attack margin, just grazing the stall warning limit around 20 seconds into the recovery, and ending up at the target airspeed. The results of this study show, that the aggressive guidance computed by this algorithm significantly improves the safety of the piloted recoveries with respect to secondary aerodynamic stalls in the high altitude scenario highlighted in this example. Essentially, the guidance uses the aircraft flight dynamics to compute how far to pitch nose-down in the initial recovery, at what airspeed to begin pitching

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[16]Actually, only a small sub-sample of the computed trajectories are shown. The actual predictive guidance computation completes with each simulator frame, at 50 frames per second.
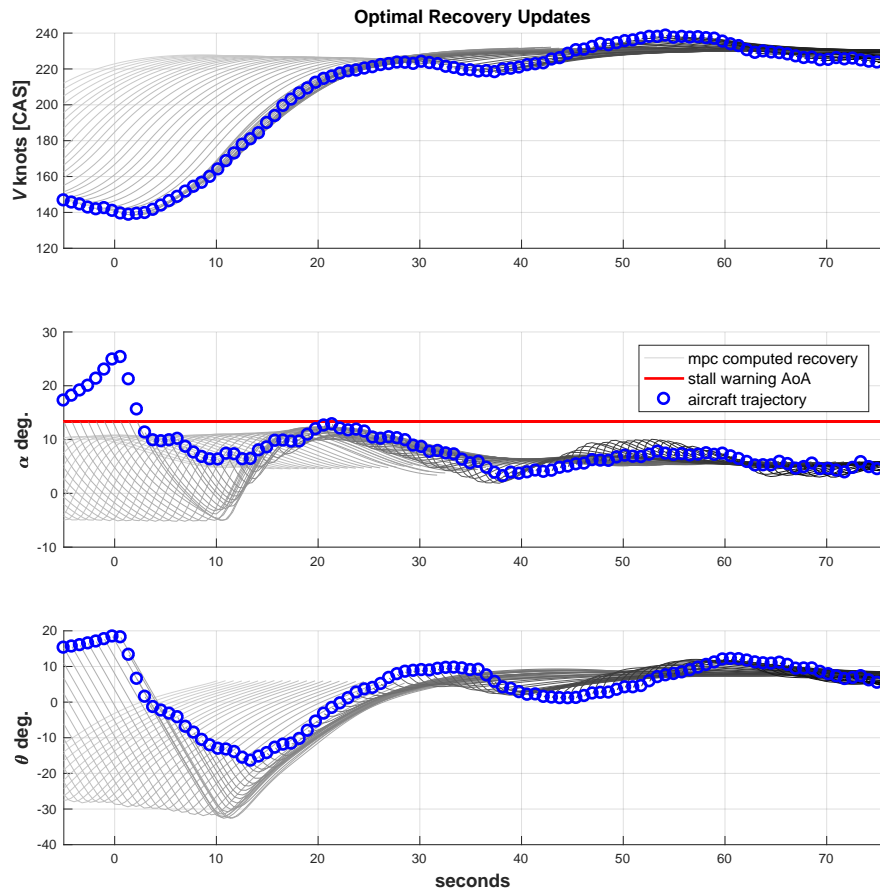
Figure 2. Model predictive control stall recovery.

up, and the pitch up rate that smoothly returns the aircraft to the target airspeed, all in one smooth maneuver.

In this initial study we sought to keep the FMPC problem formulation as simple as possible. This was done in effort to achieve the rapid and reliable convergence needed to run the algorithm well within the 50 Hz simulator loop on the Vertical Motion Simulator (VMS) computer. One of the benefits of the overall approach, however, is that it readily supports additional constraints on pitch angle and airspeed, and more sophisticated equations of motion can also be incorporated into future implementations. To a large extent, the FMPC algorithm can also be configured to work within computational time limits. The algorithm can split the full convergence computational cost across multiple simulator frames if needed, and it can provide a sub-optimal, but feasible, guidance solution if it needs to be stopped before the full convergence objective is achieved.

2.4 Energy Based Algorithm

Another approach for computing stall recovery guidance uses a physically motivated energy tradeoff analysis to derive the control guidance, while maintaining load factor limits and protecting against secondary stall [49]. The benefits of this approach are that the computational cost is minimal (especially when compared to an optimal control method), that it does not necessarily require any estimated model information, and that it is, therefore, easily implemented for online use.

The main purpose of the stall recovery strategy advised by the FAA for flight crew training, as discussed in Section 1.4, is to reduce the angle-of-attack and increase the airspeed. This can be accomplished most rapidly by trading potential energy (altitude) for kinetic energy (speed), as efficiently as possible. The only complicating factors are that, during the trade-off process, energy is dissipated through drag D, which requires the application of thrust T over time. The FAA recovery template implicitly uses these factors when it advises a pitch down to reduce the angle-of-attack (and the drag), beginning the trade-off between altitude and airspeed, and adding thrust carefully to avoid pitch trim related upsets.

The total amount of energy at any moment during the flight consists of the combination of kinetic energy E_{kin} and potential energy E_{pot}, where the total change in kinetic and potential energy over the entire recovery maneuver can be defined as:

$$
\begin{aligned}
\Delta E_{\text{kin}} &= \frac{1}{2} m \Delta V^2 = \frac{1}{2} m \left(V_{\text{end}}^2 - V_{\text{begin}}^2 \right) \\
\Delta E_{\text{pot}} &= mg \Delta h = mg \left(h_{\text{end}} - h_{\text{begin}} \right)
\end{aligned}
$$

where V is the speed, h is the altitude, m is the aircraft mass, and g is acceleration due to gravity. For stall recovery maneuvers, it can be stated that the trade off between both types of energy results in $h_{\text{end}} < h_{\text{begin}}$ and $V_{\text{end}} > V_{\text{begin}}$. In this expression, we assume that g and m do not change significantly during the course of the recovery maneuver. From the related expression for the total instantaneous energy $E_{\text{tot}} = mgh + mV^2/2$, one determines the specific total energy rate

$$
\dot{E}_{\text{s}} = \frac{d}{dt} \frac{E_{\text{tot}}}{m} = g\dot{h} + V\dot{V} = gV \sin\gamma + V\dot{V} = V \left(g \sin\gamma + \dot{V} \right). \tag{4}
$$

Here the vertical speed has been written as: $\dot{h} = V \sin\gamma$, where γ is the flight path angle defined in Figure 3.
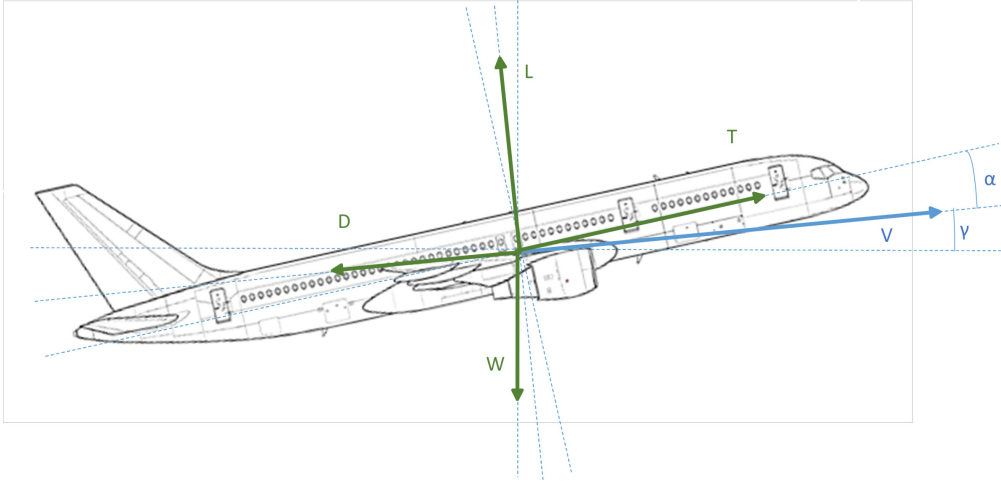
Figure 3. Acting forces on the aircraft model

The energy that is dissipated through drag and accumulated from thrust can be incorporated from the basic equations of motion. From the balance of the forces lift L, drag D, thrust T, and weight W in Figure 3, along with Newton's second law, applied to the direction of the velocity vector, one finds:

$$m\dot{V} = T\cos\alpha - D - mg\sin\gamma, \tag{5}$$

where α is the angle-of-attack. It follows that

$$\dot{V} + g\sin\gamma = \frac{T\cos\alpha - D}{m}, \tag{6}$$

and combining Equations (4) and (6) then results in

$$\dot{E}_{\mathrm{s}} = V\left(\dot{V} + g\sin\gamma\right) = V\left(\frac{T\cos\alpha - D}{m}\right). \tag{7}$$

The physical intuition behind Equation (7) is illustrated by the reservoir analogy shown in Figure 4. Here, a direct exchange between potential (altitude) and kinetic energy (speed) is possible by controlling the flight path angle γ. Figure 4 shows that the throttles add to the total energy of the aircraft system, while drag causes some of the total aircraft energy to dissipate. The flight path angle (as controlled by the elevator) then regulates the net influx of total energy into the kinetic and potential energy reservoirs or vice versa.

As a consequence, stall recovery is most efficient when one simultaneously dives, driving $\gamma < 0$, and increases the thrust. As soon as enough speed has been gained, a pull-up maneuver should be performed in order to establish level flight. During this pull-up maneuver, secondary stall and load factor limits should be avoided. This drives the constraints for angle of attack: $\alpha < \alpha_{\mathrm{stall}}$ and load factor: $n_{\mathrm{LF_{min}}} < n_{\mathrm{LF}} < n_{\mathrm{LF_{max}}}$.
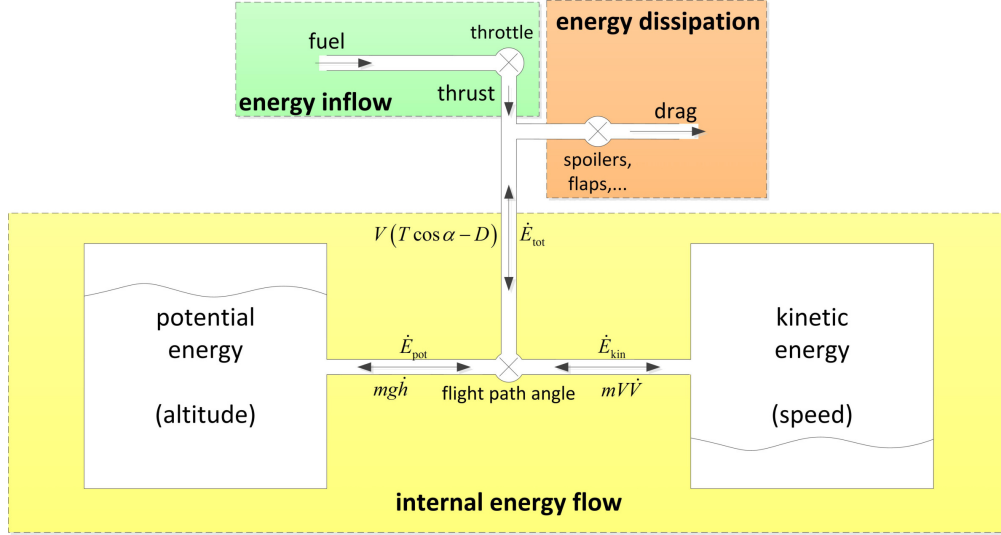
Figure 4. Energy reservoir analogy

The EBA guidance law is derived essentially by solving Equation (6) for the flight path angle required to achieve a desired acceleration

$$\gamma_{\text{guidance}} \quad = \quad \arcsin\left(-\frac{1}{g}\left[\dot{V}_{\text{required}} - \frac{T\cos\alpha - D}{m}\right]\right) \tag{8}$$

$$\overset{(6)}{=} \quad \arcsin\left(-\frac{1}{g}\left[\dot{V}_{\text{required}} - \left(\dot{V} + g\sin\gamma\right)\right]\right) \tag{9}$$

where the required speed rate $\dot{V}_{\text{required}}$ is defined as:

$$\dot{V}_{\text{required}} = \frac{1}{\tau_V}\Delta V_{\text{required}} = \frac{1}{\tau_V}\left(V_{\text{target}} - V_{\text{current}}\right). \tag{10}$$

In this expression, V_{target} is the airspeed target defined in Section 2.2, and τ_V is an associated speed control time constant. The time constant τ_V determines the responsiveness of the speed guidance: the smaller the value for τ_V, the more aggressive the dive will be in order to pick up speed.

Equations (8) and (9) provide the energy based guidance strategy calculation in two equivalent ways, depending on the prevailing conditions. Equation (9) does not require any aircraft model information, which makes the guidance independent of the aircraft model and can thus be applied on different aircraft types in a relatively straightforward way. It does, however, require sensor values for the acceleration $\dot{V}$, which is especially sensitive to turbulence, and needs additional filtering. As an alternative, Equation (8) can be used, which includes values for the thrust T and drag D. Thrust can be approximated based on the engine RPM N1, but aircraft model information is needed for the drag D. For the study detailed in this report, the model based Equation (8) was used.

Finally, constraints on γ_{guidance} and $\dot{\gamma}_{\text{guidance}}$ can be enforced to protect against secondary stalls and load factor limit exceedance, respectively. Furthermore, in

order to achieve a smooth guidance signal in the presence of turbulence, additional first order filtering is needed for the calibrated airspeed (filtering frequency $\omega_V = 2$ rad/s) and its time derivative (filtering frequency $\omega_{\dot{V}} = 4$ rad/s). Additionally, a limit of 10 deg for the maximum deviation of the guidance signal compared to the current state has been included, since this deviation is the primary driver of the steering aggressiveness of the pilots.

More details about this algorithm can be found in [49].

2.5 Computational Performance

The Vertical Motion Simulator platform selected for the study used a DEC-Alpha computer running a Real-Time Operating System at 1.25GHz. The frame rate of the simulation was 50 Hz, i.e. 20 ms per frame. For this study, it was a requirement for both algorithms to complete the guidance computation along with the simulator model calculations within this 20 ms limit.

The two guidance algorithms in this study fall on opposite ends of the computational cost spectrum. The Energy Based Algorithm uses an analytical calculation that only requires a few lines of code to evaluate (with no loops or potential convergence issues). As such, it is probably about the least expensive guidance algorithm possible. The Fast Model Predictive Control algorithm, on the other hand, is closer to the most computationally expensive algorithm that can be evaluated on the target platform and frame time limit.

Figure 5 shows the distribution of the longest model execution time for each simulation run in the experiment.[17] The plot on the left shows that the EBA algorithm adds negligible cost to the no guidance case. The plot on the right shows the FMPC performance, which takes from 3 to 10 times as long as the baseline model evaluation with no guidance. The FMPC algorithm also has significantly increased variation in evaluation time. This is caused by the difference in computation time to solve the FMPC optimization problem, through an iterative solver, from varying initial aircraft states. Still, the FMPC algorithm ran reliably without producing any frame overruns for the entire simulation experiment. Overall, this is good performance for an optimal control algorithm, especially since such algorithms are often not fast or reliable enough to work under the operating conditions required for this experiment.

2.6 Thrust Guidance Algorithm

As just discussed, effecting a stall recovery essentially involves increasing the kinetic energy of the aircraft (and reducing α). This happens by converting fuel into thrust, and by sacrificing altitude. To a first-order approximation, minimizing the altitude loss, therefore requires as much fuel to thrust conversion as possible, and this in turn means applying all available thrust as early as possible. The primary reason to limit

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[17]There are thousands of model evaluations per run (e.g., 3000 model evaluations in a 60 second run). Each of the time measurements used to create Figure 5 was the worst-case model evaluation time that occurred during a run. There were 240 runs in the EBA and FMPC distributions, and 480 runs in the no guidance distribution.
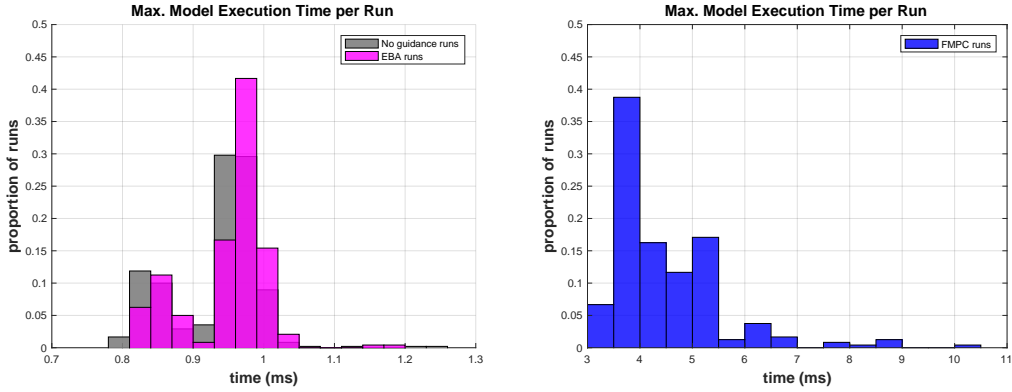
Figure 5. Distribution of maximum model execution time across all recovery runs in the experiment.

the thrust in a stall recovery then, is to maintain elevator pitch down authority for aircraft with engines and pitch trim state that are also causing an excessive nose-up pitching moment.[18]

In our implementation, we used a linear regression model for the pitching moment response to the current stabilizer, flap, and speed-brake setting, with dependencies on the elevator position δ_e, δ_e^2, α, α^2, T, pitch rate q, and a constant off-set value. Using this model we were able to solve analytically for the maximum thrust T_{max}^{elev} that could be balanced, at the current stab position, by the maximum pitch-down elevator authority (with -3 degrees of margin for the implementation in this study). The thrust guidance signal was then driven as $T_g = \min(T_{max}, T_{max}^{elev})$, i.e., the lesser of the maximum available thrust, or the maximum thrust that the elevator authority will allow. The thrust guidance, computed in units of force, was converted to a throttle position through the use of a look-up table that determined the maximum engine thrust at the current airspeed and altitude. The pitching moment model, coefficients, and engine thrust lookup tables are reproduced in Appendix B.

2.7 Roll Guidance Algorithm

Any standard roll guidance computation could, in principle, be adapted to support the roll guidance strategy discussed in Section 2.1. For this study, the roll guidance signal was driven simply by a filtered proportional error between the current aircraft roll angle and the commanded roll angle. On SRG mode entry from aerodynamic stall, the commanded roll angle was initialized to the current aircraft bank angle. When the aircraft pitched below the PLI the commanded roll angle was transitioned to zero degrees to guide the level-off phase of the maneuver in accordance with the FAA recommended procedure (see Step 3 in Table 1).

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[18]An important secondary reason, not considered in this study, is that the thrust demand on the engine should be limited at high angle-of-attack due to increased risk of compressor stall and engine flameout.

3 Experiment Design

3.1 Research Hypotheses

Primary: Guidance improves pilot stall recovery performance, specifically, by promoting

- appropriate application of pitch down to quickly eliminate aerodynamic stall, but not in excess of that needed to effectively recover.

- gentle pitch-up maneuvers to avoid secondary stalls during pull-up

- recovery at sufficient airspeed on the front side of the power curve

- reduced tendency to observe pilot induced oscillations in the recovery

- prevention of elevator saturation caused by excessive nose-up stab trim

- protection of the load factor from exceeding safety limits

Secondary: Unguided stall recovery performance is improved after training with stall recovery guidance.

The experiment contained two independent variables: guidance algorithm and stall recovery scenario.

3.2 Simulator Facility

Aircraft recovery from stall is a more dynamic maneuver than typically encountered in normal aircraft flight. For this reason, motion cueing may play a significant role in how pilots recognize and recover from stall [33]. To include as many of these effects as possible in our study, the Vertical Motion Simulator (VMS) facility at NASA Ames Research Center was selected. Historically, this facility was used, among other things, for Astronaut pilot training on Space Shuttle landing and rollout [50]. A schematic diagram of the VMS is shown in Figure 6, along with a listing of its motion capability in Table 2. The VMS can move the simulator cab with more force and extent than traditional hexapod motion simulators. This creates significantly better motion cues than a conventional simulator, and the VMS is the highest motion fidelity simulation platform currently available at NASA.

3.3 Flight Deck

A research flight deck was used with a layout similar to commercial transport aircraft cab, but without many features that would ordinarily be present in a full aircraft cockpit. As shown in Figure 7, the cockpit included rudder pedals, back-driven wheel and column, as well as a back-driven throttle quadrant with pitch trim indicator, flap, and speed-brake controls. The aircraft model selected for the experiment was representative of a two engine Boeing 757, so the 4 throttle levers on the quadrant were paired and bolted together as labeled in the figure. The speed-brake lever was not used in the experiment. The flat screen displays, from left to right, showed the recovery performance metrics (not shown while flying), the Primary Flight Display
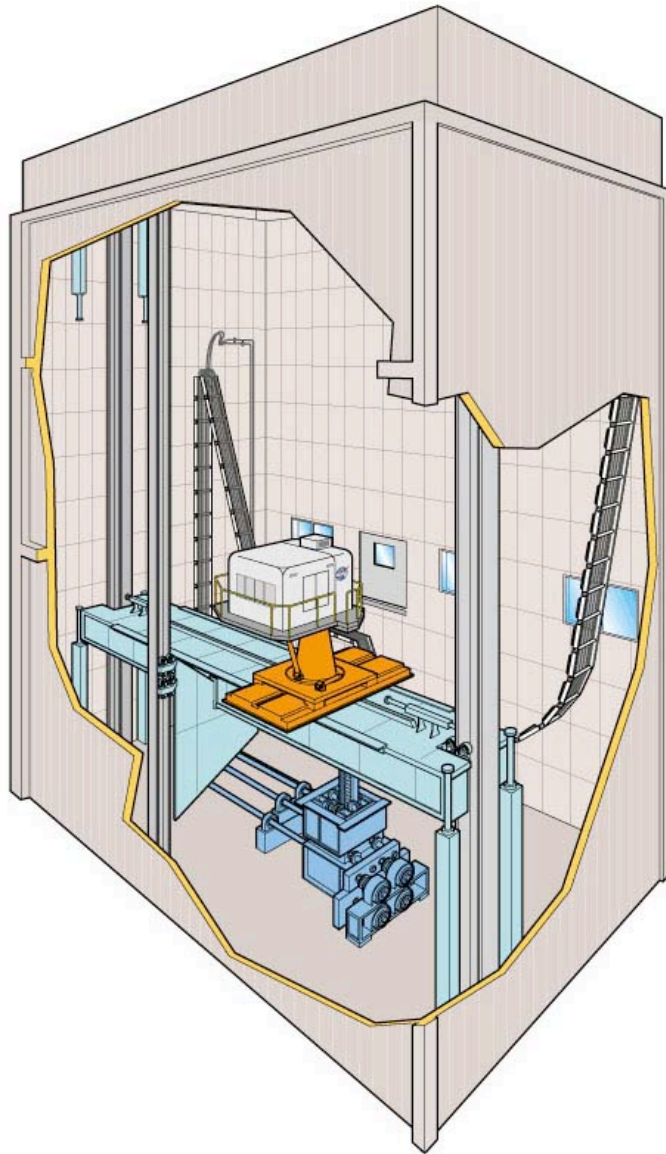
Figure 6. Vertical Motion Simulator Facility

Table 2. VMS Nominal Operational Motion Limits

AXIS	DISPLACEMENT	VELOCITY	ACCELERATION
VERTICAL	±30 ft	16 ft/sec	24 ft/sec^2
LATERAL	±20 ft	8 ft/sec	16 ft/sec^2
LONGITUDINAL	±4 ft	4 ft/sec	10 ft/sec^2
ROLL	±18 deg	40 deg/sec	115 deg/sec^2
PITCH	±18 deg	40 deg/sec	115 deg/sec^2
YAW	±24 deg	46 deg/sec	115 deg/sec^2

(PFD), Navigation Display, and Engine N1 indicators. The gear handle was directly above the left N1 indicator. The yoke had a trim hat for adjusting pitch trim only (lateral trim was inactive), an index finger emergency stop button, and two other buttons that were not used. A master warning light was provided above the left PFD.

The Primary Flight Display and stall warning system were meant to be accurate representations for a Boeing flight deck, most similar in style to a B777. The basic PFD format without guidance is shown in Figure 8. The airspeed tape included the magenta Mode Control Panel (MCP) selected airspeed and marker (though there was no physical MCP), green V_{REF} marker, amber maneuvering speed band with corresponding caution-level quadruple beep aural alert, and the red stick-shaker activation band and corresponding warning-level stick-shaker consistent with commercial aircraft equipage.[19] The stick-shaker activation airspeed was load factor dependent, and computed in accordance with FAA regulation. The Attitude Direction Indicator (central portion of the PFD) was of a standard format with aircraft reference symbol (white outlined black aircraft wing and nose markings), as well as the amber Pitch Limit Indicator (PLI) — often referred to by pilots as the "whiskers." The distance between the PLI and the aircraft reference symbol is the margin between the current angle-of-attack and the angle-of-attack at stick-shaker activation. Therefore, as the airspeed crosses into the red stick-shaker activation band, the PLI "whiskers" cross the top white outline of the aircraft reference symbol. Even though many transport category aircraft are equipped with stick pushers, one was not included in this study because it would have complicated the manual control required to track the recovery guidance cues being studied in this experiment. The calculations for the minimum maneuvering speed, stall warning airspeed, and PLI are explained in Appendix A.

3.4   Aircraft Model

Pilot simulator training facilities traditionally used aircraft math models that were invalid for full aerodynamic stall. With this limitation, commercial pilot training programs could only correctly train stick-shaker and stick pusher prevention (which by regulation occurs before aerodynamic stall). Proper recovery training from aerodynamic stall however requires a simulator model that includes the appropriate full stall aircraft dynamics.

In this study, the General Transport Model (GTM) was integrated into the Vertical Motion Simulator facility. This model is representative of a generic transport class aircraft most similar to a Boeing 757. The GTM model included more realistic stalled flight characteristics, derived from a 5.5% sub-scale polynomial aerodynamic database built from wind-tunnel and spin-tunnel testing. The sub-scale model was then developed into a full-scale model, by applying appropriate Reynolds Number corrections [51].

All of the scenarios in the experiment were flown with the "light" turbulence computed in accordance with the Dryden turbulence model military specification [52,53].

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[19]The noise created by the motor shaking the columns provides an aural cue, while the physical shaking of the column provides a tactile cue.

Figure 7. Research flight deck used for the SRG Experiment.
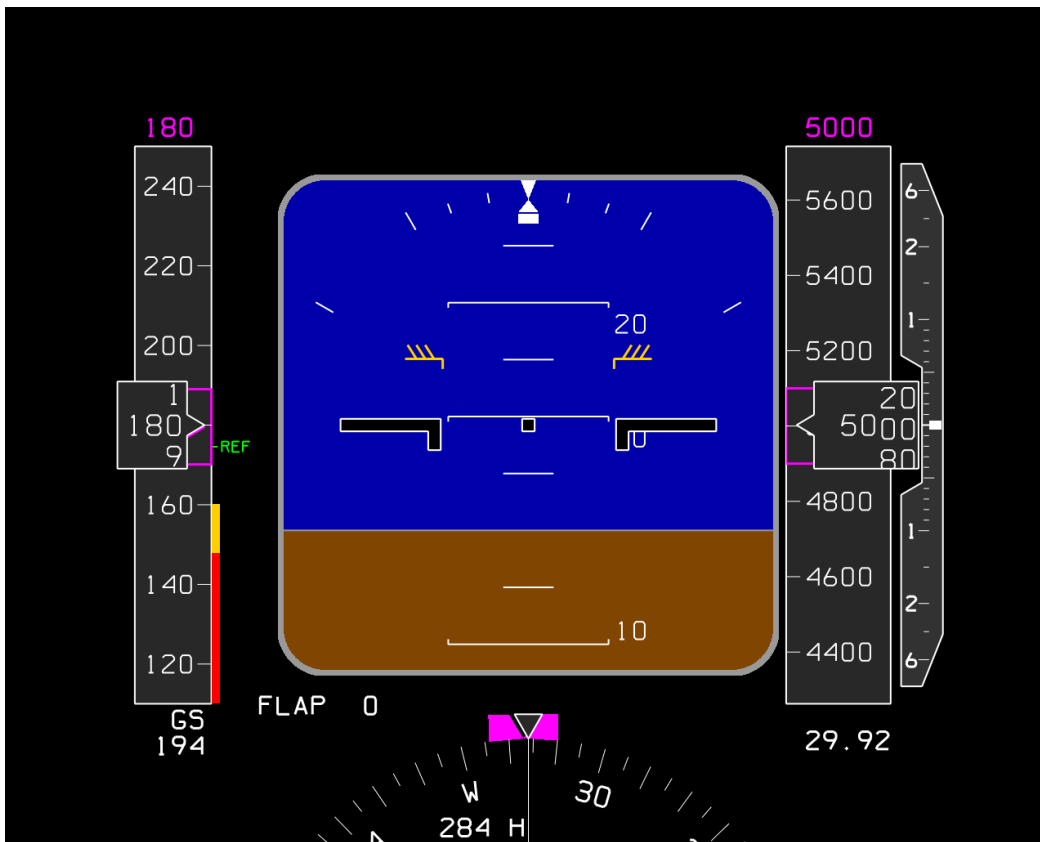
Figure 8. Primary Flight Display without guidance.

A light stall buffet effect was also added, initiating at the angle-of-attack corresponding to aerodynamic stall onset (typically, 16 degrees for the GTM model).[20] Several pilots commented that the buffet effect was not nearly as strong as what might be experienced in a real aircraft by more than a factor of two.

3.5 Guidance Cues

The split-cue (cross bar) flight director was selected to provide the pitch and roll recovery guidance because of its familiarity to commercial pilots. Figure 9 shows the guidance cues just after the stall recovery guidance mode was engaged. The stall recovery guidance mode is annunciated as SRG in red across the top of the PFD[21], along with the RECOVER directive below the PFD. The split magenta vertical and horizontal bars provide the roll and pitch guidance, respectively. The piloting task is to fly the aircraft reference symbol (black wing and nose markers outlined in white) to the magenta pitch and roll indicators as they are accustomed to during normal flight operations. Typically, pilots are trained to follow these directors by trying to get them to cross precisely through the center of the aircraft nose marker. In Figure 9, the roll director is commanding zero bank input, while the pitch director is indicating moderate pitch down input to get the nose of the aircraft below the PLI. In the particular scenario shown, the roll director will engage to level the wings only after the nose drops below the PLI, as explained in Section 2.1.

A new throttle director cue was developed to provide thrust guidance. The design was based on a previously studied concept for guiding control of the collective on helecopters [54, 55]. The throttle cue adapted for this study is depicted on the PFD shown in Figure 9 as the magenta cutout on the right wing indicator, and the two white cues directly below it. The white cues are meant to resemble the throttle handles, which should be placed on the magenta cutout. The philosophy is consistent with the other "fly to" directors used for pitch and roll. As depicted in Figure 9, the throttle cue is requesting increased thrust, in this case, from idle to maximum power (i.e., the full deflection is shown in the figure).

Alternative guidance cue concepts were considered for use in the study. These are discussed in Appendix C.

4   Scenarios

Each participant flew the four stall recovery scenarios described in this section. All of the scenarios took place in and around the San Francisco International Airport terminal area. In each scenario, the visibility was clouded to obscure the horizon, and, the automation system controlled the aircraft from its initial state into aerodynamic stall. When the desired stall condition occurred, the mode annunciators on the primary flight display (PFD) switched to "SRG" in red, and "RECOVER" was indicated in red on the bottom of the attitude director indicator (ADI), as shown

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[20]We define the angle-of-attack corresponding to aerodynamic stall onset as $\alpha = \operatorname{argmax} C_L(\alpha)$.

[21]Several pilot participants recommended simply annunciating STALL, instead of SRG, to avoid any additional workload that may be required to mentally decode the SRG acronym (that would only rarely, if ever, be seen).
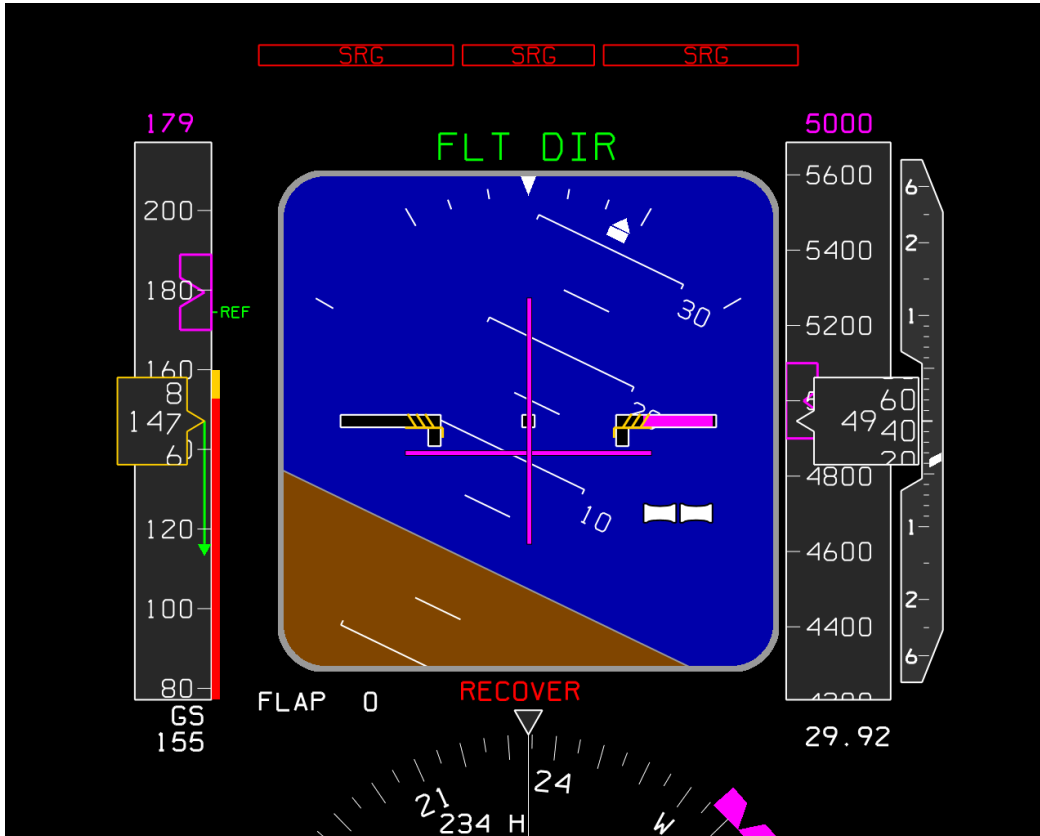
Figure 9. Primary Flight Display in Stall Recovery Guidance Mode.

in Figure 9. At this point, an alarm sounded with "Stall, Stall, Stall," and, simultaneously, the autopilot and auto-throttle systems automatically disconnected. The participants were then instructed to manually fly the stall recovery maneuver. Scenarios were flown with and without guidance in randomized order. When the guidance was available, the pilots were instructed to follow the flight director and thrust guidance cues. Each scenario was concluded by the simulation engineer when the pilot flying achieved roughly unaccelerated level or climbing flight.

4.1 High Altitude Stall

This scenario was motivated the Icelandair, Air France, and West Caribbean accidents. The aircraft was initialized at its altitude ceiling on the back side of the power curve at 170 knots. In this state, attempting to hold level flight at cruise thrust (95% N1) causes the aircraft to decelerate. The automation system was setup to hold altitude and cruise thrust until the angle-of-attack exceeded 25 degrees. From this fully developed stall attitude, the aircraft has a strong natural pitch down tendency when the auto-pilot disconnects (in part because the autopilot can not trim nose-up fast enough). The aircraft also exhibits very sensitive pitch control during the pull-up phase of the recovery, with a tendency towards pitching the aircraft nose-up into the

44

(a) PFD on initialization.   (b) PFD at start of stall recovery.
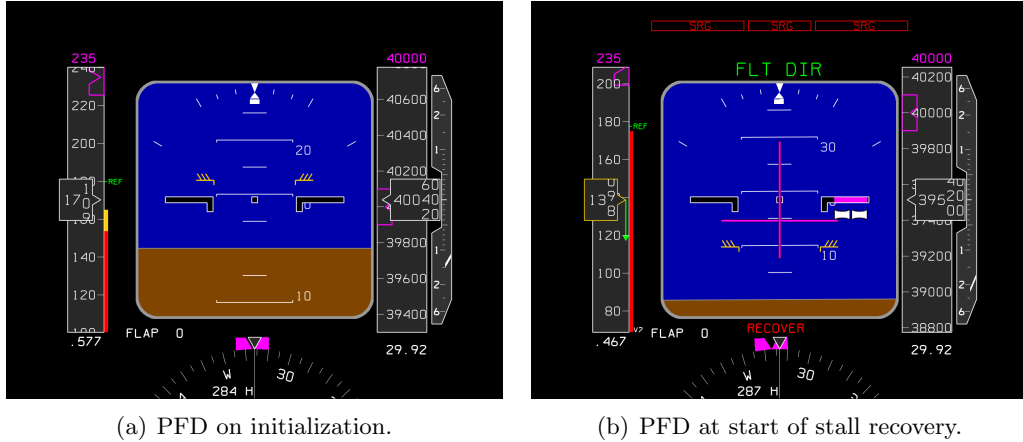
Figure 10. High altitude stall scenario PFDs.

PLI, inducing a secondary stick-shaker stall warning, and possibly even a secondary aerodynamic stall. This pitch control sensitivity is realistic and caused by the fact that aircraft at high altitude experience less aerodynamic damping [56, pg. 4].

The high altitude stall scenario was designed to examine:

- if negative g loading occurred during the pitch down phase of the recovery,

- the number of stick-shaker stall warnings that occurred,

- whether secondary aerodynamic stall occurred,

- recovery to an airspeed comfortably on the front side of the power curve.

The scenario setup parameters and performance standards are summarized in Table 3. The PFD at the beginning of the scenario is shown in Figure 10(a). From this initial state, the autopilot flies the airplane into the deep aerodynamic stall condition with PFD shown in Figure 10(b). For this scenario, the airspeed is deep into the red stick-shaker band and, correspondingly, the PLI is far below the current aircraft pitch. From this condition, participants began the manual recovery maneuver flying either with or without guidance (the case with guidance is shown in the figure).

4.2   Approach Stall

This scenario was intended to test the recovery guidance system on an approach stall at very low altitude. In this scenario, the aircraft is initialized at 1,100 ft on the glide slope to San Francisco International Airport. The autopilot stalled the aircraft at 680 feet, after the throttle was back driven to idle.

The approach stall scenario was designed to examine:

- performance with full flaps, gear down, and ground proximity,

- tendency to over correct especially on pitch down,

Table 3. High Altitude Stall Scenario

Initial State	Clean aircraft, 170 knots, 40,000 feet (altitude ceiling), −2.5 degree flight path angle, cruise thrust (95% N1, ²/₃ throttle), and light turbulence. Weather set for 8 mile visibility.
Stall Entry	Autopilot set to altitude hold, causing aircraft to level off at current thrust and the airspeed to decrease. Autopilot flies aircraft beyond stick-shaker into fully developed stall.
Start Recovery	When angle-of-attack exceeds 25 degrees. Indicated to pilot when "RECOVER" appears in red on the PFD.
End Recovery	When unaccelerated level or climbing flight is achieved.

Recovery Standards	**Desired**	**Adequate**
Max. speed exceedance	0	0
Secondary stall warnings	≤ 1	≤ 2
Min. load factor	0 g	−1 g
Max. load factor	2.4 g	2.5 g
Min. altitude	35,000 ft	30,000 ft

Tracking Standards	**Desired**	**Adequate**
Pitch director capture time	< 3 sec.	< 6 sec.
Max. pitch tracking error	2.5 deg.	5 deg.
Throttle tracking error > 25%	< 3 sec.	< 6 sec.

- tendency to exceed flap limit airspeed after pulling into climb out,

- whether the guidance reduces the tendency to recover with pitch attitude above the PLI, or, equivalently, with angle-of-attack in the margin between stall warning and full stall.

The scenario setup parameters and performance standards are summarized in Table 4. The PFD at the beginning of the scenario is shown in Figure 11(a). From this initial state, the autopilot flies the airplane into the aerodynamic stall onset condition with PFD shown in Figure 11(b). From this condition, participants began the manual recovery maneuver flying either with or without guidance (the case with guidance is shown in the figure). At the onset of the recovery, the thrust guidance requests full thrust from its current idle setting, while the pitch guidance requests a nose-down pitch input to just below the PLI. Notice, also, the relatively limited set of safe airspeeds between 130 knots, and the flap overspeed limit at 160 knots.

Table 4. Approach Scenario

Initial State	Full flaps, gear down, 140 knots, 1,100 feet, wings level, 700 ft/min descent, thrust set to trim attitude (51% N1, $^1/_4$ throttle), and light turbulence. Weather set for 38 mile visibility, with cloud layer at 1500 ft and 500 ft visibility in cloud.
Stall Entry	Autopilot set to hold -3 degree glide slope. Auto-throttle commands throttle to idle 4 seconds after start. Aircraft decelerates.
Start Recovery	At aerodynamic stall onset, when angle-of-attack exceeds 16 degrees. Indicated to pilot when "RECOVER" appears in red on the PFD.
End Recovery	When unaccelerated level or climbing flight is achieved.

Recovery Standards	Desired	Adequate
Max. speed exceedance	0	0
Secondary stall warnings	≤ 1	≤ 2
Min. load factor	0 g	-1 g
Max. load factor	1.9 g	2.0 g
Min. altitude	500 ft	200 ft

Tracking Standards	Desired	Adequate
Pitch director capture time	< 3 sec.	< 6 sec.
Max. pitch tracking error	2.5 deg.	5 deg.
Throttle tracking error > 25%	< 3 sec.	< 6 sec.

(a) PFD on initialization.   (b) PFD at start of stall recovery.
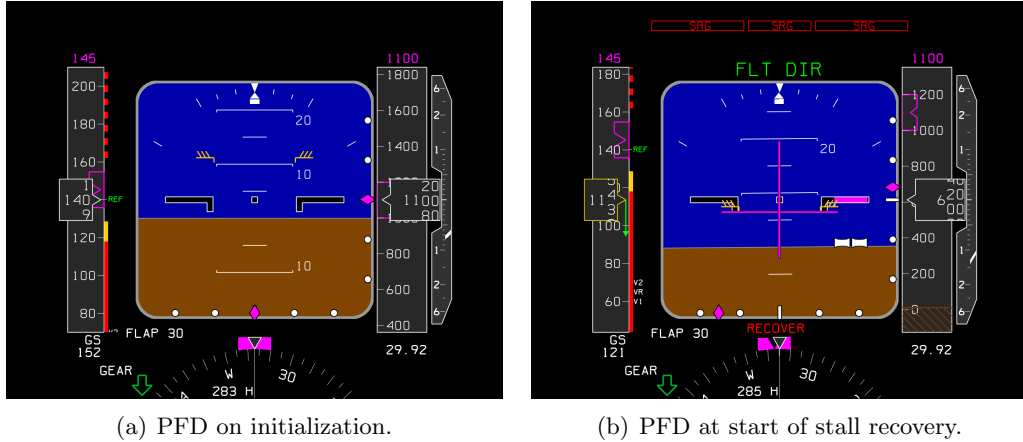
Figure 11. Approach stall scenario PFDs.

4.3   Low Altitude Stall

This baseline scenario was included to study whether the guidance contradicted pilot expectations while flying a straightforward stall recovery.

The low altitude stall scenario was designed to examine:

- a standard recovery requiring pitch, roll, and thrust inputs,

    - especially with roll instability at low airspeed,

- whether the guidance supports pilot expectations, and the fundamental aspects of the FAA stall recovery template.

The scenario setup parameters and performance standards are summarized in Table 5. The PFD at the beginning of the scenario is shown in Figure 12(a). From this initial state, the autopilot flies the airplane into the aerodynamic stall onset condition with PFD shown in Figure 12(b). From this condition, participants began the manual recovery maneuver flying either with or without guidance (the case with guidance is shown in the figure). At the onset of the manual recovery in this scenario, the throttle guidance is requesting full power (from the current idle thrust setting), and a pitch down input. The roll director is requesting to hold the current bank angle in accordance with the recovery strategy adopted for the guidance.

4.4   Low Altitude Stall with Excessive Nose-Up Pitch Trim

This scenario was motivated by the Thompson Fly and Colgan Air accidents, where the autopilot may have commanded excessive nose-up pitch trim that would have further complicated the recovery maneuver. This scenario is the same as the baseline low altitude scenario, except that excessive nose-up stab trim to 9 degrees was commanded while the aircraft decelerated towards stall. For the particular aircraft model used in the experiment, the 9 degrees nose-up trim was about the minimum amount required to cause the aircraft to pitch-up, exceeding the elevator authority of

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Table 5. Low Altitude Stall Scenario

Initial State	Clean aircraft, 180 knots, 5,000 feet, thrust set to trim level flight (56% N1, 1/4 throttle) and light turbulence. Weather set for 8 mile visibility.
Stall Entry	Autopilot set to altitude hold and commands 25 degree bank left. Auto-throttle commands throttle to idle six seconds after start. Aircraft decelerates.
Start Recovery	At aerodynamic stall onset, when angle-of-attack exceeds 16 degrees. Indicated to pilot when "RECOVER" appears in red on the PFD.
End Recovery	When unaccelerated level or climbing flight is achieved.

Recovery Standards	**Desired**	**Adequate**
Max. speed exceedance	0	0
Secondary stall warnings	≤ 1	≤ 2
Min. load factor	0 g	-1 g
Max. load factor	2.4 g	2.5 g
Min. altitude	4,000 ft	3,000 ft

Tracking Standards	**Desired**	**Adequate**
Pitch director capture time	< 3 sec.	< 6 sec.
Max. pitch tracking error	2.5 deg.	5 deg.
Throttle tracking error > 25%	< 3 sec.	< 6 sec.

(a) PFD on initialization.　　　　　(b) PFD at start of stall recovery.

Figure 12. Low altitude stall scenario PFDs.

the column to pitch down *when full thrust was also applied* for a significant duration of time. For comparison, in the baseline low altitude scenario, the autopilot normally commanded only 2 degrees nose-up stab trim. In this scenario, if the pilot did not manually adjust the pitch trim nose-down before applying full thrust, a pitch up moment would build with airspeed to the point where it exceeded the full elevator authority to pitch down. As the aircraft then pitched up uncontrollably, it would rapidly decelerate back towards stall.

The low altitude stall with excessive nose-up trim scenario was designed to examine:

- a recovery requiring pitch, roll, thrust, *and nose-down stab trim* inputs,

    - with a comparison to recovery in the baseline low altitude scenario,

- margin to pitch down elevator saturation,

- effectiveness of throttle guidance to reduce thrust.

The scenario setup parameters and performance standards are summarized in Table 6. The PFD at the beginning of the scenario is shown in Figure 13(a). From this initial state, the autopilot flies the airplane into the aerodynamic stall onset condition, while applying excessive nose-up trim. The PFD at the beginning of the recovery maneuver is shown in Figure 13(b). From this condition, participants began the manual recovery maneuver flying either with or without guidance (the case with guidance is shown in the figure). The PFD at the beginning of the stall recovery is nearly identical to the PFD for the low altitude scenario, with the notable exception that the thrust guidance cue requests no additional thrust input because the airplane is in an excessive nose-up stab trim condition.

4.5　Performance Standards

Each of the above scenario tables specified two sets of standards for categorizing desired and adequate performance. The first set of *recovery standards* defines the

Table 6. Low Altitude Stall with Excessive Nose-Up Trim Scenario

Initial State	Clean aircraft, 180 knots, 5,000 feet, thrust set to trim level flight (56% N1, 1/4 throttle) and light turbulence. Weather set for 8 mile visibility.
Stall Entry	Autopilot set to altitude hold and commands 25 degree bank left. Auto-throttle commands throttle to idle six seconds after start. Aircraft decelerates. Stab trim position commanded to 9 degrees nose-up at 0.5 deg/sec.
Start Recovery	At aerodynamic stall onset, when angle-of-attack exceeds 16 degrees. Indicated to pilot when "RECOVER" appears in red on the PFD.
End Recovery	When unaccelerated level or climbing flight is achieved.

Recovery Standards	Desired	Adequate
Max. speed exceedance	0	0
Secondary stall warnings	≤ 1	≤ 2
Min. load factor	0 g	-1 g
Max. load factor	2.4 g	2.5 g
Min. altitude	4,000 ft	3,000 ft

Tracking Standards	Desired	Adequate
Pitch director capture time	< 3 sec.	< 6 sec.
Max. pitch tracking error	2.5 deg.	5 deg.
Throttle tracking error > 25%	< 5 sec.	< 10 sec.

(a) PFD on initialization.   (b) PFD at start of stall recovery.
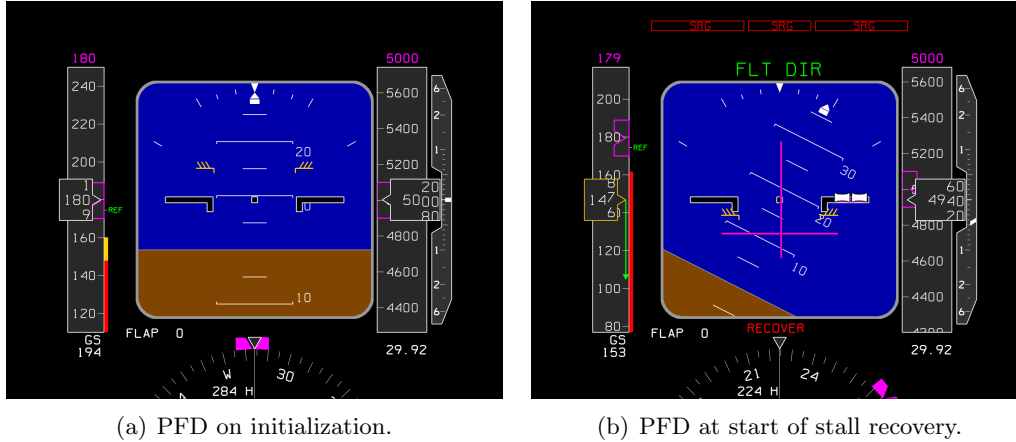
Figure 13. Low altitude excessive nose-up trim scenario PFDs.

safety related performance measures, while the second set of *tracking standards* defines the measures for categorizing how well the participants were able to track the guidance cues.

The recovery standards apply to all scenario runs, both with and without guidance. They are meant serve as aircraft performance metrics for each recovery. The commercial pilots were shown the recovery standards after flying each scenario, and were asked to use them to complete post-run surveys.

- The **max. speed exceedance** metric was meant to ensure no over speed condition occurred during the recovery (of either VMO, or max flap speeds).

- The **secondary stall warning** metric established the number of times the pilot exceeded the stick-shaker warning airspeed. Multiple stick-shaker warnings are prone to occur when the aircraft exhibits a sensitive pitch response, especially at high altitude, or when the pilot wishes to recover with minimum altitude loss by recovering near the stick-shaker angle-of-attack (indicated by the PLI). Since there is some margin between the angle-of-attack where the stick-shaker occurs and where aerodynamic stall occurs, a stick-shaker event may be within the margin of error for a particular recovery. It is, however, important that secondary stall does not occur. With pilot feedback, it was subjectively decided for this experiment that the performance is desirable with up to one stick-shaker, adequate with 2, and inadequate otherwise.

- The **min./max. load factor** metrics are meant to ensure recoveries were executed within the safety load factor limitations for the aircraft. A load factor of less than 0 g will cause any passengers or objects not secured to strike the aircraft ceiling significantly increasing the potential for injury. The maximum structural load for a typical commercial aircraft is 2.5 g for a clean configuration, and 2.0 g if flaps have been deployed. The desired and adequate load factor metrics for this study were based only on maintaining passenger safety (with 0.1 g margin for the desired metric), not comfort.

- The **min. altitude** metric is the minimum absolute altitude registered for the recovery. Altitude loss minimization is no longer a performance consideration for pilot stall recovery training. This is because it contributes to a reluctance to arrest an impending stall, or full stall, by pitching down to reduce the angle-of-attack. However, it is still an important metric for assessing stall recovery guidance technology. In particular, while following the guidance, the altitude loss should not be excessive. The minimum altitude performance metrics were decided from an assessment for each scenario to determine appropriate values, with the objectives of the experiment in mind.

In addition to the recovery performance standards listed above, the following three guidance tracking metrics were also defined:

- The **pitch director capture time** is the amount of time to reduce the pitch guidance error to less than 2.5 degrees.

- The **max. pitch tracking error** is the maximum pitch error permitted for a particular standard after the capture.

- The **throttle tracking error** was the total amount of time that the throttle guidance error exceeded 25%.

Values for these tracking metrics were determined subjectively based on a test pilot evaluation for each of the scenarios. The test pilots who participated in the experiment used the tracking standards to providing a Cooper-Harper rating of the guidance technology with respect to the pitch and throttle guidance cues. While the roll guidance *strategy* was an important element in the study, an assessment of the tracking performance of the roll director was not of interest.

5   Experiment Procedure

The experiment included a total for 40 pilot participants spread over 23 days. On each day, one or two pilots participated in a session requiring 24 stall recoveries per pilot, each recovery lasting 20-60 seconds. There was typically only one session held each day, with the exception of day 16, during which 2 additional pilots participated in an afternoon session. At the beginning of each session, the participants were briefed on the important aspects of the experiment as itemized below:

- **Motivation**: A very brief summary of the Commercial Aviation Safety Team motivation for the work was provided. It was noted that the experiment was focused on a baseline test of new stall recovery guidance algorithms and displays. The presentation emphasized that in practice stall is typically the final result of a series of cascading safety issues usually involving distraction, automation confusion, and ultimately inappropriate control action.

- **Experiment Overview** A high level description of the experiment was provided. The experiment objective "to develop guidance technology that helps pilots efficiently recover from stall" was stated. It was emphasized that the

recovery guidance was meant to be easy to follow, especially given the typical issues complicating matters in the cockpit when stall recoveries are required. Pilots were told they would be flying a B757-like aircraft model developed from wind tunnel testing, and that each would individually fly the same recovery algorithm and display cues through four stall recovery scenarios.

- **FAA Recovery Template**. The participants were shown the abbreviated Stall Recovery Template provided by the FAA in AC120-109A, as shown in Table 1. The basic recovery procedure was discussed.

- **Technology Benefits**. The use of flight dynamics to compute scenario and aircraft specific recovery guidance was briefly summarized as the primary benefit of stall recovery guidance.

- **Cockpit Layout**. A picture of the research cockpit layout was shown and discussed.

- **Flight Directors**. The stall recovery guidance mode and flight directors were presented. Since the thrust director was the only new director, two short videos (with combined duration less than 50 seconds) demonstrating its operation were shown. The second video specifically covered its operation in an excessive nose-up pitch trim scenario.

- **Scenarios**. Each of the four scenarios was briefed in full detail. Participants were informed that this was a baseline experiment, where their purpose was to evaluate the recovery guidance technology as a pilot aid in consideration of the fact that distraction would probably be present during operational use (even though the experiment included no attempt to distract the participants while they evaluated the technology).

- **Recovery Metrics**. For each scenario, the participants were told to recover from stall to unaccelerated flight, with a flight path angle greater than or equal to zero, without excessive altitude loss, while avoiding secondary stall and the tendency to induce oscillation in pitch, roll, or throttle control. It was explained that following each run, performance metrics would be made available for use in filling out post-run evaluation surveys. A brief summary of the performance metrics was provided. Test Pilot participants were also briefed on the tracking performance metrics and Cooper-Harper rating task (see Figure 42).

- **All participants** were told that their primary purpose was to evaluate the recovery guidance technology in scenarios and conditions that are exceedingly rare in operational practice. They were also informed that they could take breaks, or end their participation at any time.

After the briefing, the participants were asked to fill out a short pre-sim survey, and were then provided with a tour of the simulator safety features and procedures. The information from the survey was used to assign a recovery guidance algorithm (so that experience and skill levels would be balanced across the two algorithms). From

the algorithm assignment, one pilot was selected to go first based on a pre-established test matrix. The selected pilot was positioned in the cab with an "instructor" pilot, and permitted to fly the aircraft freely until he or she felt familiar with the controls and alerting systems.[22] Following the familiarization run, the experiment began.

The overall experiment procedure was approved by a Human Research Institutional Review Board. Each scenario was flown three times, both with and without guidance according to the established test matrix. After each set of three runs, the participant filled out a post-run survey, which included a Cooper-Harper rating for the research pilots only. The test session proceeded as follows. The first participant would fly a cab familiarization run followed by two scenarios. This participant would then break outside of the cab while the second participant flew the cab familiarization run and two scenarios. The experiment proceeded in this fashion until the full test matrix was completed, with one cab familiarization run and the four stall recovery scenarios. At all times only one participant flew in the cab, while the resting participant waited in an area where he could not view the performance of the other pilot. The sequence of the scenarios, and whether or not guidance was provided, was semi-randomized across the experiment. The full experiment test matrix is listed in Appendix E. After completing their respective set of 24 stall recovery runs, each pilot filled out a post-sim survey, and both pilots (if there were two) participated together in a debriefing with the researchers.

6   Participants

6.1   Commercial Pilots

Thirty active commercial pilots, a mix of both Captains and First Officers, with current certification on Boeing transport aircraft with glass cockpit were requested for the experiment.[23] The pilots were recruited by an independent company that solicited participation using the short experiment description presented below. One recently retired pilot (within 1 year) that was still current on a Boeing transport aircraft was admitted into the study. Pilots from multiple companies participated, including American Airlines, Delta, Southwest, United, United Parcel Service, Federal Express, Cathay Pacific, and Kaiser Air (a charter airline).

The number of flight hours, self reported by each participant, ranged from 5,000 to over 28,000. Twenty-six of the pilots reported being familiar with the FAA stall recovery guidelines. Ten of the pilots were trainers (check flight instructors or other), ten had military aircraft experience and training, and seven reported experience flying general aviation acrobatic maneuvers.

During each simulation run, the commercial pilots were asked to follow the guidance when it was provided, or their standard operational practice if guidance was not provided. After flying a scenario 3 times, they were asked for subjective ratings, based on the recovery performance metrics listed in Section 4. An overall

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[22]In most cases the instructor pilot was an experienced test pilot. At times when the test pilot was unavailable, the principle investigator, though not an actual pilot, served as the "instructor pilot" for the purposes of the research cab familiarization.

[23]B737, 747, 757, 767, 777, 787.

assessment of the guidance system was provided on a post simulation run survey, that was the same for all pilots (including the research test pilots). The surveys are reproduced in Appendix D.

> **Participant Invite**: Though rare, stall related accidents and incidents still occur in commercial aircraft. To partially address this concern, the Stall Recovery Guidance experiment is investigating the degree to which several candidate algorithms and displays can serve as a pilot aid during manual stall recovery. In support of this study, participants are needed to fly simulated stall recovery scenarios in the terminal area around SFO, and provide subjective feedback on recovery guidance cues. The experiment will take place in the Vertical Motion Simulator Facility at NASA Ames Research Center, April-May 2017.

6.2   Research Pilots

Two research pilots from NASA Armstrong Flight Research Center (AFRC), at Edwards Air-force base in California, participated in shakedown testing and advised the refinement of the stall recovery guidance strategy and experiment procedure three months prior to the start of the experiment. The lead pilot for this effort coordinated the involvement of 8 other research pilots from AFRC in the final experiment. These two pilots also participated in the official study, and we chose keep the data collected from their runs in the analysis. Since all pilot participants were briefed on the experiment procedure and stall scenarios, the inclusion of their data was expected to have negligible impact. Any outlier performance was cross checked against their participation, and called out in the data analysis where it occurred.

In all, ten pilots from AFRC participated in the study. They self-reported between 1,800 and 10,000 flight hours. Nine of them reported familiarity with the FAA stall recovery guidelines, 9 of them were trainers (check flight instructors or other), 9 had military aircraft and training experience, and 5 reported additional experience flying general aviation acrobatic maneuvers. Several of them had former experience developing or testing stall protection systems for both commercial and military aircraft.

Research test pilots are trained to fly modified aircraft according to a specific test plan. Part of that training, includes learning to follow a standardized process for rating handling qualities according to the Cooper-Harper scale (see Figure 42), which must include quantitative performance measures. For this reason, research test pilots offer an important capability for assessing aircraft technologies.

The research pilots, followed the same experiment procedure and answered the same survey questions as the commercial pilots. In addition, they provided Cooper-Harper ratings on the proposed guidance system, based on the guidance tracking performance metrics specified in Section 4.

7 Results

7.1 Outliers

Forty pilots participated in the study. The experiment protocol required each one to fly 3 iterations of the 4 scenarios, with and without guidance, for a total of 24 runs per pilot. Of course, the execution of the run sequences were not always perfect, and in some cases extra runs were collected. Typically, this occurred when either the pilot accidentally pushed an emergency stop button,[24] when an inadvertent auto-throttle position command error occurred, or when a participant flew a recovery that activated a safety stop (usually caused by excessive roll leading to over travel on the lateral axis of the VMS). In total, 979 run data sets were recorded, including 19 runs where a mistake led to a repeat of at least one run.

In a few cases, the participants flew anomalous recoveries. Three of these are worth mentioning here. In the first case, during an approach scenario run, a pilot flew the aircraft into the 85 foot minimum altitude that triggered an automatic simulation stop. In the second case, the participant flew with an excessive amount of guidance tracking error in a high altitude scenario run, which led to large oscillations in angle-of-attack, airspeed, and altitude. In addition, this was one of the few secondary aerodynamic stalls that occurred with FMPC guidance in the high altitude scenario. The solid blue line in Figure 14, shows the recovery relative to all other pilots flying with FMPC guidance in the same scenario (collection of gray lines). This was the first run of the day flown by this particular pilot, and his second two attempts were normal with respect to the participant pool. After flying the second attempt, the pilot commented on how a former instructor used to say "nail that flight director ... man he used to hammer that." The dashed blue line in Figure 14 shows the third case. In this case, a pilot flying the high altitude recovery scenario *without* guidance, essentially recovers to the stick-shaker angle-of-attack and corresponding airspeed on the backside of the power curve. At this airspeed and angle-of-attack, the plane experiences too much drag to hold level flight and ends up on a continuously descending trajectory, never quite able to recover level flight within the time duration of the run.

Much effort went into the experiment design, and the resulting data collected for this report. In the presentation of the results, we therefore strive to show the raw, unprocessed, data as much as possible. This means including the outliers, as long as their inclusion does not lead to a misinterpretation of the results. We also make frequent use of the histogram to properly convey the spread of the data, instead of simply reporting the mean and the standard deviation for the quantities of interest.

7.2 Recovery Performance by Scenario

In this section, the quantitative analysis of the flight recovery performance data with respect to each of the scenarios is presented.

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[24]For safety, the pilots could use a simulation reset button on the control wheel to stop the simulation.
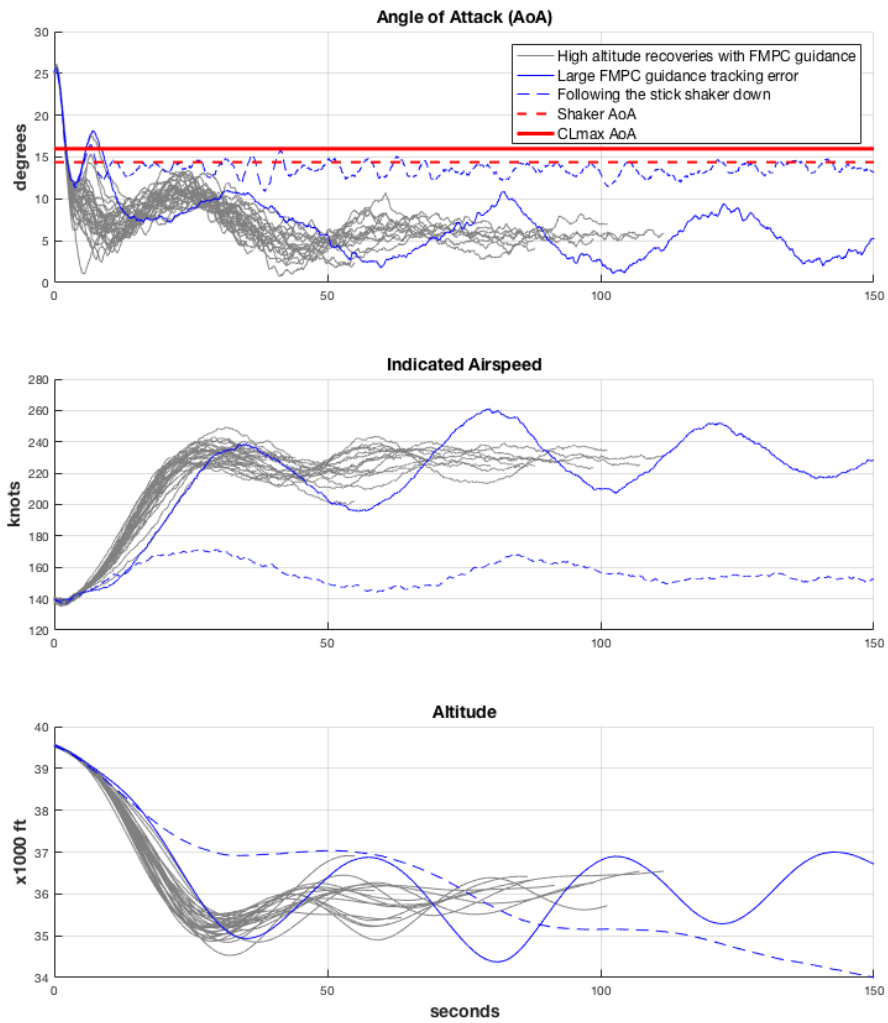
Figure 14. Two outlier recoveries from the High Altitude Scenario data.

7.2.1 High Altitude Stall Scenario

The difference between the EBA and FMPC guidance algorithms was most apparent in the high altitude scenario. The primary factor in the observed difference was that the FMPC guidance was significantly more aggressive in the initial pitch down maneuver. In particular, the FMPC algorithm commanded the aircraft to roughly -20 degrees pitch, before beginning the pull-up maneuver at greater airspeed. The EBA algorithm, on the other hand, pushed the aircraft down to about -7 degrees pitch, before beginning a more gentle pull-up maneuver. Figure 15 shows a comparison between the load factors for all high altitude scenario runs with no guidance, FMPC guidance, and EBA guidance. The stall recovery maneuver begins at zero seconds in the plot, a convention that we will maintain throughout this report. The figure confirms the expected more aggressive maneuver commanded by the FMPC algorithm,[25] but in all cases, no pilot risked exceeding any load factor limit. This is expected due to the lower airspeed at which stall recovery typically occurs.
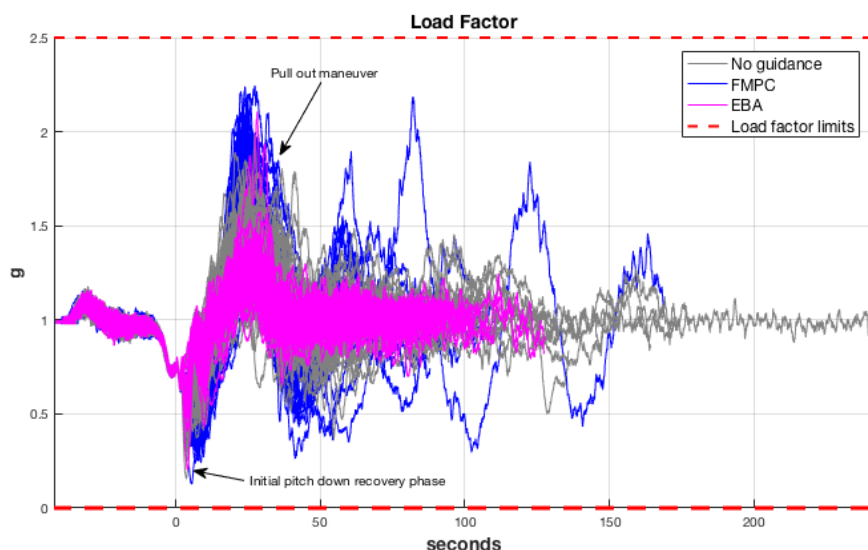
Figure 15. High altitude stall scenario: Load factors for all runs.

An important aspect of this study was to look at the effectiveness of the stall recovery guidance system, given that training on such a system may occur somewhat infrequently, and that it would likely be used under adverse piloting conditions. More generally though, systems intended to help humans should be easy to use. In an effort to test the guidance system for ease of use, we did not allow the pilots to practice using the system prior to data collection. This enabled us to measure the effectiveness of the system given no experience with it, other than the short 20 minute briefing that covered its basic operation.

Even if a participant flew the guidance system on a different scenario, the high

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[25]The large oscillatory FMPC load factor trace in Figure 15 corresponds to the large tracking error outlier case discussed in Section 7.1
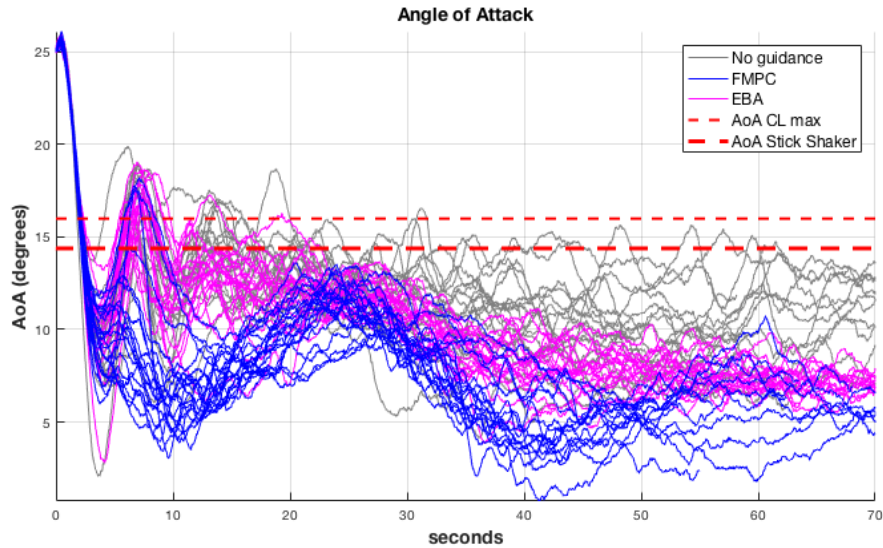
Figure 16. High altitude stall scenario: recovery in angle-of-attack for each participant's first run.

altitude scenario added a new element. This element was that for pilots not experienced with it, the large transport class aircraft response at high altitude can be surprisingly pitch sensitive, especially at high angle-of-attack and low airspeed. In fact, when flying without guidance, only one pilot in twenty was able to avoid a secondary stall warning on the first attempt,[26] and only five out of twenty were able to avoid a secondary aerodynamic stall.

Figure 16 shows the recovery in angle-of-attack for each pilot's first recovery attempt. By first attempt, we mean either the first attempt at flying a recovery without guidance (before having flown with any guidance system), or the first attempt at flying a recovery with the guidance system.[27] It is clear that when flying without guidance most pilots attempted to recover near the PLI (as they would have done for the lower altitude scenarios). However, with the pitch sensitive aircraft response, the normal tendency was to over correct and exceed the PLI, causing a secondary stall warning and often an aerodynamic stall as well, typically with a load factor greater than 1 g.

The distribution of the number of secondary stall warnings and aerodynamic stalls (sustained for greater than 0.2 seconds to eliminate mis-counts caused by turbulence), across all 20 first recovery attempts for the EBA, FMPC, and No guidance

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[26]This pilot, however, participated in an earlier shakedown of the experiment three months prior to his participation in the official study.

[27]Two technical caveats apply: (1) For the EBA or FMPC guidance cases, half of the runs were from pilots who flew the recovery without guidance first, which might have helped to observe fewer secondary stall warnings and aerodynamic stalls when the guidance system was turned on; (2) Runs with no guidance *always* occurred before the participant flew with the guidance system — so for the no guidance case, the participants were not made aware of the pitch sensitive aircraft response on a previous run.
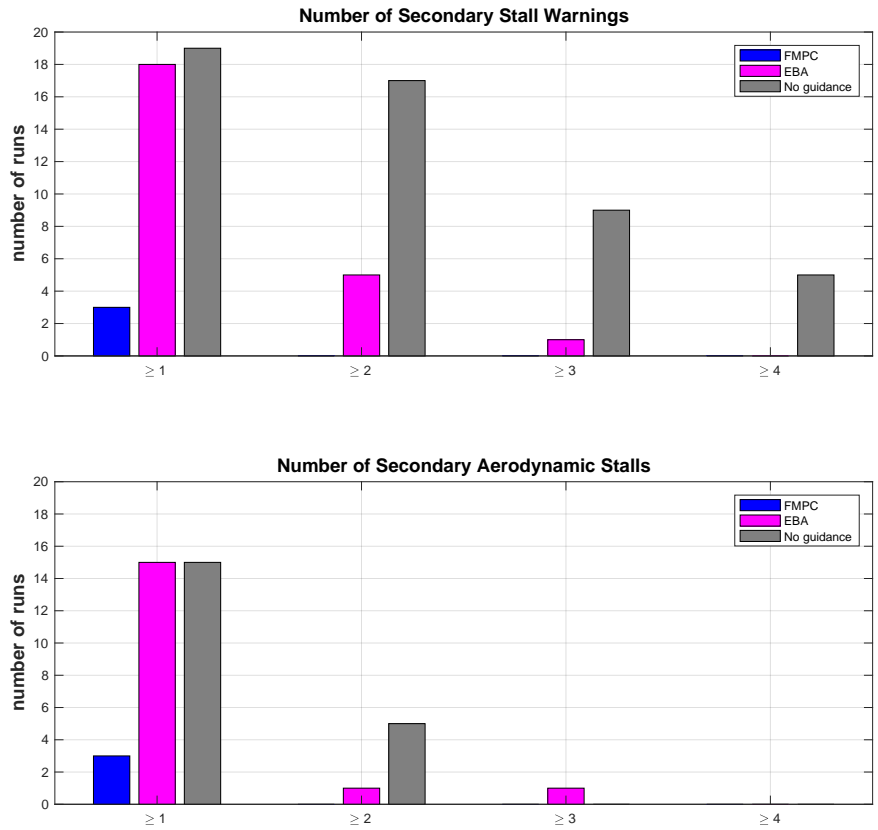
Figure 17. High altitude stall scenario: number of stick-shaker alerts (stall warnings), and secondary aerodynamic stalls for each participant's first recovery attempt ($n = 20$ for each of the three categories).

runs, is plotted in Figure 17. This figure shows that the EBA algorithm was somewhat effective at reducing the number secondary stall warnings and aerodynamic stalls, but the number of cases where at least one secondary aerodynamic stall occurred was the same without guidance. The more aggressive FMPC algorithm was however, extremely effective. Seventeen out of twenty pilots flew their recoveries without any secondary stall warning on their first attempt with the FMPC system, while only one pilot was able to meet this criteria without guidance, as noted earlier. Looking at the minor angle-of-attack oscillation that occurs in Figure 16, at about 5 seconds into the recovery, one observes that the FMPC guidance also got the pilots to overcome their instinct to pitch up too early. This result is a major finding of this study. It shows that aggressive pitch down guidance can significantly help with high altitude stall recovery. This is in stark contrast with a low altitude stall recovery where significantly less pitch down input is needed.
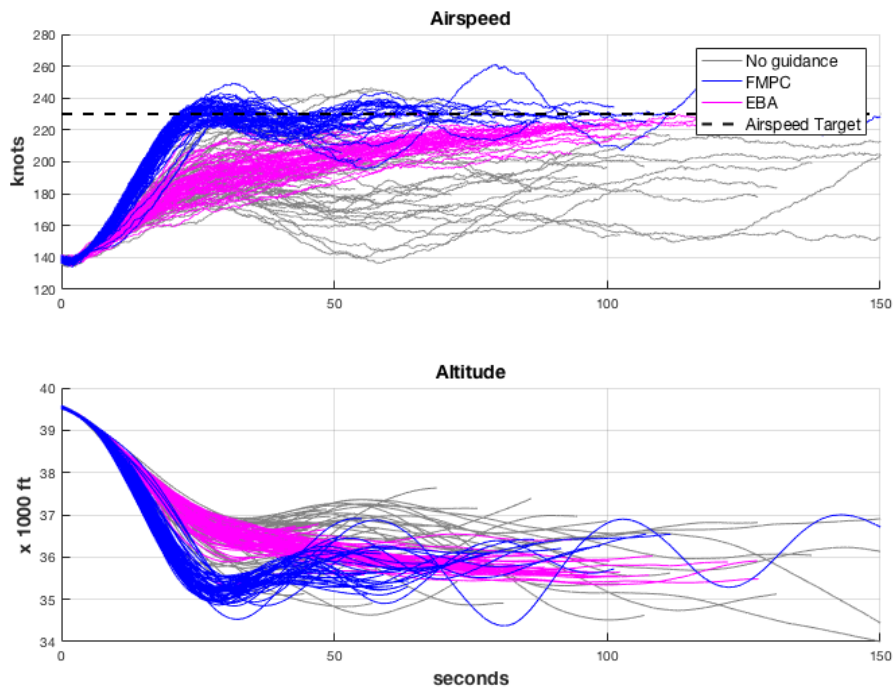
Figure 18. High altitude stall scenario: airspeed and altitude recovery vs. time, all runs ($n = 60$ for each of the three categories).

Figure 18 shows the altitude and airspeed recovery profiles for all runs of the high altitude scenario. The more aggressive pitch down action commanded by the FMPC algorithm brings the airspeed up faster at the expense of more altitude loss over the EBA algorithm. Typically, the difference in altitude was about 500 ft, as shown in the distributions of the minimum altitude across all runs, presented in Figure 19. Internally, both guidance algorithms attempted to control airspeed to a target value of 230 knots. The FMPC algorithm was more directly able to hit the target, but also exhibited a small oscillation in airspeed control. The EBA algorithm, on the
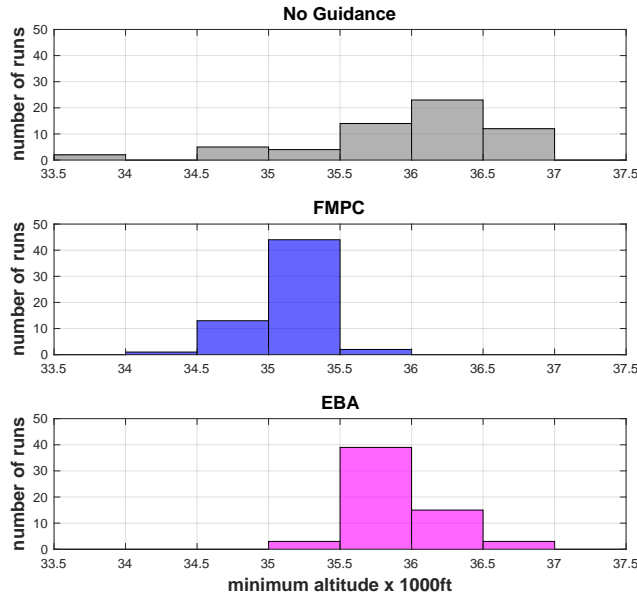
Figure 19. High altitude stall scenario: distribution in minimum altitude across all runs ($n = 60$ for each of the three categories).

other hand, had a slower, but smoother, airspeed response that more asymptotically hit the target airspeed. Because of the slower response, many of the runs with EBA guidance were stopped before reaching the full target airspeed, and this may have contributed to some of the better altitude performance observed with that algorithm. In general, though, both guidance algorithms improved the consistency of the airspeed recovery over the cases where pilots flew without guidance. As a consequence, both of the guidance algorithms helped the pilots to recover safely on the front side of the power curve.

Finally, Figure 20 shows the pitch guidance signal presented to the pilots, in addition to the tracking error associated with flying the guidance. For both algorithms, the guidance signals were continuously recomputed from the current aircraft state, so the overall guidance observed through time depended on how well the pilots were able to track the guidance. The large discrepancy between the EBA and FMPC algorithms in pitch down guidance is directly visible in the top plot. Also, in the bottom tracking error plot, at about 5 seconds, one can observe that the FMPC algorithm was commanding more pitch down, while the EBA algorithm commanded pitch up. After the initial pitch down capture, around 7 seconds into the recovery, the FMPC guidance incurred less overall tracking error. Looking at the top plot, one can also observe that the EBA algorithm was in good agreement with the recoveries flown by pilots without guidance, though, in this scenario the reduced pitch down tendency lead to more secondary aerodynamic stalls as discussed above.

Figure 20. High altitude stall scenario: pitch guidance tracking performance across all runs ($n = 60$ for each of the three categories). For recoveries flown without guidance, the actual pitch recovery is shown on the top plot.

7.2.2 Approach Stall

For the most part, there were no discernible differences in the piloted recoveries flown with the FMPC and EBA guidance algorithms. Both algorithms essentially matched most of the recovery maneuver that the pilots flew before seeing any guidance. This result is shown in Figure 21, which presents the recovery in angle-of-attack for the first runs of this scenario (in the same manner as Figure 16).[28] Figure 23 shows that in all three categories (No guidance, FMPC, and EBA) the group of pilots achieved about the same minimum altitude, with the mean between 350–400 ft (note the stall recovery started at 680 ft, with some variation due to turbulence), and essentially the same spread in minimum altitude among each of the categories, 60–100 ft standard deviation. Though not shown, the load factors for all of the recoveries in this scenario were well within limits (between 0, and 2 g for the aircraft in landing configuration). The overall consistency between the guided and un-guided recoveries occurred because the guidance algorithms were able to calculate that there was enough thrust authority at the lower altitude, and in landing configuration, to recover the aircraft near the PLI. Furthermore, the guidance algorithms worked with the PLI as a maximum constraint on the pitch, while pilots flying without the guidance were sometimes able to improve on the minimum altitude for the maneuver by flying slightly above the PLI. The approach scenario was also a validation test for the guidance algorithms, essentially showing that neither algorithm degraded the current pilot recovery procedure, which is already optimized through the use of the well established PLI.
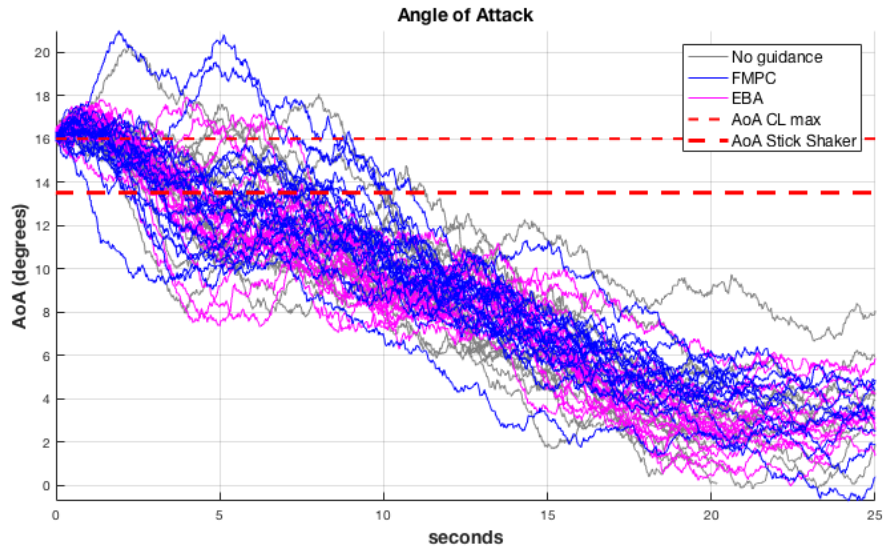
Figure 21. Approach scenario: first run recovery in angle-of-attack.

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[28]The dataset used for the first recoveries shown in Figure 21, however, does not include the one pilot that hit the altitude minimum of 80 ft while flying without guidance, or another pilot that mistakenly hit the simulation reset button (on the yoke), prematurely ending one first run with FMPC guidance.
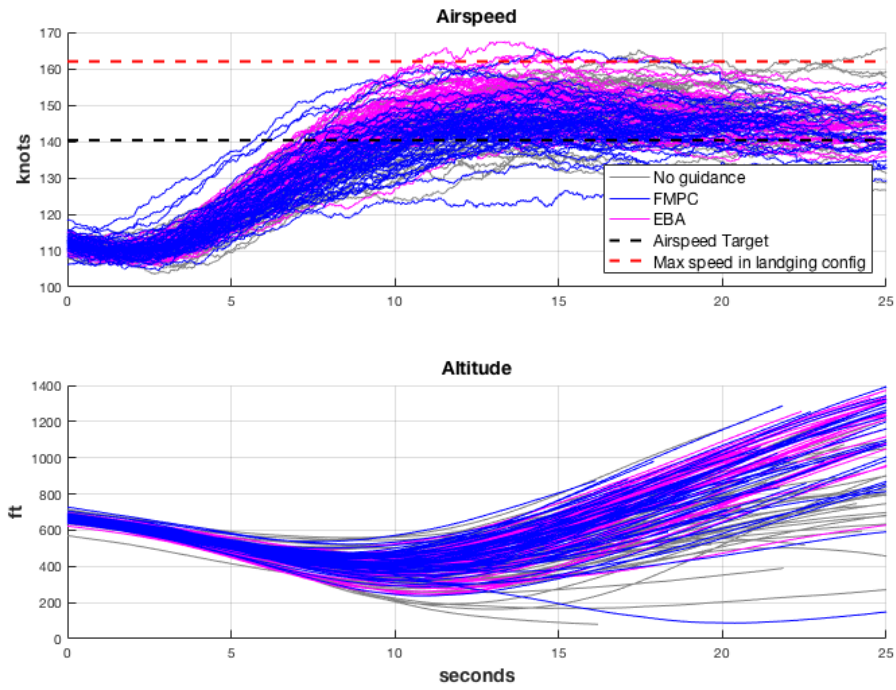
Figure 22. Approach scenario: airspeed and altitude recovery, for all runs ($n = 60$ for each of the three categories).
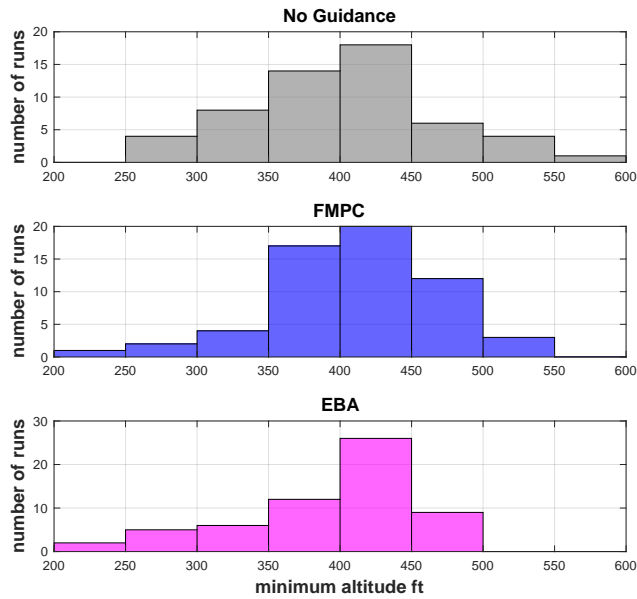
Figure 23. Approach scenario: minimum altitude of the recovery, for all runs ($n = 60$ for each of the three categories).

Even though the recovery profiles in angle-of-attack, airspeed, and altitude are mostly the same, a careful look at the airspeed recovery in Figure 22 reveals that the margin for overspeed is better with guidance. The extent of this trend can be observed in Figure 24, which shows a histogram of the maximum speeds obtained from each of the approach scenario recoveries. In total, the no guidance case had 5 runs where at least one overspeed occurred. The EBA had 4 such occurrences, while the FMPC algorithm had only 1. This result however, is not statistically strong enough to conclude that the FMPC algorithm performed better with respect to protecting against an overspeed condition with 95% confidence.

In addition, Figure 25 shows that while the participants flew similar pitch attitude recoveries, there was a notable difference in the pitch tracking performance between the FMPC and EBA algorithms. In particular, the EBA algorithm produced a sharper pitch down command in the first few seconds of the recovery, which the pilots tracked with increased error. It is also worth noting, that while the tracking error is generally greater for the EBA algorithm throughout the recovery, the actual pitch guidance after the first 5 seconds of the recovery is effectively the same as the FMPC pitch guidance. The "No guidance" traces shown in the top plot of Figure 25, show the actual pitch recoveries flown by the pilots without guidance.
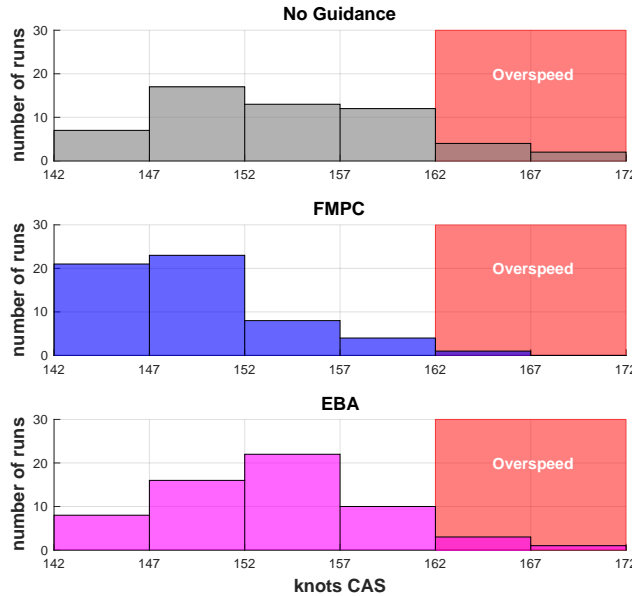
Figure 24. Approach scenario: histogram of maximum speed obtained from each run ($n = 60$ for each of the three categories).

7.2.3 Low Altitude Stall

The primary purpose of the low altitude stall recovery was to examine the effect of the guidance on a normal stall recovery scenario. Like the approach scenario, pilots are trained and expected to use the PLI to minimize their altitude loss during
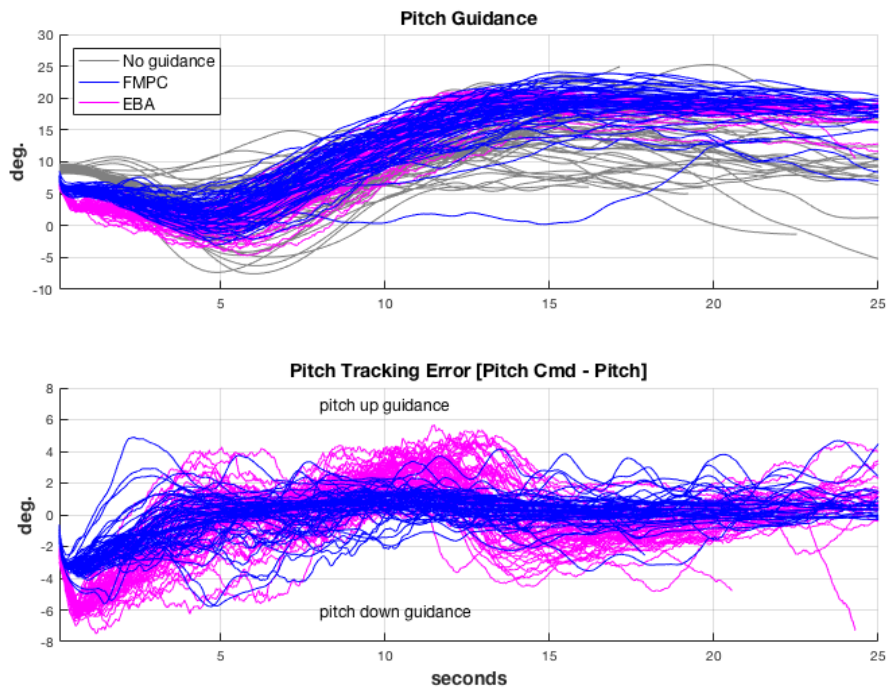
Figure 25. Approach scenario: pitch guidance tracking performance across all runs ($n = 60$ for each of the three categories). For recoveries flown without guidance, the actual pitch recovery is shown on the top plot.

the recovery, sometimes at the expense of hitting multiple stick-shaker warnings. Multiple stall warnings are acceptable as long as secondary aerodynamic stalls are avoided. Figure 26, shows the angle-of-attack recovery for the first attempt either with or without guidance. Other than producing mildly tighter recoveries in angle-of-attack, the guidance technologies did not have a significant impact on how the pilots recovered without guidance. This was the expected result, since, both technologies produced guidance that also recovered near the PLI. It is also an important result because it indicates the guidance system had no significant adverse affect on recoveries that pilots should be able to fly without guidance.

Figure 26 shows a few outlier cases, which all occurred on the first attempted recovery either with or without guidance.[29] In one extreme case, without guidance, a pilot exacerbated that stall by increasing the angle-of-attack to about 20 degrees, and was then slow to get the nose of the aircraft down, taking about 20 seconds to do so. In another case, a pilot flying with FMPC guidance, rejected a high pitch command late in the recovery, and then pulled the throttle back to level out. This pilot then flew a pitch attitude above the guidance command (which factored in the reduced throttle setting), ultimately causing the aircraft to stall again (around 40 seconds), and all this after having effected a good recovery up until that point.
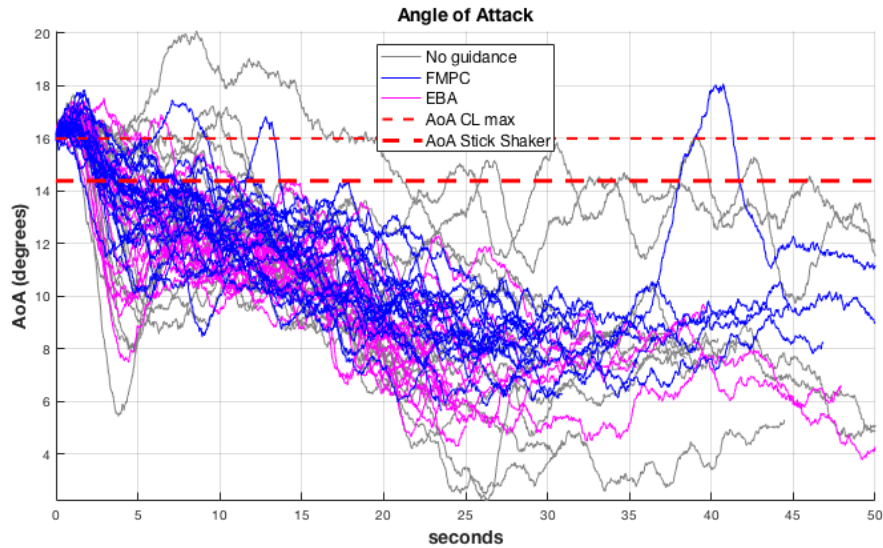
Figure 26. Low altitude scenario: all first attempt recoveries in angle-of-attack ($n \approx 20$ for each category, one or two first attempts were dropped due to run execution issues).

The load factors sustained throughout all recoveries in this scenario were well within limits, with the EBA algorithm producing slightly larger values this time. Figure 27 shows the number of stall warnings (stick-shaker alerts), and secondary stalls encountered with each guidance algorithm, and without guidance. Here the

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[29]While the outlier cases occurred during the first runs, the general trends observed were also true for all the runs in the low altitude scenario.

EBA guidance does a better job helping pilots avoid stall warnings, while both guidance algorithms reduced the number secondary aerodynamic stalls. This result is expected from the slightly more aggressive initial pitch down guidance provided by the EBA algorithm, which is observable in the first few seconds of the pitch guidance plot in Figure 28. This figure also shows that the guidance algorithms, and the FMPC algorithm in particular, produced greater pitch up commands during the later stage of the recovery. The reason for this was that pilots tended to fly below the pitch guidance during the pull-up phase of the recovery. The result was a tendency to recover above the target airspeed, which the guidance would compensate for with a higher pitch command. While this strategy helped to avoid overspeed in the approach scenario, in this scenario, some pilots opted to ignore the guidance towards the end of the recovery. They had good motivation for doing so, since by ignoring the guidance the pilots were able to increase their airspeed, and more importantly, maintain compliance with the current air traffic control altitude clearance (reasonably assumed to be the scenario starting altitude of 5000 ft). These effects are observable on speed and altitude recovery plots in Figure 29. Also, Figure 30 shows the minimum altitude achieved for all the recoveries in this scenario. The recoveries flown with guidance are more tightly controlled in altitude loss, with significantly more pilots able to recover above 4600 ft while flying with guidance.

7.2.4 Low Altitude Stall with Excessive Nose-Up Trim

The low altitude stall with excessive nose-up trim scenario was the most complex of the three scenarios. The setup for this scenario was exactly the same as for the low altitude scenario, except that excessive stab trim to -9 degrees (vs. -2 degrees for the low altitude scenario) was commanded while the aircraft decelerated towards stall. One initial consequence of the setup, was that the autopilot provided increasing pitch down elevator deflection to hold an approximately level flight path as the stabilizer was trimmed nose-up. This nose-down pitch input, however, was released when the system switched into manual recovery mode, and the result was an initial pitch up moment that increased the angle-of-attack significantly (usually to values in excess of 20 degrees). It typically took pilots between 1 and 3 seconds to arrest this increase. This initial dynamical behavior is shown in the first few seconds of Figure 31, which shows the angle-of-attack recovery for the first attempt either with or without guidance. A comparison with the corresponding figure for the low altitude scenario (Figure 26), reveals overall that the maximum angle-of-attack is 5–10 degrees greater, and the time to reduce the angle-of-attack below the stall warning threshold is 5–10 seconds longer than for the basic low altitude scenario. The load factors, however, for this scenario were all well within the structural limits for the aircraft.

Figure 31 also shows several outlier recoveries. In one case without guidance, it took the pilot just over 40 seconds to eliminate aerodynamic stall. In this case, the pilot added full throttle early on and flew well above the PLI without increasing airspeed, until he applied nose-down trim shortly before arresting the stall. A second outlier case without guidance was flown by another pilot on the same day. In this case, the pilot initially arrested the stall at around 25 seconds, but then got into

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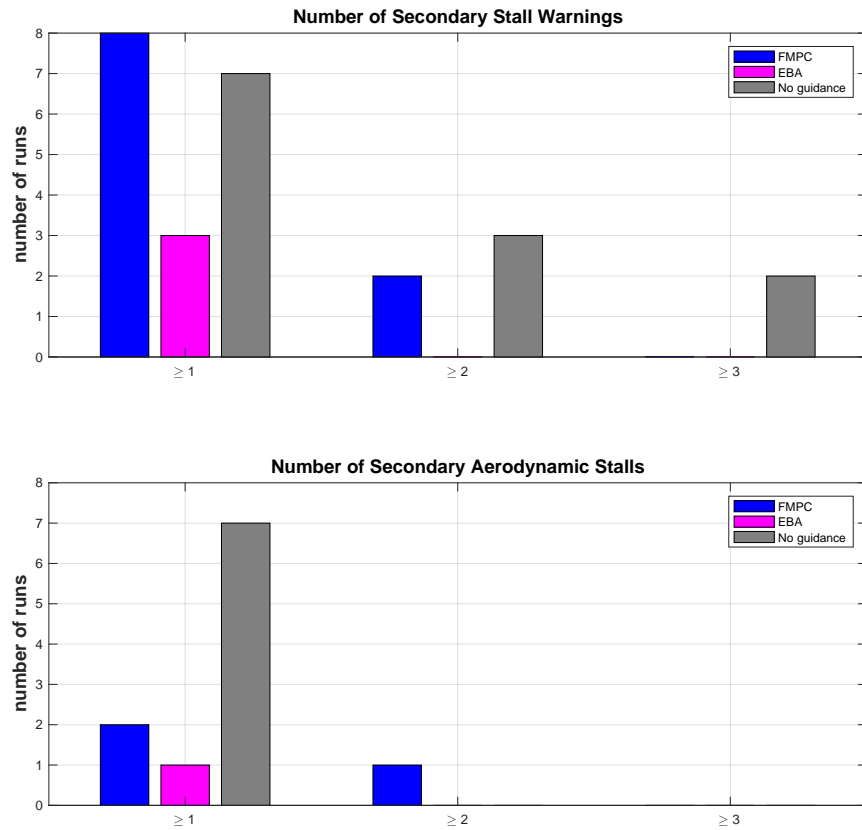
Figure 27. Low altitude scenario: number of stick-shaker alerts (stall warnings), and secondary aerodynamic stalls across all first recovery attempts ($n \approx 20$).
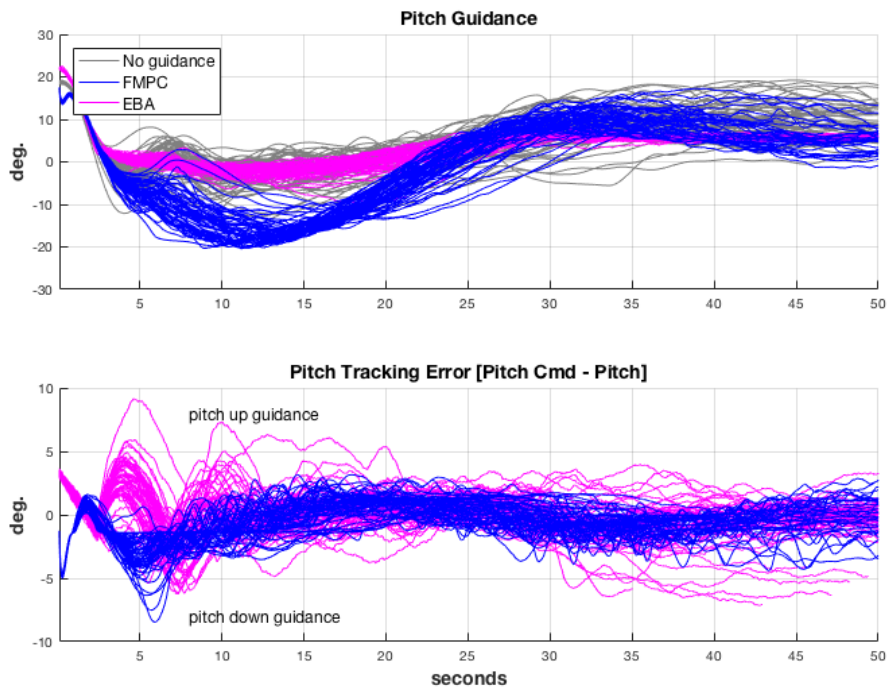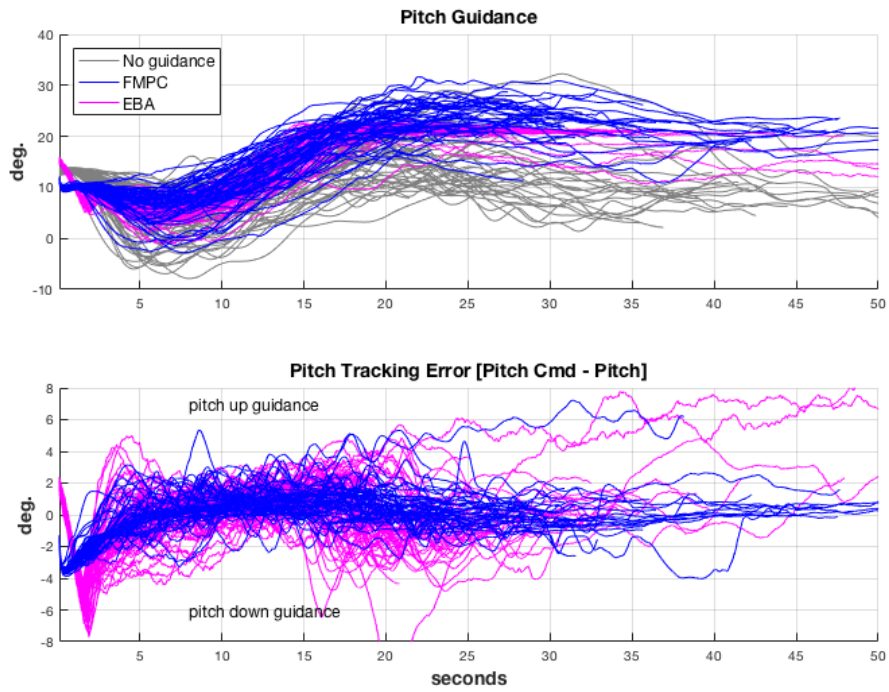
Figure 28. Low altitude scenario: pitch guidance tracking performance across all runs ($n = 60$ for each of the three categories). For recoveries flown without guidance, the actual pitch recovery is shown on the top plot.
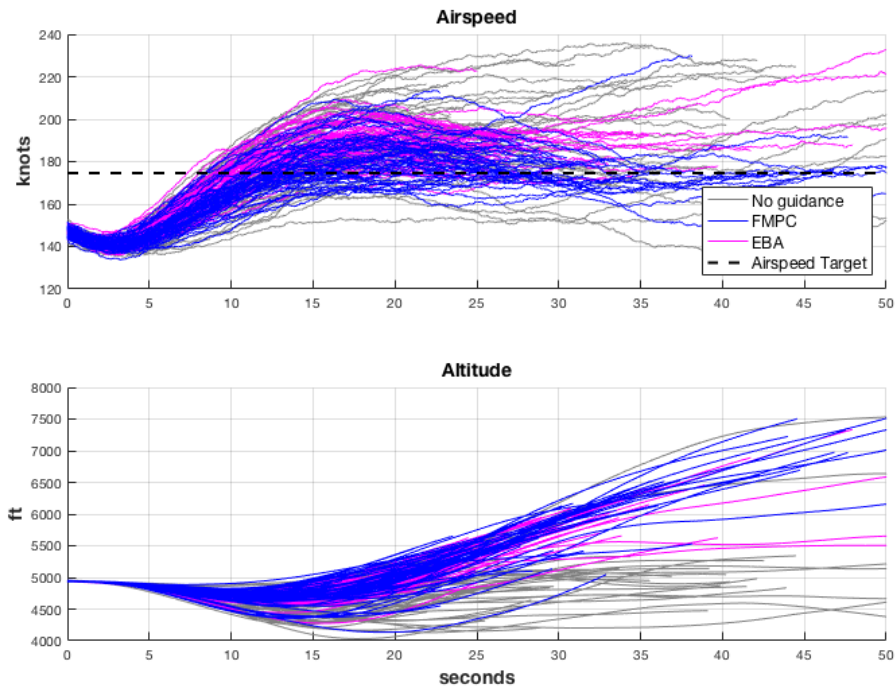
Figure 29. Low altitude scenario: airspeed and altitude recovery, for all runs ($n = 60$ for each of the three categories).
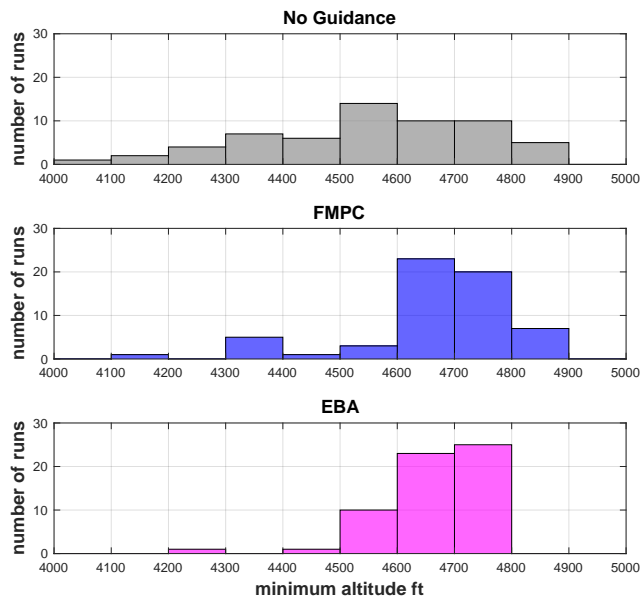
Figure 30. Low altitude scenario: minimum altitude of the recovery, for all runs ($n = 60$ for each of the three categories).
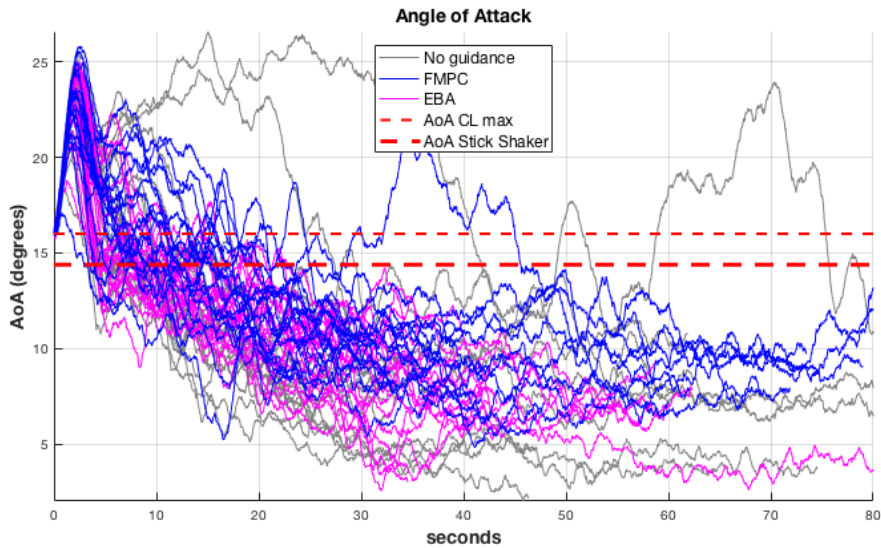
Figure 31. Low altitude stall with excessive nose-up trim scenario: first attempt recovery in angle-of-attack. ($n \approx 20$ for each category, one first attempt was dropped for the No guidance and FMPC cases do to run execution issues).

two sustained secondary aerodynamic stalls — one beginning at about 49 seconds, and the other beginning at 59 seconds. A closer look at the throttle input data (not shown), revealed the pilot initially increased the throttle to about 75%, then back down to 50% just before arresting the initial stall, then gradually back up to around 75%. He also gradually applied nose-down trim, but without significant effect until after 114 seconds into the recovery. Finally, there was also a pilot flying the FMPC algorithm, where a 15 second sustained secondary stall occurred starting around 32 seconds. While flying the run, the researcher monitoring gave the pilot a verbal cue to start trimming the aircraft just after this secondary stall occurred. After completing the run, the pilot noted difficulty seeing the PFD because it was obstructed by the simulator wheel and column (this was a common complaint among the participants), adjusted his seat position, and went on to fly normal recoveries for this scenario.

Figure 31 also shows that, in general, participants took longer to stabilize their angle-of-attack below the stick-shaker angle-of-attack, than they did for the basic low altitude recovery scenario. In addition, they often crossed the secondary stick-shaker and aerodynamic stall thresholds multiple times during each recovery. Figure 32 shows that this situation was somewhat exacerbated with the guidance technologies. In particular, 10 out of 19 participants flying without guidance on their first run for this scenario,[30] encountered more than one stick-shaker, but only 3 out of the 10 went on to develop full secondary stalls. When guidance was included, roughly the same number of stick-shaker warnings occurred, but nearly all them went on to become secondary stalls. The simple explanation may be that the addition of

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[30]One run out of the 20 was thrown out due to a simulator issue.
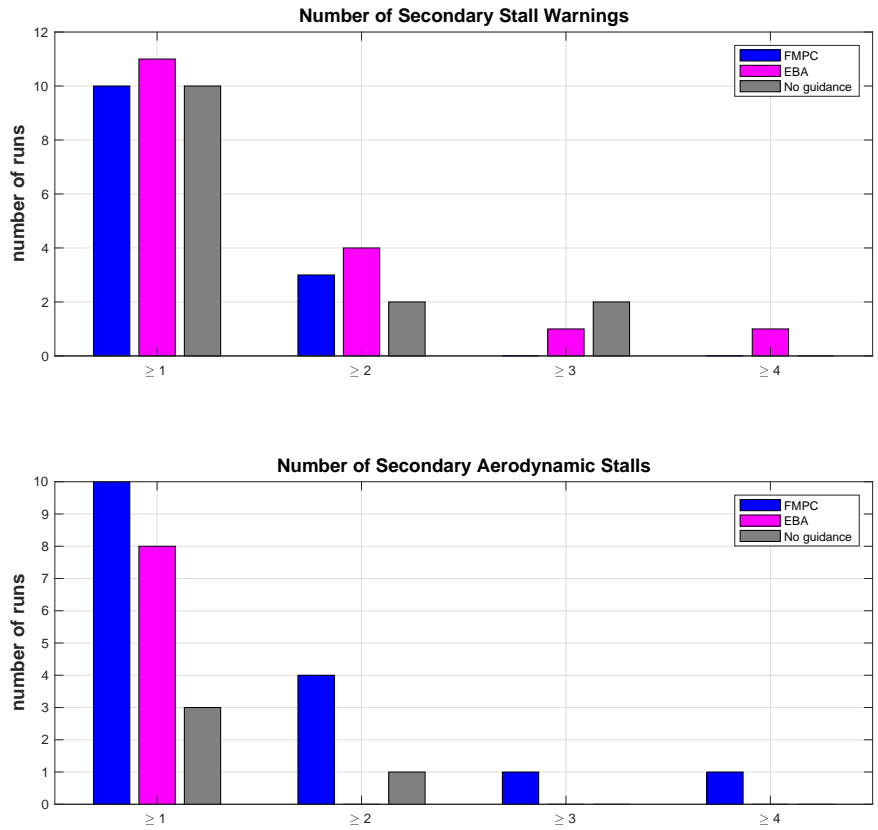
Figure 32. Low altitude stall with excessive nose-up trim scenario: number of stick-shaker alerts (stall warnings), and secondary aerodynamic stalls across all first recovery attempts ($n \approx 20$).

thrust guidance pulled the pilots attention away from the PLI (or pitch guidance if it was included in the run), and increased the likelihood of exceeding the PLI by a larger degree, and thus, more secondary aerodynamic stalls were observed. This is however, only one possible hypothesis supported by the data.

Figure 32 also shows that the EBA guidance was better at preventing more than one secondary aerodynamic stall. Figure 33 shows that this could be because the EBA algorithm was a little more aggressive in the initial pitch down recovery. The EBA guidance also presented more pitch error during the initial recovery that would have been more noticeable, and perhaps, viewed with an increased priority by the pilots.
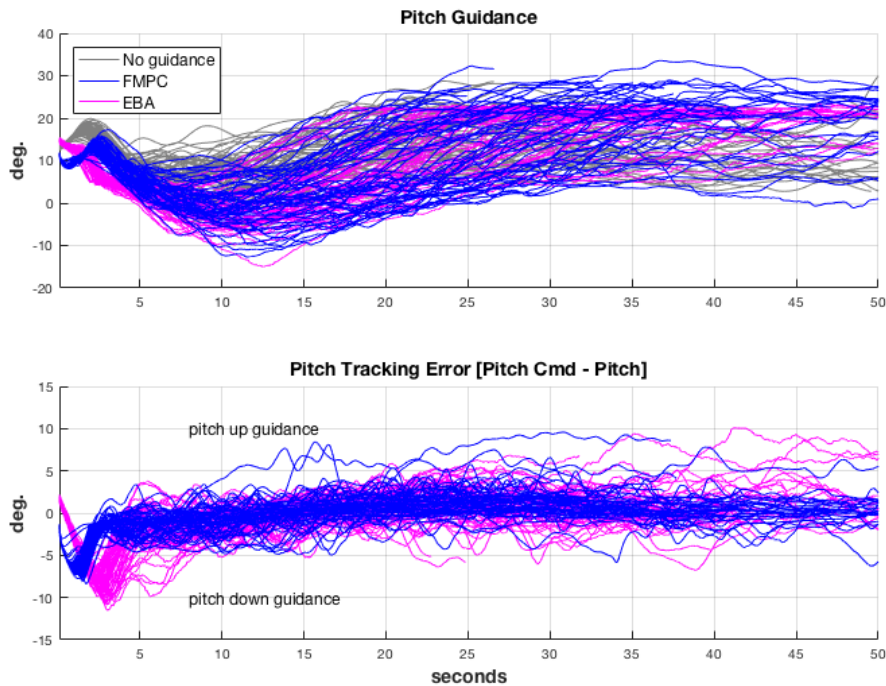
Figure 33. Low altitude with excessive nose-up pitch trim scenario: pitch guidance tracking performance across all runs ($n = 60$ for each of the three categories). For recoveries flown without guidance, the actual pitch recovery is shown on the top plot.

The primary objective of the excessive nose-up trim condition in this scenario, however, was to see if the addition of thrust guidance could reduce the risk of saturating the elevator control, and therefore, the risk of an uncontrollable pitch up tendency for aircraft with engines mounted below the wings. The thrust guidance system was the same for both pitch guidance algorithms, and it was designed to compute the maximum permissible thrust, at the current stab position, that would not saturate the pitch down control. For all of the other scenarios, the application of full thrust was desirable to minimize the altitude loss of the recovery. Since this was the only scenario where the guidance requested a reduction in throttle, sometimes

against the instinct of the pilot flying, the first question is simply whether the throttle guidance cue was effective with little training.[31]

Figure 34, shows that the thrust guidance was indeed very effective at getting the pilots to reduce the application of thrust while the aircraft was in an excessive nose-up trim condition. The histogram was compiled from the throttle position traces for all of the runs in this scenario, in a manner such that the height of each bar includes the amount of time spent at a particular thrust allocation (out of a maximum of the first 50 seconds of each recovery). Each bar, therefore, represents the percentage of the total recovery time spent with the throttle position falling into any particular bin. Overall, the figure shows that the participants flying with thrust guidance were 3.1 times more likely to keep their thrust at a safer level (below 50%) while in an excessive nose-up trim condition.
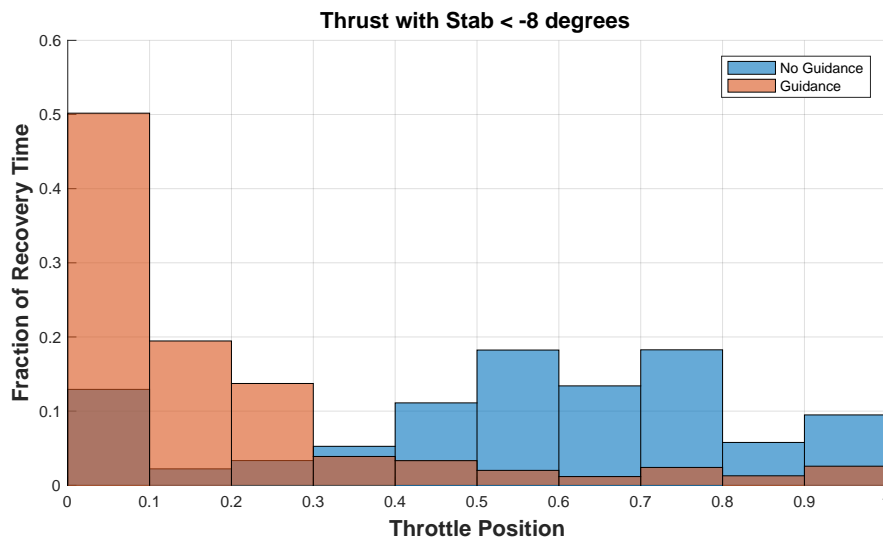
Figure 34. Low altitude with excessive nose-up pitch trim scenario: comparison of the applied thrust, both with and without guidance, when the stabilizer was in an excess nose-up trim condition (stab position < -8 degrees). The histogram was compiled from the time traces for all 120 runs with guidance, and all 60 runs where the recovery was flown without guidance first.

Figure 35 compares the corresponding histograms for the elevator positions obtained across all the runs, and in the same manner used for the thrust case just discussed. The elevator position was saturated, or within 2 degrees of saturation, at its 20 degree nose-down limit for only a small overall portion of the recovery time ($< 2\%$). Still, without guidance the participants spent 6.4 times longer with an elevator deflection greater than 17 degrees (within 3 degrees of saturation), than they did with guidance.

Finally, Figures 36 and 37 show the airspeed and altitude recoveries flown for

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[31]The throttle guidance was explained during the pilot briefing in about 5 minutes. During this time two brief videos were shown to demonstrate its operation, but no physical practice runs were conducted prior to data collection.
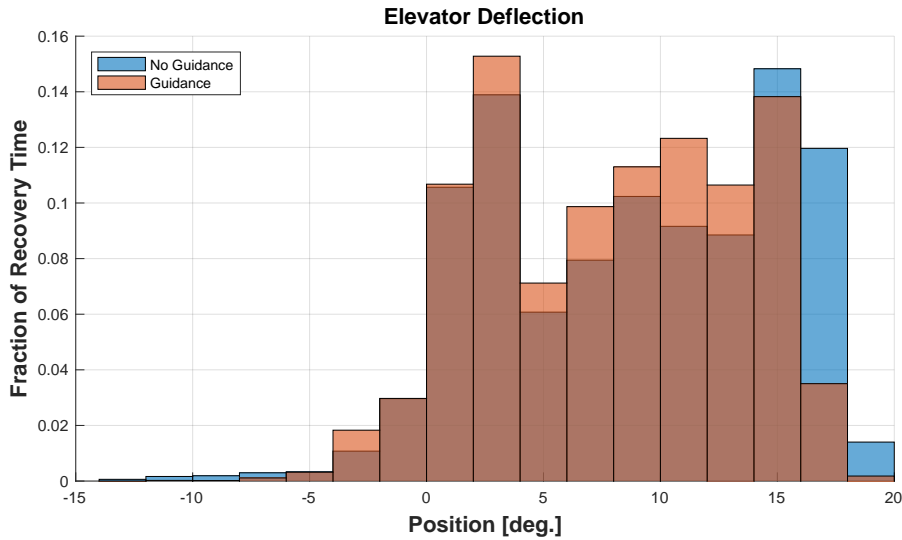
Figure 35. Low altitude with excessive nose-up pitch trim scenario: comparison of the elevator positions obtained, both with and without guidance. The histogram was compiled from the time traces for all 120 runs with guidance, and all 60 runs where the recovery was flown without guidance first.

all of the runs. As one would expect, the airspeed recoveries with guidance are a little tighter. However, we have just seen that the throttle guidance limited the amount of throttle the participants would have used without guidance. With less overall energy put into the system with guidance, one can expect greater altitude loss. This result shows up directly in Figure 37. One can contrast this with the corresponding Figure 30 from the low altitude scenario (without excessive trim), where the guidance actually helped the pilots put more energy into the system to improve the altitude performance.

In summary, the thrust guidance was effective at limiting thrust while in an excessive nose-up trim condition, and this improved the safety margins with respect to saturating the elevator controls. But these gains did not come without tradeoffs. The additional workload associated with following the thrust guidance may have increased the risk of secondary aerodynamic stall, due to less precise tracking of the PLI (or pitch guidance when provided). It also caused a greater loss in altitude, since the pilots spent a larger percentage of the recovery time at a limited thrust setting.

7.2.5 Learning Effects

The primary purpose of this study was to determine whether the candidate guidance system was a helpful piloting tool for stall recovery, and not whether the guidance system was an effective teaching tool. In particular, the participants in this study were briefed to assess the guidance technology with respect to this primary purpose as users, and to a fair degree, as subject matter experts. We expect that a study to
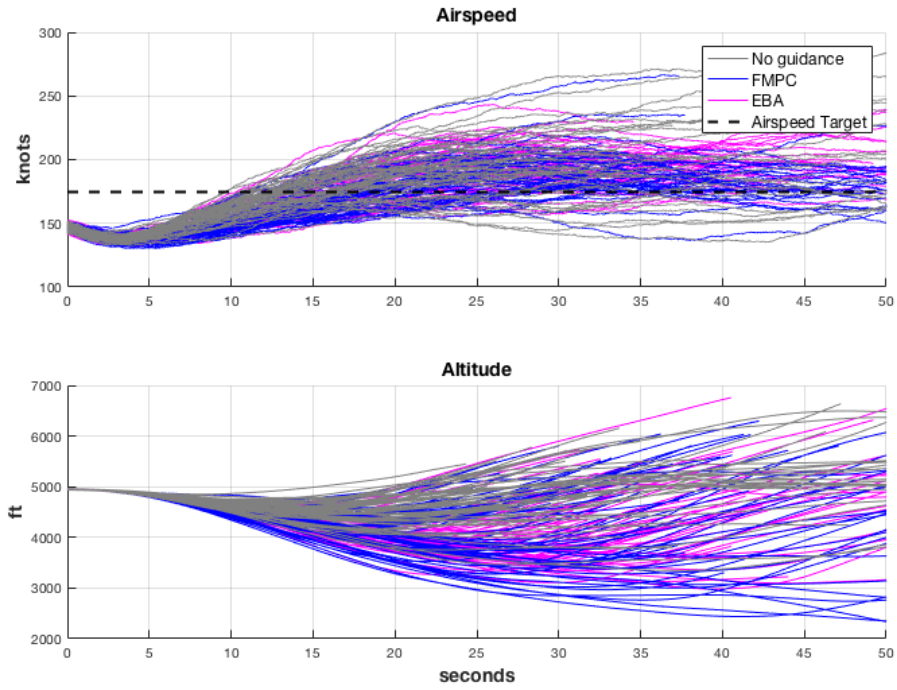
Figure 36. Low altitude with excessive nose-up pitch trim scenario: airspeed and altitude recovery, for all runs ($n = 60$ for each of the three categories).
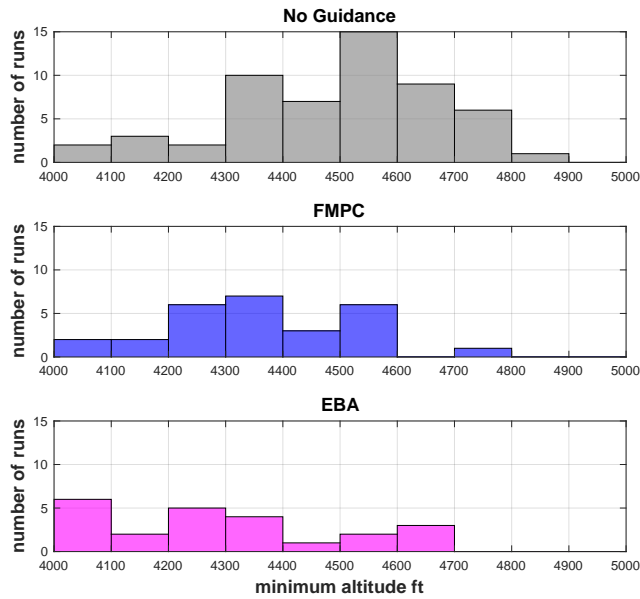
Figure 37. Low altitude with excessive nose-up pitch trim scenario: minimum altitude of the recovery, for all runs ($n = 60$ for each of the three categories).

assess the guidance technology as a pilot training aid would be designed differently. Still, it remains a curiosity to assess whether the participants learned anything from the guidance system with the study designed as it was.
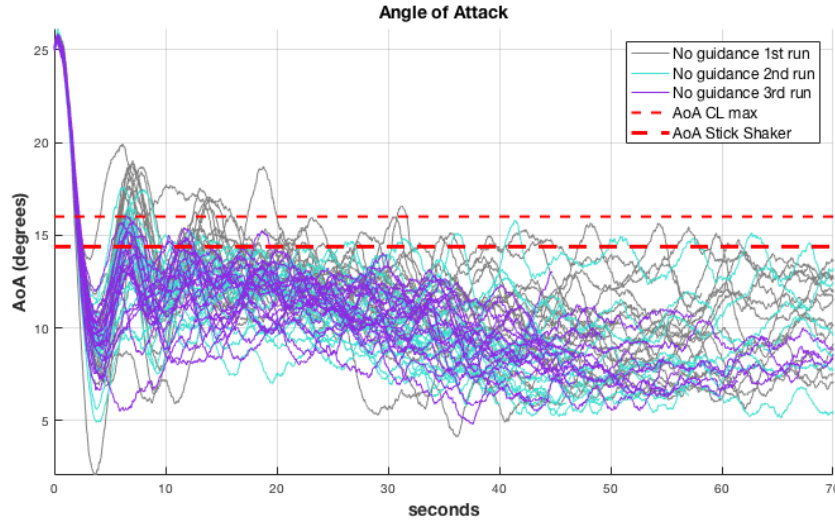
Figure 38. Learning across runs *without* recovery guidance, and before flying with guidance, in the high altitude stall scenario ($n = 20$ for each of the three categories).

The most significant finding of the study was with respect to the high altitude stall recovery, where we saw that aggressive pitch down guidance had a positive effect on reducing the number of secondary aerodynamic stalls in the recoveries flown by the participants. Figure 38 shows that the participants were able, as a group, to improve their performance across multiple runs without any guidance, and by the third attempt, to eliminate all occurrences of secondary aerodynamic stall. However, even after three attempts without guidance, there were still more secondary stall warnings, and there was significantly less margin to the full stall angle of attack during the recovery (compare Figure 16) than there was when the guidance system was on.

The other salient learning consideration, is of course whether the pilots flying recoveries *after* having flown 3 recoveries with guidance, improved their performance at recoveries without guidance in the high altitude stall scenario. The data reveals the trend shown in Figure 39. The purple traces in the plot show the third (most practiced) run without guidance, before having flown with FMPC guidance (these are in correspondence with half of the purple runs shown in the previous Figure 38). The blue traces show the most practiced run with the FMPC guidance. The orange traces show the first run without guidance, just after having flown three FMPC guidance runs. The plot shows, that some learning occurred after flying with the guidance, since the orange runs loosely split the difference between the practiced recoveries with and without guidance. Also, in all three of the cases shown, there were no secondary aerodynamic stall occurrences. However, when flying with guidance, there were no secondary stall warnings, and there was more margin in

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angle-of-attack.

The results from the previous two paragraphs show that the guidance still provided a benefit, even after pilots had practiced three runs without guidance. Furthermore, this supports the conclusion that an instructor and/or guidance system may be necessary to improve the robustness of piloted stall recoveries at high altitude, an important aspect, considering unlucky pilots do not get multiple stall recovery attempts.
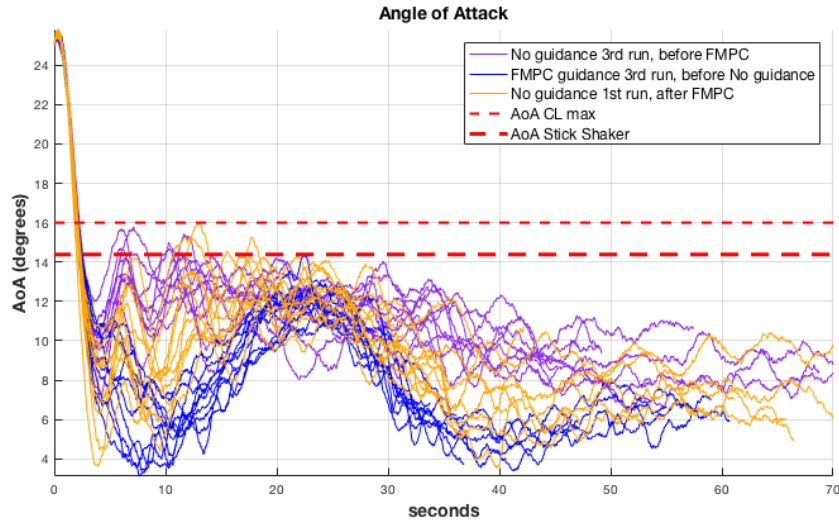
Figure 39. Learning before and after having flown with guidance in the high altitude stall scenario ($n = 10$ for each of the three categories).

The low altitude scenario with excessive nose-up trim, was the other non-standard recovery where learning may have occurred. Here, the thrust guidance strategy in particular, was intended to help pilots limit their initial thrust input in an excessive nose-up trim condition. Figure 40 shows that this was indeed the case. The plot reveals that the pilots (as a group) put more thrust into the system with excessive nose-up trim on their third, most practiced, recovery before seeing the guidance strategy. This result does not necessarily demonstrate any inappropriate or unsafe use of thrust (with or without guidance). It does, however, display a trend towards confirming the hypothesis that the pilots internalized the guidance strategy and applied a more cautious use of thrust on their first run without guidance, after having flown 3 runs with the thrust guidance system.

7.3   Survey Results

The experiment protocol required each participant to complete 10 surveys: one before starting the simulation, one after completing each set of 3 runs for a particular scenario (either with or without guidance for a total of 8 surveys), and one after completing all the runs. The full surveys are reproduced in appendix D. The key results from these surveys are collected in this section.
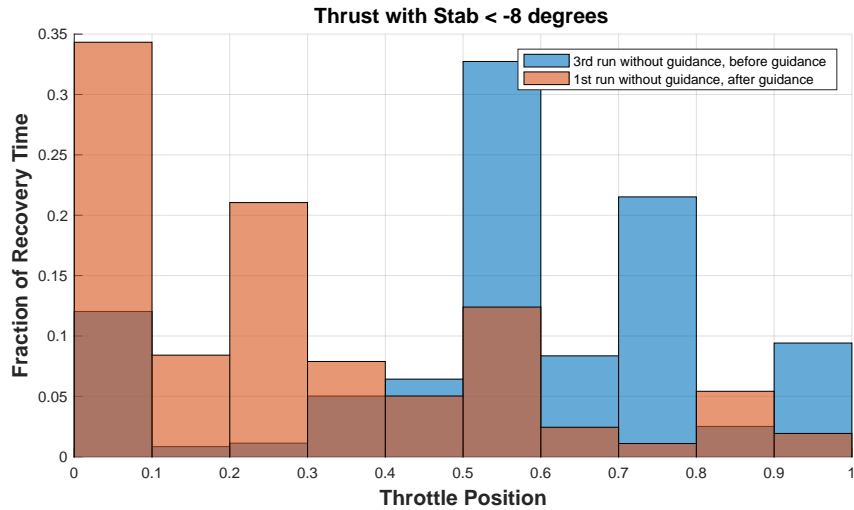
Figure 40. Learning before and after having flown with guidance in the low altitude excessive nose-up trim scenario. The histogram was compiled from the time traces for 20 runs in each of the two categories.

7.3.1 System Usability Scores

The standard System Usability Scale (SUS) was designed in 1996 to be a quick and easy survey for a *global* assessment of a given system's usability [57]. In a SUS survey participants are asked 5 positively charged, and 5 negatively charged questions, after performing an initial evaluation of a given product or service. A composite score on a scale of 0–100 is then produced from the 10 question responses, with higher scores indicating better usability. After completing all the simulation runs, each participant was asked to complete a post-simulation questionnaire that included a modified System Usability Scale survey. The survey was modified slightly to make some of the questions more relevant for the evaluation of a stall recovery system, which is typical in the use of SUS surveys for different applications [58, §2.1]. The specific questions used in our SUS survey are listed on page 109 in Appendix D.3. In 2008, Bangor et. al. analyzed 2,324 SUS surveys from 206 different studies, spanning multiple user interfaces (e.g., cellular phone, graphical, and web based), and found a median score of 69.69 with a standard deviation of 11.87 [58].

Of the 40 pilots who participated in our study, two did not complete the SUS survey (inadvertently, we think). Figure 41 shows the histogram of the composite SUS rating for the remaining 38 participants. One pilot in the pool gave an outlier rating of 42, which indicates an indifference with respect to the usability of the system. In his written feedback, he indicated that the roll and throttle guidance strategies caused confusion, and may require additional pilot training to improve acceptance. Still, the mean usability rating was 81.8 (including the outlier case), which is comparable to the A rating assessment given to other aircraft situation awareness systems studied in [59]. With the given sample size, no significant difference was detected between the SUS scores across the two guidance algorithms

studied in the experiment.
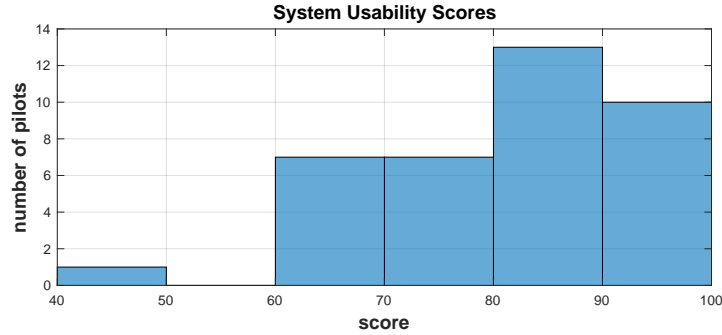
Figure 41. Histogram of the overall System Usability Scores.

7.3.2 Cooper-Harper Ratings

The Cooper-Harper rating scale, shown in Figure 42, is a standard set of subjective criteria for evaluating aircraft handling qualities, primarily for use by trained test pilots and flight test engineers [60, 61]. Each of the 10 research pilots who participated in the study were asked to provide a Cooper-Harper rating on the post run survey. This survey was completed after flying each set of 3 runs for a particular scenario. When flying a run without guidance, the pilots provided their rating based on the task workload, and corresponding aircraft handling quality for the scenario at hand. When the guidance was on, the tracking performance standards were used as the basis for the rating. The scenario specific tracking standards were listed in Section 4.

The pilots were also asked to rate the thrust and pitch guidance systems separately because these systems were developed to meet separate objectives.[32] The fact that the thrust guidance cue was completely new, while the pitch guidance cue was already part of the standard flight director system, was also a factor in the decision to use separate ratings for the pitch and thrust guidance systems.

The overall Cooper-Harper ratings for all the scenarios and guidance algorithms are presented in Figure 43. The bulk of the ratings occur between 2 and 5, indicating a representative result that splits the system performance between the best "satisfactory without improvement" rating category, and the next "deficiencies warrant improvement" rating category. Overall, this result aligned well with the positive subjective feedback provided by most of the participants, along with the constructive suggestions for improving minor aspects of the system (see Section 8) — with opinions split between whether making those improvements should be required before putting the system into operational practice.

The overall ratings, however, blend together the individual ratings for each of the stall recovery scenarios. Since each scenario focused on testing different aspects

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[32]The thrust guidance technology objective was to minimize altitude loss without exceeding the elevator authority to pitch down. The pitch guidance objective was to recover a target aircraft state without exceeding load factors or angle-of-attack limitations (assuming the current thrust setting).
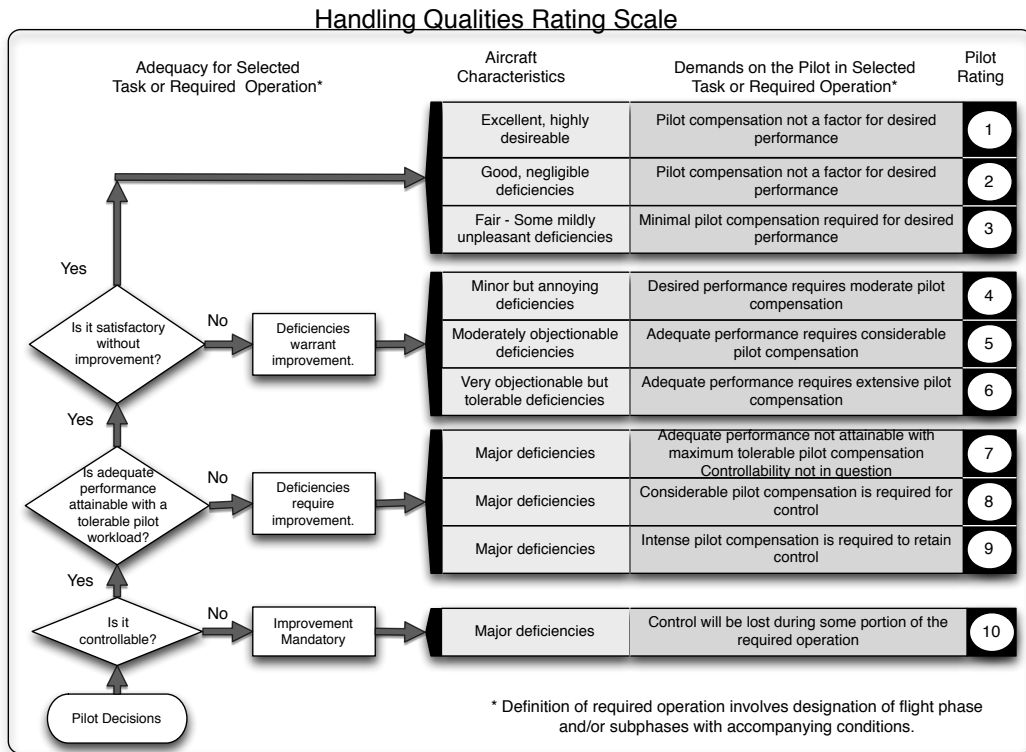
Figure 42. Cooper-Harper rating scale.
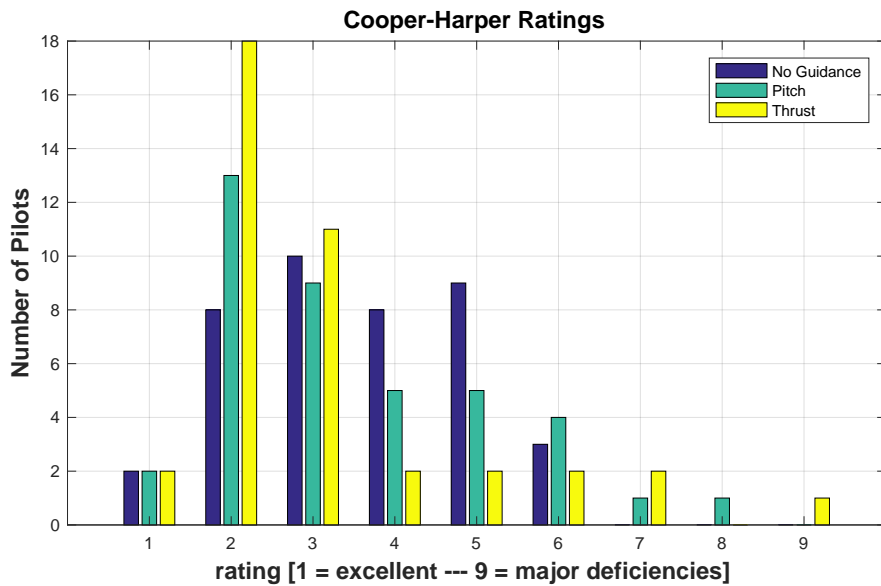
Figure 43. Overall Cooper-Harper ratings across all guidance algorithms and recovery scenarios. Non-integer ratings were rounded to the nearest integer, and $n = 40$ for each of the three categories (no guidance, pitch, and thrust).
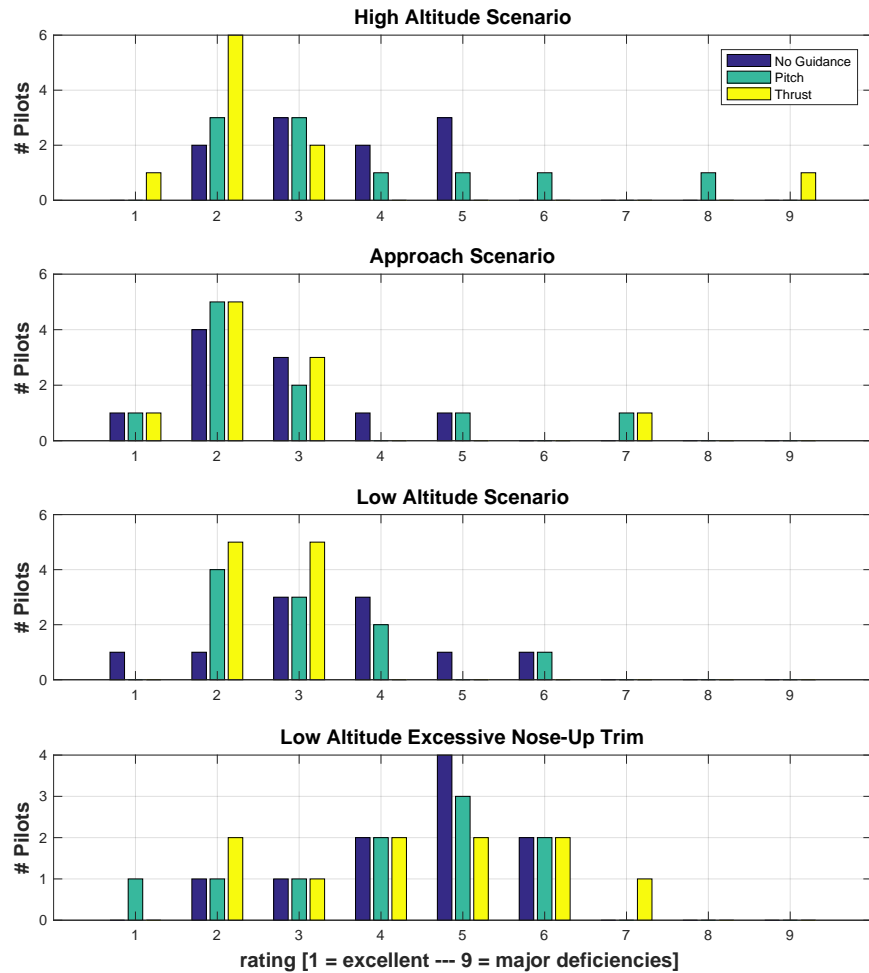
Figure 44. Scenario specific Cooper-Harper ratings across all guidance algorithms. Non-integer ratings were rounded to the nearest integer, and $n = 10$ for each of the three categories (no guidance, pitch, and thrust).

of the recovery guidance system, the scenario specific ratings shown in Figure 44 are important. The findings for each scenario are summarized below:[33]

High Altitude Scenario: Nine out of ten pilots agreed that the thrust guidance system rated "satisfactory without improvement," mainly because the scenario simply required full thrust. The one worst outlier rating of 9 was given without further comment. Six out of ten pilots rated the pitch guidance system the same way. The two worst pitch guidance ratings came from pilots flying the EBA algorithm who felt the "pitch guidance exacerbates PIO [Pilot Induced Oscillation] tendency," and was "difficult to track in the initial part of the recovery without overshooting into a secondary stall." The other poorer ratings were provided by pilots who didn't quite meet the tracking performance criteria, but felt the deficiency was negligible and dependent on familiarity with the aircraft response.

Approach Scenario: A strong majority of the pilots (9 out of 10 and 8 out of 10 pilots) rated the thrust and pitch guidance systems as "satisfactory without improvement." The poorest throttle guidance rating came from a pilot that stated difficulty following the pitch guidance at full thrust in the later half of the recovery (but the initial pitch guidance was good). The poorest pitch guidance system score came from a pilot who felt the EBA algorithm produced a fast pitch reversal at one point during the recovery.

Low Altitude Scenario: This baseline scenario produced another strong majority of ratings in the "satisfactory without improvement" category for both the pitch and thrust guidance systems. The poorest pitch guidance score came from a pilot who felt he had a "tendency to over control during the later stages of the recovery."

Low Altitude with Excessive Nose-Up Trim Scenario: This high-workload scenario easily produced the most variation in the ratings provided by the pilots, the majority of which fell into the "Deficiencies Warrant Improvement" category. The pilot who provided the poorest thrust guidance rating commented that scale information would have been nice to have (e.g., an indicator for the range from idle to maximum available thrust) — and he was not the only participant to make this comment even though the thrust guidance was always the relative error between the throttle position and where it needed to be (as opposed to the absolute error). Another issue that presented itself, was that the combined pitch and throttle guidance competed for pilot attention, and in some cases pilots were burdened by pressure to maintain fine tracking of the throttle guidance (even though that was a consideration in the determination of the tracking metrics, and the design of the display). Furthermore, we expected pilots would apply nose-down trim as a natural reaction to forward column pressure. There was, however, a spectrum of comfort level with forward column pressure and an associated dispersion in the application of nose-down trim. Several pilots commented that it was not obvious when to apply nose-down trim, and that an indicator to this effect would be beneficial.

Finally, Figure 45 shows the ratings break down between the FMPC and EBA pitch guidance technologies. In general, the FMPC algorithm received higher, and

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[33]The same research pilot provided at least one of the poorer ratings in each of the scenarios, along with excellent constructive feedback.

more tightly grouped ratings — perhaps with the exception of the excessive nose-up trim scenario where both algorithms were rated about the same. The pitch guidance ratings were tied to tracking performance metrics, and they are supported by the generally observed tighter tracking errors for the FMPC algorithm observed in the numerical data, see Figures 20, 25, 28, and 33.
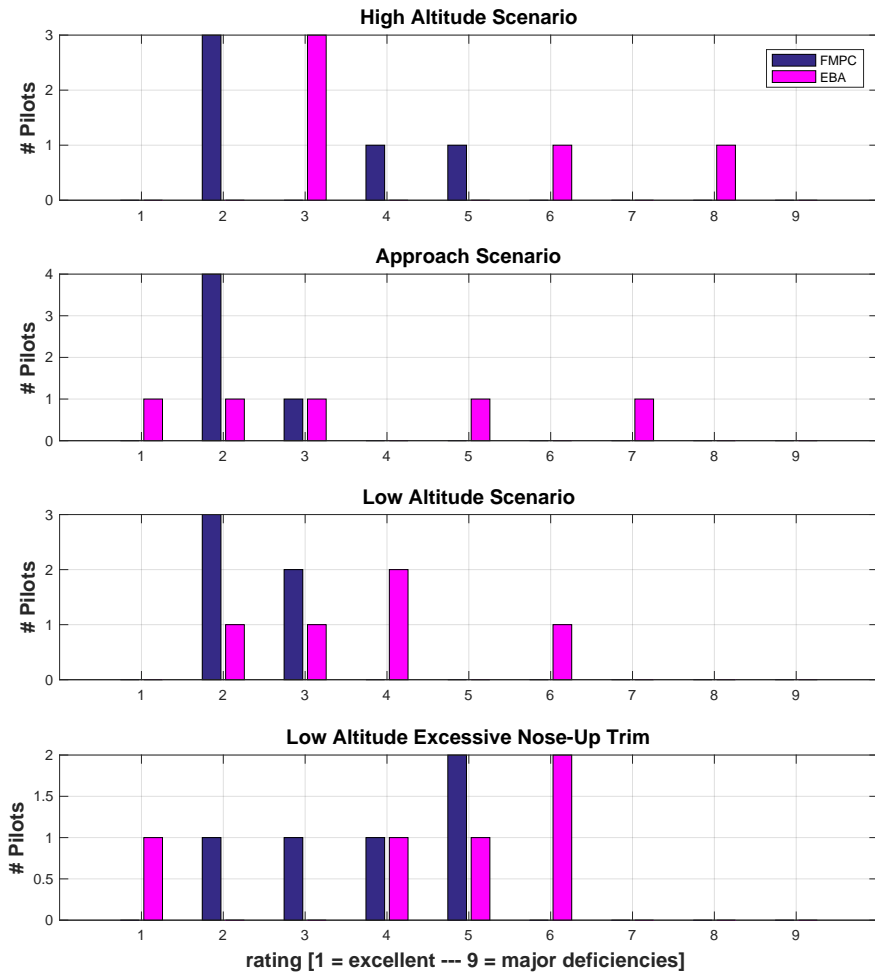
Figure 45. Cooper-Harper ratings breakout by scenario, for the EBA and FMPC pitch guidance technologies. Non-integer ratings were rounded to the nearest integer, $n = 5$ for each algorithm in each scenario.

7.3.3 Counter-Intuitive Aspects

After completing all 24 stall recovery runs, pilots were asked in the post simulation survey whether they found any aspect of the guidance counter-intuitive, or in

contradiction with their flight line training. A few more than half of them said yes (22/40), but for a wide variety of reasons that exposed both areas for improvement, and beneficial aspects of the system. For example, several pilots remarked that it was counter-intuitive to pull power back on the recoveries where excess nose-up trim was involved, or that the guidance commanded more pitch down in the high altitude scenario than expected. These counter-intuitive aspects improved the stall recovery performance, and this re-enforces the usefulness of the guidance. Several other pilots commented on the nature of the high pitch angle commanded during the pull-up phase of some recoveries, or that the roll director had too much gain and a surprise tendency to level the wings only after pitching the nose of the aircraft below the PLI. These are aspects that can certainly be improved. Another important comment was that pilots are currently trained to ignore the flight director when recovering from stall, so in some sense it was counter-intuitive to follow it in this experiment. Finally, bear in mind, that just under half of the participants (18/40) did not feel the guidance was counter-intuitive, or in contradiction with their training.

7.3.4 Learning from the Recovery Guidance

The post simulation survey also asked the participants whether they learned something from the stall recovery guidance that should be applied to stall recoveries *without* recovery guidance. Their response was requested on a continuous scale ranging from 'Disagree' to 'Indifferent' to 'Agree,' which was mapped to a numerical score from zero to one, with one representing full agreement. The histogram of the responses from all 40 participants is shown in Figure 46. The pilots who tended to disagree, noted that they felt adequately trained to fly the recoveries, or that the PLI was an adequate tool. However, most of the pilots felt they had learned something. For the excessive nose-up trim scenario, several noted that they became more considerate of using less throttle input until the nose trim was corrected. Many pilots learned from the high altitude scenario, commenting that it got them to be more aggressive in the initial pitch down maneuver. The quantitative data shown in Section 7.2.5 supports the pilot comments for these two scenarios. Interestingly, there were no specific written comments made with regard to the approach and basic low altitude scenarios, perhaps because these are considered more standard training cases.

7.3.5 Workload and Usefulness

For each scenario, participants flew 3 stall recoveries both with and without guidance. After flying each set of 3 recoveries, a post-run survey was completed that asked for the mental demand and time pressure required to complete the recovery on a scale from zero to one, where, 0, 0.5, and 1, represented low, average, and high workload, respectively. For this experiment, the time pressure rating was very closely correlated to the mental demand rating, so only the mental demand rating is discussed here.

Figure 47 compares the mean workload rating across the pool of 40 pilots for each of the recovery scenarios, flown with and without guidance. In three of the
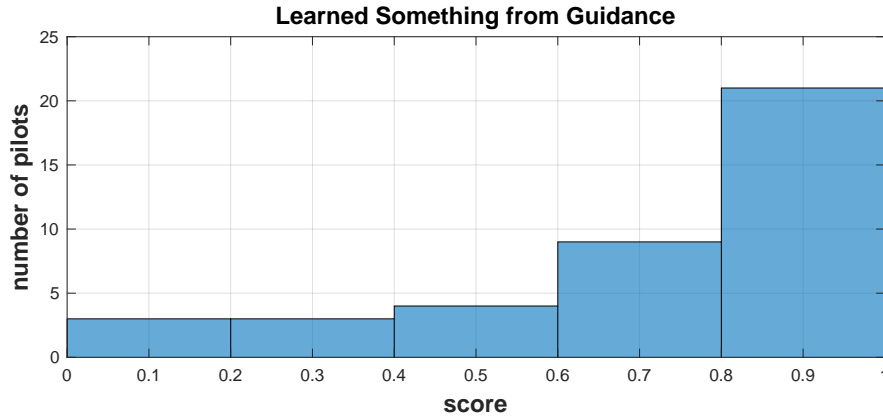
Figure 46. Histogram of response to whether something was learned from the stall recovery guidance.

four scenarios, the guidance diminished the workload. Several pilots noted one possible reason for the diminished workload was that the guidance focused their attention to the center of the PFD. This is in contrast to recoveries flown without guidance, which required splitting ones attention across the PFD to monitor the airspeed and vertical speed during the recovery. For the low altitude scenario with excessive nose-up trim, the guidance increased the average workload rating. Some of the participants noted that the addition of having to manage trim while also processing the thrust guidance cue (on top of the pitch and roll cues) contributed to the increased difficulty in this scenario. Overall, though, the workload assessment for each scenario was not significantly changed through the addition of the guidance. This finding is significant, given the participants also found the guidance system useful.
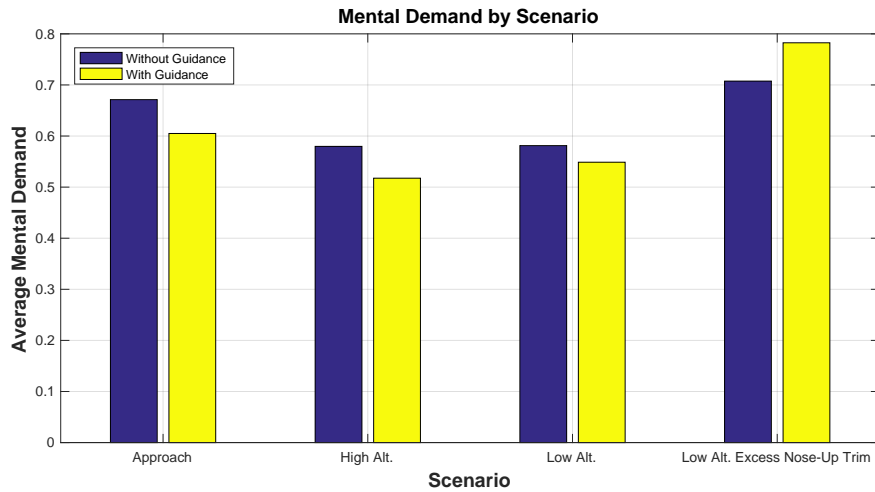
Figure 47. Average mental demand by scenario, with and without guidance.

Participants were also asked to rate the usefulness of the guidance, after flying 3 recovery runs with guidance for each scenario. The rating was provided on a continuous scale from 'Unnecessary' to 'Highly Useful,' which was converted to a percentage usefulness score from 0–100% useful. Each pilot rated the pitch, roll, and throttle guidance sub-systems, in addition to the overall guidance system. The usefulness breakdown across the pool of 40 pilots is shown by scenario in Figure 48. A strong majority of pilots rated the system at least 'Somewhat Useful' (50%), with more than half of the ratings towards the 'Highly Useful' category. Lower usefulness ratings for thrust and roll guidance, were often provided by pilots who observed that the associated indicators were not necessary to complete the recovery task. For example, the high altitude and approach scenarios did not involve roll at the stall onset (which was somewhat unrealistic), and the throttle guidance always indicated full thrust. Other lower ratings occurred when a participant found the recovery guidance strategy counter-intuitive. For example, in the low altitude scenario, the roll guidance would snap to level the wings only after the pitch attitude was reduced below the PLI (and that was not a universally liked strategy). The lowest rating for the pitch guidance came from a pilot who felt the EBA pitch guidance tended to promote pilot induced oscillation, and a tendency for secondary stall. Overall though, the system received significant positive feedback. For example, one pilot thought the "pitch guidance will be very helpful [to optimize the] recovery," and another felt the system "works well to get us climbing at [reference] speed."

8   Findings and Lessons Learned

In summary, a stall recovery guidance system was tested across 4 scenarios on 30 commercial pilots, and 10 research test pilots. In all cases the same split-cue flight director was used to display pitch and roll guidance, while a new thrust director was developed to provide thrust guidance. Two alternate intelligent algorithms were tested for generating pitch recovery guidance from flight dynamics principles. As such, each algorithm was tuned only once, before the experiment started, and it was able to compute the guidance for all altitude and aircraft configurations. A thrust guidance algorithm was developed to help prevent uncontrollable combinations of thrust and excessive nose-up pitch stabilizer trim. A simple roll guidance algorithm was also developed to level the aircraft wings only after arresting the aerodynamic stall and the aircraft stall warning system — but roll guidance was not a focus of this effort. The combined pitch, roll, and thrust guidance recovery system was designed to be as simple and intuitive to use as possible, since operational use would likely occur under excessive workload demands and adverse piloting conditions from external sources. The system was also designed specifically to conform with the FAA stall recovery template, for general large commercial transport class aircraft with *engines mounted below the wings.* Below we itemize the specific findings and lessons learned for each of the component subsystems for pitch, thrust, and roll guidance.
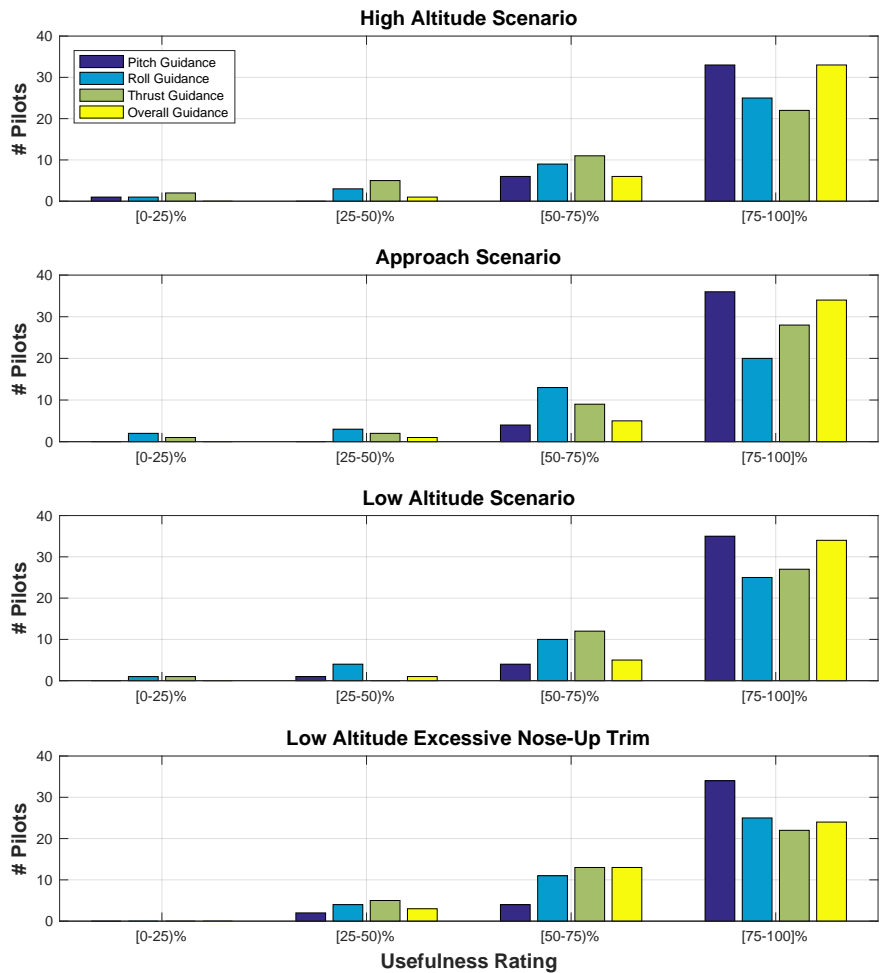
Figure 48. Guidance usefulness rating by scenario.

8.1 Pitch Guidance

Overall the pitch guidance system was quantitatively effective at improving the safety of the recovery, and qualitatively well liked by the pilots. In the high altitude stall scenario, the FMPC pitch guidance algorithm generated aggressive pitch down commands that significantly reduced the likelihood of secondary aerodynamic stall with very little training on the guidance system. The FMPC algorithm also received better Cooper-Harper ratings, and produced a little less tracking error across all of the scenarios than the EBA algorithm. Both algorithms, however, had comparable performance in all of the remaining scenarios. In the approach and low altitude scenarios, the pitch guidance often exceeded 20 degrees nose-up, especially if pilots lagged the guidance in the pull-up phase of the recovery (which was typical). Many pilots commented that this aspect of the guidance felt excessive. For the approach scenario, however, several pilots exceeded the maximum flap airspeed during the pull-up phase of the recovery at full thrust when flying without guidance. The slightly more aggressive pitch up produced by the FMPC system seemed to help pilots prevent the overspeed condition (but this result is not statistically significant).

8.2 Thrust Guidance

In the scenarios without excessive nose-up pitch, the thrust guidance immediately commanded full thrust at the onset of the recovery, somewhat in contradiction with the FAA stall recovery template. The contradiction, however, was intentional, because, the guidance system can compute when maximum thrust will not create an uncontrollable pitch-up moment, while pilots, on the other hand, can not perform this calculation nearly as fast. Earlier application of thrust reduces the altitude loss required by the recovery, and in the low altitude scenario pilots flying with guidance were more consistent in their ability to recovery without losing excessive altitude. In the approach scenario, however, there was less variability in altitude loss because pilots likely felt they did not have time to be more cautious with the application of thrust, and therefore, more consistently applied full thrust at the onset of the maneuver. Overall, many pilots liked the throttle guidance system, rating it relatively more useful in some cases than the pitch guidance.

The most interesting case for the thrust guidance was the low altitude stall with excessive nose-up pitch trim scenario. This was the one scenario where the guidance commanded idle thrust at the onset of the maneuver. The guidance was effective at getting pilots to fight their instinct to push excessive thrust in combination with excessive stabilizer trim. As a result they maintained more elevator margin to saturation with guidance, though no pilot in the study experienced a sustained elevator saturation with an uncontrollable pitch up moment. A consequence of the additional thrust guidance element however, was an increase in the number of secondary aerodynamic stalls over the case without guidance. The guidance also increased the amount of time it took some pilots to recover, because it was not always immediately obvious that the pitch trim state was connected to the throttle guidance — even though this aspect was briefed at the beginning of the study. The Cooper-Harper ratings were significantly more scattered for the thrust guidance

system in this scenario, showing wide disagreement among the research pilots that participated in the study. A common suggestion for improvement was to include a mis-trim cue, and possibly an aural alert to better connect the thrust guidance cue with the mis-trimmed stabilizer. In addition, the quantitative results suggest that more aggressive pitch down guidance may be needed to help pilots prevent secondary aerodynamic stalls while also processing the thrust guidance information. More work is required to refine the thrust guidance system in these respects.

8.3 Roll Guidance

The roll guidance system was not a focal point for this study, but the underlying strategy used to implement it was important. At the onset of the recovery, the guidance commanded the roll angle at stall entry until the aircraft pitch angle was reduced to below the PLI. When the pitch was reduced below the PLI, a roll to level the aircraft wings was commanded. This approach was meant to reinforce the FAA stall recovery template. Many pilots, however, commented that it was more natural to fly the pitch and roll axes simultaneously, and that the employed strategy was counter-intuitive, especially if a pilot successfully rolled towards wings level before pitching the aircraft nose-down, since in that case the guidance would command an increased bank angle. A better strategy might set the guidance command to follow the current roll angle if it is moved towards wings level. Another artifact of the roll guidance strategy, though one that is easily fixed, was that at times the roll guidance appeared to jump towards wings level as the aircraft pitch crossed below the PLI.

8.4 Training Relevance

Even though all participants in this study were trained to FAA standards current at the time of the study, they were not trained ahead of time on the specific aircraft model or the guidance system used in this study. The idea was to evaluate the effectiveness and usability of the guidance technology with minimal requirements on training (both with and without guidance). It was also meant to serve as a crude approximation for having to use the system under high workload, fatigue, and some elapsed time or poor retention from the last training session on stall recovery.

By not training the pilots to proficiency on the specific aircraft model ahead of time, we designed the experiment to maximize the benefit we could show for the guidance system (on pilots fully expecting to fly stall recoveries). An alternative would have been to train each pilot to proficiency without the guidance system first, and then to focus the analysis on determining any benefit added by the guidance. This would be a minimum benefit analysis of sorts. For the participants in this study, the results presented in the Learning Effects section 7.2.5 show what we might expected from this analysis. Such results, however, may not reflect the minimum benefit relative to pilots trained according to new stall recovery procedures that are currently moving into effect.

8.5 Other Remarks

The recovery guidance system implemented for this study did not automatically abide even typical Air Traffic Control (ATC) clearances. In particular, high altitude recoveries require more than 1,000 ft altitude loss to recover the aircraft. This can potentially cause a loss of separation with other aircraft flying below. In the lower altitude scenarios as well, carelessly following the guidance beyond the stall recovery could quickly cause the aircraft to exceed its altitude clearance during climb-out at full thrust. To resolve these issues, the guidance system could potentially be integrated with ADS-B, TCAS, and ATC clearance restrictions.

8.6 Future Work

Overall the system was well liked by the participants. Several pilots acknowledged, that while not perfect, the present system would have great benefit in today's commercial aircraft. While most of the areas for improvement were relatively minor and easily remedied, the primary one pertains the increased likelihood of secondary aerodynamic stall in the excessive nose-up trim scenario while the thrust guidance system commands idle thrust. In this one scenario, it seemed that the guidance system improved the elevator safety margin to uncontrolled nose-up pitch, while sacrificing some safety margin with respect to angle-of-attack. This is not an acceptable tradeoff, and the issue should be resolved so that there is a net safety benefit to the system in this scenario, just as there was for the other scenarios.

An important aspect of the study was also to baseline the recovery guidance system, before looking at how the addition of more realistic complicating factors such as distraction will affect it. This step was necessary in order to be able to identify fundamental issues that are inherent to the guidance system, such as the undesirable tradeoff between the elevator and angle-of-attack margins in the excessive nose-up trim case just discussed. While the guidance system was designed to serve as a support tool to help pilots recover from stall under high demands on mental workload, its effectiveness in this regard was not directly measured in the study reported here.

Furthermore, the guidance system in this study was designed specifically for large transport class aircraft with jet engines mounted below the wings. The guidance strategy would be different for aircraft with engines mounted either on the wings (as is the case for some turbo-prop aircraft), or engines mounted at the tail end of the aircraft. In particular, the thrust guidance strategy would be different, since there is no longer a risk of creating an uncontrollable pitch-up moment. The roll and pitch guidance strategies may also need to be more sophisticated for aircraft with T-tail configurations. This is because for high angle-of-attack stall, the elevator can lie in the wake of the wings, making it impossible to initially pitch the aircraft nose-down. The current guidance system should be generalized to handle these other common commercial transport aircraft types as well.

This study also did not consider the effect of angle-of-attack on engine response. At high angle-of-attack, the flow at the compressor face becomes distorted and the risk of compressor stall and engine flameout increases. Commanding full thrust

before reducing the angle-of-attack may make the situation worse, and the risk is even more significant for aircraft with aft-mounted engines. This is an important consideration that can be incorporated into the thrust guidance. The simulation model used in this study, however, did not include this effect.

Finally, the guidance system has so far been designed assuming valid sensor and aircraft model information is available. Additional work is required to make the system more sensor fault tolerant, especially with respect to the airspeed sensors. This should be possible given that airspeed can be estimated from other information available on-board the aircraft. For example, both the Global Positioning System receiver, and the angle-of-attack sensors, can be used to infer airspeed (with some uncertainty) when the pitot-static system has failed. In addition, the flight-dynamics model estimation and assumptions do not need to be perfectly accurate to produce useful guidance, and these can also be developed for robust operation under known failure modes.

Appendix A

Stick-Shaker and PLI Warning System

The stall warning airspeed V_{SW} is defined in 14 CFR §1.2 as the speed at which onset of natural or artificial stall warning occurs. For this study, a working definition meant to satisfy the more specific requirements of 14 CFR §25.207 was employed. With this definition, we are able to relate V_{SW} to a stall warning angle-of-attack α_{SW}, and a corresponding value that defines the location of the Pitch Limit Indicator (PLI).

First we define the stall reference angle-of-attack α_{SR}, as the angle-of-attack that first maximizes the underlying *nonlinear* lift curve $C_L(\alpha)$ for the aircraft in its current configuration. The value of α_{SR} can be determined from representative aerodynamic coefficient lookup tables, or by flying the particular maneuver defined in 14 CFR §25.103, while measuring the load factor corrected lift coefficient.

With the value α_{SR} that maximizes C_L, and the load-factor defined as,

$$n_{\mathrm{LF}} = \frac{L}{W} = \frac{\rho S V^2 C_L(\alpha)}{2mg}, \tag{A1}$$

we can solve for the stall reference speed V_{SR} as a function of the load-factor (for $n_{\mathrm{LF}} \geq 0$)

$$V_{\mathrm{SR}}(n_{\mathrm{LF}}) = \sqrt{\frac{2 n_{\mathrm{LF}} mg}{\rho S C_L(\alpha_{\mathrm{SR}})}} \times \frac{V_{\mathrm{CAS}}}{V_{\mathrm{TAS}}} \ \text{ knots [CAS]}, \tag{A2}$$

where the ratio $V_{\mathrm{CAS}}/V_{\mathrm{TAS}}$ converts true airspeed to calibrated airspeed. With this definition, $V_{\mathrm{SR}}(1)$ is the level flight airspeed, in knots, that corresponds to α_{SR}. Finally, in accordance with 14 CFR §25.207, we chose to define

$$V_{\mathrm{SW}}(n_{\mathrm{LF}}) = \max(1.05 V_{\mathrm{SR}}(n_{\mathrm{LF}}), V_{\mathrm{SR}}(n_{\mathrm{LF}}) + 5) \ \text{ knots [CAS]}, \tag{A3}$$

which has an explicit dependency on the load-factor, such that V_{SW} increases when the aircraft is "pulling g's."

For values of $\alpha < \alpha_{\mathrm{SR}}$, the lift and drag coefficients are approximated by

$$
\begin{aligned}
C_D(\alpha) &= C_{D_0} + C_{D_\alpha}\alpha + C_{D_{\alpha^2}}\alpha^2 & (A4)\\
C_L(\alpha) &= C_{L_0} + C_{L_\alpha}\alpha, & (A5)
\end{aligned}
$$

where the aerodynamic derivatives $C_{D_0}, C_{D_\alpha}, C_{D_{\alpha^2}}, C_{L_0}$, and C_{L_α} are functions of the aircraft configuration, i.e., flap and speed-brake settings, known ahead of time, either through look-up tables or online system identification methods such as the one developed in References [62] and [63]. The coefficient values obtained for the GTM are listed in Table B1 below.

The stall warning angle-of-attack α_{SW}, is found by evaluating $V_{\mathrm{SW}}(n_{\mathrm{LF}})$ at $n_{\mathrm{LF}} = 1$, and using (A5) and (A1) to obtain

$$\alpha_{\mathrm{SW}} = \frac{2mg}{\rho S C_{L_\alpha} \left[V_{\mathrm{SW}}(1) \times V_{\mathrm{TAS}}/V_{\mathrm{CAS}} \right]^2} - \frac{C_{L_0}}{C_{L_\alpha}}. \tag{A6}$$

The use of (A5) is warranted, because the lift curve should be linear in the neighborhood of α_{SW} to a good degree of approximation. Furthermore, by using $\hat{n}_{\text{LF}} = \max(n_{\text{LF}}, 1)$, the pair $V_{\text{SW}}(\hat{n}_{\text{LF}})$ and α_{SW}, can be used to drive the stall warning indicator (stick-shaker), and Pitch Limit Indicator (PLI), such that $\theta_{PLI} - \theta = \alpha_{\text{SW}} - \alpha$, on the Primary Flight Display (PFD). From 14 CFR §25.125, one also obtains the definition of the (minimum) landing reference speed $V_{\text{REF}} = 1.23V_{\text{SR}}(1)$ in knots CAS. While V_{REF} is typically defined for landing configuration, for the purpose of this experiment, it was computed for the current aircraft configuration, and was present on the airspeed tape for all scenarios, including non-landing scenarios.

For this experiment, the minimum maneuvering airspeed (top of the amber band shown in Figure 8) was set to correspond to a 1.15 g maneuver capability to stall warning, i.e., at $V_{\text{SW}}(1.15)$. When flying at this airspeed, the stall warning would trigger if the aircraft attempted a level turn at 30 degrees bank.

Appendix B

GTM Model Approximation

The stall warning and recovery guidance systems require only an approximation for the flight dynamics in the nominal flight regime. For the GTM model this corresponds to $\alpha \leq \alpha_{\text{SR}} = 16$ deg. Within this regime, suitable approximations for the non-dimensional drag and lift coefficients are

$$
C_D(\alpha) = C_{D_0} + C_{D_\alpha}\alpha + C_{D_{\alpha^2}}\alpha^2 + C_{D_{\delta_{\text{sp}}}}\delta_{\text{sp}} +
$$
$$
C_{D_{\delta_{\text{fl}}}}\delta_{\text{fl}} + C_{D_{\delta_{\text{lg}}}}\delta_{\text{lg}} + C_{D_{\alpha\delta_{\text{fl}}}}\alpha\,\delta_{\text{fl}} \tag{B1}
$$

$$
C_L(\alpha) = C_{L_0} + C_{L_\alpha}\alpha + C_{L_{\delta_{\text{sp}}}}\delta_{\text{sp}} + C_{L_{\delta_{\text{fl}}}}\delta_{\text{fl}} + C_{L_{\delta_{\text{lg}}}}\delta_{\text{lg}} \tag{B2}
$$

where δ_{sp} is the spoiler deflection, δ_{fl} is the flap deflection, and $\delta_{\text{lg}} \in [0, 1]$ is the gear setting. The equation for C_m is

$$
C_m = C_0 + C_{m_{\delta_e}}\delta_e + C_{m_{\delta_e^2}}\delta_e^2 + C_{m_T}\frac{T}{\bar{q}d_{\text{eng}}^2}, \tag{B3}
$$

where,

$$
C_0(\alpha, q, i_{\text{h}}, \delta_{\text{sp}}, \delta_{\text{fl}}, \delta_{\text{lg}}) = C_{m_0} + C_{m_\alpha}\alpha + C_{m_{\alpha^2}}\alpha^2 + C_{m_q}\frac{q\bar{c}}{V} +
$$
$$
C_{m_{i_{\text{h}}}}i_{\text{h}} + C_{m_{\delta_{\text{sp}}}}\delta_{\text{sp}} + C_{m_{\delta_{\text{fl}}}}\delta_{\text{fl}} + C_{m_{\delta_{\text{lg}}}}\delta_{\text{lg}}.
$$

In this equation, i_{h} is stabilizer position, δ_{sp} is the spoiler position, δ_{fl} is the flap position, δ_{lg} is the gear position, $\bar{c}$ is the mean aerodynamic chord, d_{eng} is the engine diameter, and $\bar{q} = (1/2)\rho V^2$ is the dynamic pressure.

Equations (A4) and (A5), follow from (B1) and (B2) by fixing the associated terms for the aircraft configuration, i.e., values for δ_{sp}, δ_{fl}, and δ_{lg}. Representative values for the required derivatives are presented in Table B1. Typical values used in the experiment were: aircraft mass $m = 83{,}806$ kg (approximately landing weight), wing surface area $S = 181.25$ m^2, mean aerodynamic chord $\bar{c} = 5.072$ m, engine diameter $d_{\text{eng}} = 2.146$ m, and the air density ρ varied with altitude according to the 1976 U.S. Standard Atmosphere [64].

Table B1. Approximate GTM Aerodynamic Coefficients ($\alpha \leq 16$ deg.)

C_{D_0}	C_{D_α}	$C_{D_{\alpha^2}}$	$C_{D_{\delta_\text{sp}}}$	$C_{D_{\delta_\text{fl}}}$	$C_{D_{\delta_\text{lg}}}$	$C_{D_{\alpha\delta_\text{fl}}}$
0.02	-0.086	2.7	-0.011	0.13	0.037	0.81

C_{L_0}	C_{L_α}	$C_{L_{\delta_\text{sp}}}$	$C_{L_{\delta_\text{fl}}}$	$C_{L_{\delta_\text{lg}}}$
0.11	4.6	0.88	1.5	-0.027

C_{m_0}	C_{m_α}	$C_{m_{\alpha^2}}$	C_{m_q}	$C_{m_{\delta_\text{e}}}$	$C_{m_{\delta_\text{e}^2}}$	$C_{m_{i_\text{h}}}$	C_{m_T}	$C_{m_{\delta_\text{sp}}}$	$C_{m_{\delta_\text{fl}}}$	$C_{m_{\delta_\text{lg}}}$
0.33	-3.2	6.0	-15	-1.7	-0.54	-3.3	0.0082	-0.12	-0.35	0.013

Table B2. GTM Engines Maximum Thrust (lbf)

Alt. (feet)	CAS (knots)				
	0	210	250	300	350
10	87260.6172	65623.6954	62191.75	59206.125	57001.3008
1,000	85581.0078	64686.9102	61308.0234	58519.293	56329.2226
5,000	79461.375	60337.3476	57377.8594	55300.9102	53393.5118
10,000	69371.8672	52469.1954	50374.461	48508.6992	46988.3164
12,000	64113.3946	49660.1602	47730.7812	45903.082	44620.1562
20,000	46226.211	36214.6562	34736.3046	33533.2226	32676.4218
25,000	37289.2578	27598.246	26609.9922	25825.1524	25124.7872
30,000	29814.8536	23585.7598	22887.8652	22169.707	21617.211
35,000	23609.0918	19129.07812	19575.1836	18977.72852	18736.76758
39,000	19481.1543	16033.1836	16123.85352	15584.70898	2564.39136

Appendix C

Alternative Guidance Displays Considered

In our review of candidate recovery guidance display cues, we developed and performed preliminary testing on several approaches. Two of these alternatives are presented in Figure C.

Figure C.1(a) shows a standard flight-path symbol based guidance director. The guidance objective in this case is to center the white flight path symbol on the magenta circle. The location of the white, right-pointing acceleration caret indicates the current longitudinal acceleration. The location of the magenta caret indicates the desired acceleration. The flight path guidance in the figure is requesting additional bank to the right and reduced acceleration, which can be accommodated by reducing thrust. This approach is more consistent with guidance indicators typically presented on the Heads Up Display (HUD). If guidance is shown on the HUD, consistency (and FAA regulation) would dictate that the same guidance be shown on the heads down displays as well. This approach is perhaps more forward looking, and readily incorporated into new flight deck designs that include HUDs and synthetic vision, such as the acceleration caret and speed error symbol used on the Rockwell Collins HGS-3500 [65]. The guidance is also more compact and centrally located. The drawback is the fine level of detail required to include thrust guidance, possibly requiring the inclusion of yet another small display component built onto the flight path symbol. The main reason this approach was not selected for this experiment, however, was because fewer line pilots would have been familiar with it, and a primary objective of the experiment was to develop and test a concept that would require the least amount of additional training.

Figure C.1(b) shows an alternative thrust guidance indicator, along the left edge of the ADI. This thrust guidance symbology was a modified version of the display presented in the joint work of NASA Langley Research Center and Barron Associates [17, 18]. With this concept, the current thrust is shown by the white, left-pointing triangle, while the recommended thrust is shown by the magenta, right-pointing triangle. The red band on top of the magenta triangle indicates a restriction due to an excessive nose-up stab trim condition. The benefit of this approach, is that the guidance includes the context of the full throttle range. This is in contrast with the relative thrust director that was actually used in the experiment. The drawback is that it is a new, somewhat detailed, indicator placed off to the side of the pilot's focus. During initial exploratory testing with multiple research pilots, this display was almost completely ignored; a detriment that is perhaps surmountable with additional training.
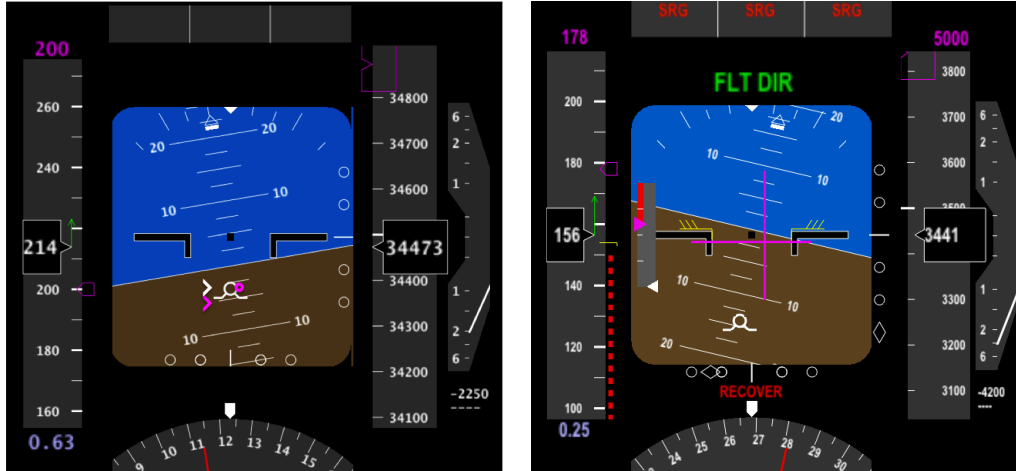
(a) Flight path director cues, with acceleration guidance caret.

(b) Alternative thrust guidance indicator cue.

Figure C1. Alternative guidance cues.

Appendix D

Pilot Surveys

The participants in the study provided their subjective feedback on three survey forms. The *pre-sim* survey was completed as part of the initial pilot briefing. The *post-run* surveys, were completed after each set of 3 runs, one with and one without guidance for each scenario (so each pilot completed a total of 8 *post-run* surveys). For the research pilots only, a Cooper-Harper rating was requested on each of the post-run surveys. For the runs with guidance, the Cooper-Harper rating was based on the tracking standards for each of the scenarios (defined in Section 4). For the runs without guidance, the Cooper-Harper rating was based on the task workload for the scenario alone. Finally, the *post-sim* survey was completed as part of the debrief meeting that concluded each session. The questionnaire for each survey is reproduced below. The mean participant response and sample standard deviation are also printed next to each question, when appropriate. Since the main body of this report focused more on the constructive critical comments, here we have included some of the more positively charged (or interesting) written comments that the pilots provided. In these comments, the following abbreviations for the scenarios were used: High Altitude Stall (HAS), Approach Stall (APS), Low Altitude Stall (LAS), Low Altitude Nose Up Stall (LANUS). [Notes or other comments not shown to the participants are enclosed in brackets like this].

D.1 Pre-sim questionnaire

1. Are you familiar with the FAA stall recovery guidelines? [35/40 `pilots said yes.`] ☐ Yes ☐ No

2. Are you a trainer? (CFI or other) [19/40 `pilots said yes.`]
   ☐ Yes ☐ No

3. Have you experienced any stick shakers (or stalls) before, besides simulator training? [26/40 `pilots said yes.`]
   ☐ Yes ☐ No
   If yes, please explain context:

   [`During flight instruction was the most common reason.`]

   [Research Pilot Comment: "Lear 25 to shaker as part of stall system calibration."]

   [Research Pilot Comment: "I've conducted straight and level stalls in a U-2 aircraft."]

   [Research Pilot Comment: "C17 development testing."]

   [Research Pilot Comment: "As a Boeing production test pilot, checked stick shaker speeds on new aircraft."]

4. Have you experienced any stalls as part of simulator training?
   [36/40 `pilots said yes.`]
   ☐ Yes ☐ No
   If yes, please explain context:

5. What is your flying background?

   ☐ transport category (part 25) [35/40]
   ☐ general aviation (part 23)
      ☐ normal [25/40]
      ☐ utility [11/40]
      ☐ acrobatic [12/40]
      ☐ commuter [7/40]

   ☐ military [19/40]
   ☐ other: _____
   ☐ other: _____
   ☐ other: _____

6. Number of flight hours: [13,855 ± 6,933]

7. Aircraft types flown:

D.2 Post-run questionnaire

For the stall recovery task you just flew:

1. Were you, at any point during this run, confused about what the stall recovery guidance signals were doing?
   ☐ Yes   ☐ No
   If yes, please explain:

2. Please rate the following:

   - Level of mental demand (mental and perceptual activity):

Low		Average		High

   - Level of time pressure (pace):

Low		Average		High

3. If applicable, please rate the usefulness of the:

   - Pitch guidance:

Unnecessary		Somewhat useful		Highly useful

   - Roll guidance:

Unnecessary		Somewhat useful		Highly useful

   - Throttle guidance:

Unnecessary		Somewhat useful		Highly useful

   - Guidance system, with all indicators working together:

Unnecessary		Somewhat useful		Highly useful

4. Summary – Good/Bad Features?

[Pilot Comment: [LANUS] "Very useful! Especially the throttle guidance."]

[Pilot Comment: [APS] "Good if after a long flight and not aware of the situation."]

5. Did anything happen in this run that we should know about? Do you have any comments or remarks to share?

[Pilot Comment: [APS] "Guidance makes it easier to recover."]

6. **Cooper-Harper Handling Qualities Rating Scale**

   - No guidance (task workload only):

   ```
   1      2      3      4      5      6      7      8      9      10
   ```

   - Pitch guidance:

   ```
   1      2      3      4      5      6      7      8      9      10
   ```

   - Throttle guidance:

   ```
   1      2      3      4      5      6      7      8      9      10
   ```

   - Please explain your Cooper-Harper Rating here, more detail is especially appreciated for higher ratings.

[Note: Question 6 was not shown to the commercial pilots.]

D.3 Post-sim questionnaire

Considering all of the stall recovery tasks you flew today:

1. How would you grade the overall realism of the stall scenarios, given the scope of this experiment? $[0.80 \pm .30]$

   Unreal   Acceptable   Excellent

   Comments or suggestions for improvement?

2. Did you find any aspect of the guidance counter-intuitive, or in contradiction with your flight line training? $[22/40$ `pilots found some aspect of the system counter-intuitive`$]$

   ☐ Yes   ☐ No

   If yes, please explain:

3. Please rate the overall usefulness of the individual guidance signals:

   - Pitch guidance: $[0.84 \pm .18]$

     Unnecessary   Somewhat useful   Highly useful

- Roll guidance: $[0.69 \pm .24]$

Unnecessary	Somewhat useful	Highly useful

- Throttle guidance: $[0.69 \pm .29]$

Unnecessary	Somewhat useful	Highly useful
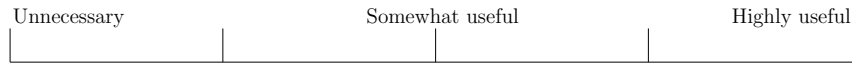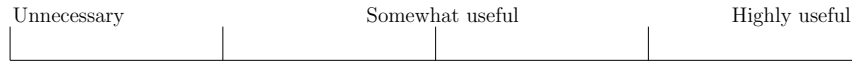
4. Please put the following new indications in order from the most useful for you at the top of the list to the least useful at the bottom:

☐ Pitch recovery guidance $[1.25 \pm .44]$

☐ Roll recovery guidance $[2.70 \pm .52]$

☐ Throttle guidance $[2.0 \pm .72]$

Explain if you like:

[Pilot Comment: "All of them are just as useful. But it depends on the scenario. At low altitude thrust was more useful than at high altitude. Therefore, I still believe pitch is most useful, the other ones are very valuable as well."]

5. Were the indicators as used on the PFD clear to you? $[0.97 \pm .34]$

Very unclear	Indifferent	Very clear
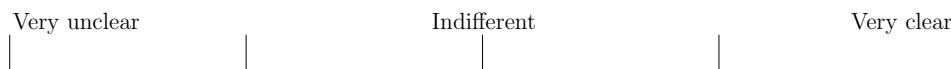
Comments:

6. Was it clear to you when you were in recovery mode or not? $[0.88 \pm .17]$

Very unclear	Indifferent	Very clear
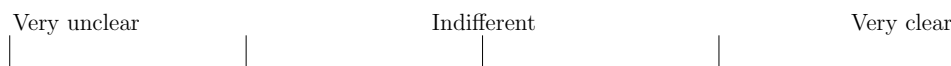
Comments:

7. Was it always clear what the guidance system was telling you to do? $[0.86 \pm .12]$

Very unclear   Indifferent   Very clear
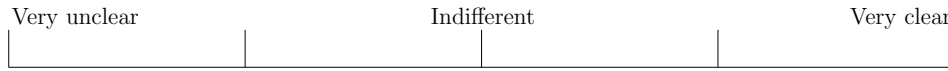
Comments:

[Pilot Comment: "Yes it was. However, at times it put my brain in competing priorities, i.e., when attempting to roll out, concentrating on throttle position made me forget (for a bit) about trimming (nose down)."

8. Was the throttle guidance presented clearly? $[0.81 \pm .20]$

Very unclear   Indifferent   Very clear
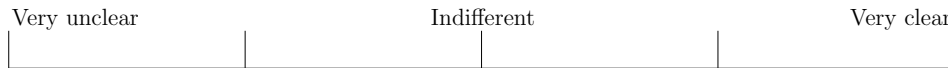
Do you have any suggestions to improve it?

9. How useful was the entire guidance system, with all guidance signals working together? $[0.85 \pm .16]$

Unnecessary   Somewhat useful   Highly useful
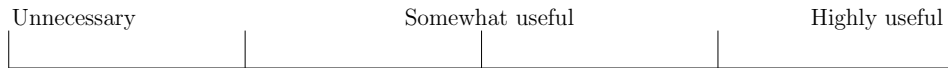
Any suggestions for improving how the recovery guidance signals and indicators work together?

10. Overall, I felt the stall recovery guidance assisted me to refine my recovery strategy. Agree or Disagree? $[0.81 \pm .22]$

Disagree   Indifferent   Agree
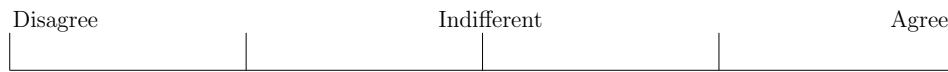
Comments:

[Pilot Comment: "The guidance recovery system assisted me during recovery with guidance. But just as importantly it provided training for what to do when I did not have guidance."]

11. Overall, I learned something from the stall recovery guidance presented today, which I should use in a stall recovery where guidance is not provided. Agree or Disagree? $[0.73 \pm .30]$

Disagree   Indifferent   Agree
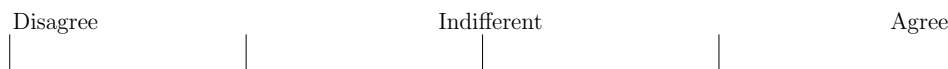
Comments:

[Pilot Comment: "Very much so!!!"]

12. Is there any additional information that would have been helpful to support your piloting task? $[10/40$ `Pilots thought additional information would have been useful.`$]$
    ☐   No.   ☐   Yes, namely:

[Pilot comment: "A good concept. Would be a great benefit in todays fleet."]

13. Please indicate your responses: [*System Usability Score*]

- I think that I would like to use this system if I was in a stall situation. [0.87 ± .20]

  Disagree   Indifferent   Agree
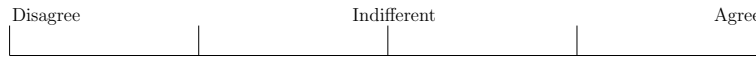
- I found the system unnecessarily complex. [0.17 ± .20]

  Disagree   Indifferent   Agree
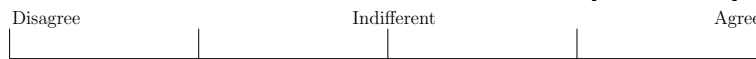
- I thought the system was easy to use. [0.86 ± .13]

  Disagree   Indifferent   Agree

- I think that pilots need an extensive briefing to be able to use this system. [0.41 ± .30]

  Disagree   Indifferent   Agree
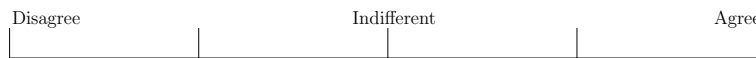
- I found the various functions in this system were well integrated. [0.83 ± .17]

  Disagree   Indifferent   Agree

- I thought there was too much inconsistency in this system. [0.12 ± .15]

  Disagree   Indifferent   Agree

- I would imagine that most pilots would use the system with very little training. [0.78 ± .22]

  Disagree   Indifferent   Agree
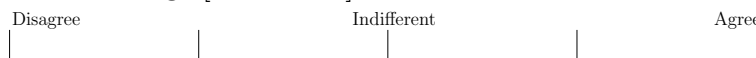
- I found the system very cumbersome to use. [0.13 ± .13]

  Disagree   Indifferent   Agree
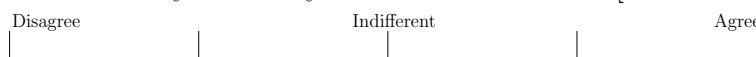
- I felt very confident using the system. [0.85 ± .18]

  Disagree   Indifferent   Agree
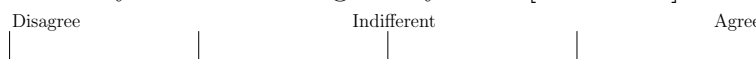
- I needed a lot of training before I could get going with this system. [0.18 ± .21]

  Disagree   Indifferent   Agree

14. Summary – What is your overall impression of the system?

[Pilot Comment: "Very impressed. Easy to understand."]

[Pilot Comment: "I think it would save lives."]

[Pilot Comment: "Good for training for crews of various backgrounds. Would be good in aircraft because stalls are not expected events."]

[Pilot Comment: "The system is good if you do not know the basics for a stall recovery. It is also good after or during a long flight when aircraft situational awareness is at a low."]

15. Is there anything else you think we should know? Events that you think we should know about or comments you would like to make?

[Pilot Comment: "Pilots should be trained in basic recovery with the guidance system as backup."]

Appendix E

Experiment Test Matrix

The full experiment test matrix is printed below in chronological order. The abbreviations used are: Algorithm (**Alg.**), Scenario (**Scn.**), Sequence (**Seq.**), Iteration (**Itr.**), Military (**Mil.**). The two algorithms under test were the energy based algorithm (eba), and the fast model predictive control (fmpc) algorithm. There were four scenarios: low altitude stall (las), high altitude stall (has), approach stall (aps), and the low altitude with nose-up stall (lanus).

The sequence (**Seq.**) field indicates whether an algorithm, scenario, and run combination was flown before or after providing guidance. FMPC and EBA guidance are encoded as 1 and 2, respectively, and the sign is negative if runs were flown beforehand without guidance for the particular scenario involved. For example, a -2 indicates a run where no guidance (hence **Alg.** none) was flown first, and was then followed by a sequence of EBA runs.

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
01	none	las	16	1	-2	1	yes	yes
01	none	las	16	2	-2	2	yes	yes
01	none	las	16	3	-2	3	yes	yes
01	none	las	16	4	-2	4	yes	yes
01	eba	las	16	5	-2	1	yes	yes
01	eba	las	16	6	-2	2	yes	yes
01	eba	las	16	7	-2	3	yes	yes
01	eba	las	16	8	-2	4	yes	yes
01	eba	has	16	9	2	1	yes	yes
01	eba	has	16	10	2	2	yes	yes
01	eba	has	16	11	2	3	yes	yes
01	none	has	16	12	2	1	yes	yes
01	none	has	16	13	2	2	yes	yes
01	none	has	16	14	2	3	yes	yes
01	none	lanus	16	15	-2	1	yes	yes
01	none	lanus	16	16	-2	2	yes	yes
01	none	lanus	16	17	-2	3	yes	yes
01	eba	lanus	16	18	-2	1	yes	yes
01	eba	lanus	16	19	-2	2	yes	yes
01	eba	lanus	16	20	-2	3	yes	yes
01	eba	lanus	16	21	-2	4	yes	yes
01	eba	aps	16	22	2	1	yes	yes
01	eba	aps	16	23	2	2	yes	yes
01	eba	aps	16	24	2	3	yes	yes
01	none	aps	16	25	2	1	yes	yes
01	none	aps	16	26	2	2	yes	yes
01	none	aps	16	27	2	3	yes	yes
02	none	las	15	28	-1	1	yes	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
02	none	las	15	29	-1	2	yes	no
02	none	las	15	30	-1	3	yes	no
02	fmpc	las	15	31	-1	1	yes	no
02	fmpc	las	15	32	-1	2	yes	no
02	fmpc	las	15	33	-1	3	yes	no
02	fmpc	has	15	34	1	1	yes	no
02	fmpc	has	15	35	1	2	yes	no
02	fmpc	has	15	36	1	3	yes	no
02	none	has	15	37	1	1	yes	no
02	none	has	15	38	1	2	yes	no
02	none	has	15	39	1	3	yes	no
02	none	lanus	15	40	-1	1	yes	no
02	none	lanus	15	41	-1	2	yes	no
02	none	lanus	15	42	-1	3	yes	no
02	fmpc	lanus	15	43	-1	1	yes	no
02	fmpc	lanus	15	44	-1	2	yes	no
02	fmpc	lanus	15	45	-1	3	yes	no
02	fmpc	aps	15	46	1	1	yes	no
02	fmpc	aps	15	47	1	2	yes	no
02	fmpc	aps	15	48	1	3	yes	no
02	none	aps	15	49	1	1	yes	no
02	none	aps	15	50	1	2	yes	no
02	none	aps	15	51	1	3	yes	no
03	none	las	18	52	0	1	no	yes
03	none	aps	18	53	-2	1	no	yes
03	none	aps	18	54	-2	2	no	yes
03	none	aps	18	55	-2	3	no	yes
03	eba	aps	18	56	-2	1	no	yes
03	eba	aps	18	57	-2	2	no	yes
03	eba	aps	18	58	-2	3	no	yes
03	none	las	17	59	0	1	no	no
03	none	aps	17	60	-1	1	no	no
03	none	aps	17	61	-1	2	no	no
03	none	aps	17	62	-1	3	no	no
03	none	aps	17	63	-1	4	no	no
03	fmpc	aps	17	64	-1	1	no	no
03	fmpc	aps	17	65	-1	2	no	no
03	fmpc	aps	17	66	-1	3	no	no
03	eba	has	18	67	2	1	no	yes
03	eba	has	18	68	2	2	no	yes
03	eba	has	18	69	2	3	no	yes
03	none	has	18	70	2	1	no	yes
03	none	has	18	71	2	2	no	yes
03	none	has	18	72	2	3	no	yes
03	none	las	18	73	-2	1	no	yes
03	none	las	18	74	-2	2	no	yes
03	none	las	18	75	-2	3	no	yes
03	eba	las	18	76	-2	1	no	yes
03	eba	las	18	77	-2	2	no	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
03	eba	las	18	78	-2	3	no	yes
03	fmpc	has	17	79	1	1	no	no
03	fmpc	has	17	80	1	2	no	no
03	fmpc	has	17	81	1	3	no	no
03	none	has	17	82	1	1	no	no
03	none	has	17	83	1	2	no	no
03	none	has	17	84	1	3	no	no
03	none	las	17	85	-1	1	no	no
03	none	las	17	86	-1	2	no	no
03	none	las	17	87	-1	3	no	no
03	fmpc	las	17	88	-1	1	no	no
03	fmpc	las	17	89	-1	2	no	no
03	fmpc	las	17	90	-1	3	no	no
03	eba	lanus	18	91	2	1	no	yes
03	eba	lanus	18	92	2	2	no	yes
03	eba	lanus	18	93	2	3	no	yes
03	none	lanus	18	94	2	1	no	yes
03	none	lanus	18	95	2	2	no	yes
03	none	lanus	18	96	2	3	no	yes
03	fmpc	lanus	17	97	1	1	no	no
03	fmpc	lanus	17	98	1	2	no	no
03	fmpc	lanus	17	99	1	3	no	no
03	fmpc	lanus	17	100	1	4	no	no
03	none	lanus	17	101	1	1	no	no
03	none	lanus	17	102	1	2	no	no
03	none	lanus	17	103	1	3	no	no
04	none	las	19	104	0	1	no	no
04	eba	has	19	105	2	1	no	no
04	eba	has	19	106	2	2	no	no
04	eba	has	19	107	2	3	no	no
04	none	has	19	108	2	1	no	no
04	none	has	19	109	2	2	no	no
04	none	has	19	110	2	3	no	no
04	none	lanus	19	111	-2	1	no	no
04	none	lanus	19	112	-2	2	no	no
04	none	lanus	19	113	-2	3	no	no
04	eba	lanus	19	114	-2	1	no	no
04	eba	lanus	19	115	-2	2	no	no
04	eba	lanus	19	116	-2	3	no	no
04	eba	aps	19	117	2	1	no	no
04	eba	aps	19	118	2	2	no	no
04	eba	aps	19	119	2	3	no	no
04	none	aps	19	120	2	1	no	no
04	none	aps	19	121	2	2	no	no
04	none	aps	19	122	2	3	no	no
04	none	las	19	123	-2	1	no	no
04	none	las	19	124	-2	2	no	no
04	none	las	19	125	-2	3	no	no
04	eba	las	19	126	-2	1	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
04	eba	las	19	127	-2	2	no	no
04	eba	las	19	128	-2	3	no	no
05	none	las	21	129	0	1	no	no
05	eba	aps	21	130	2	1	no	no
05	eba	aps	21	131	2	2	no	no
05	eba	aps	21	132	2	3	no	no
05	none	aps	21	133	2	1	no	no
05	none	aps	21	134	2	2	no	no
05	none	aps	21	135	2	3	no	no
05	none	las	20	136	0	1	no	no
05	fmpc	aps	20	137	1	1	no	no
05	fmpc	aps	20	138	1	2	no	no
05	fmpc	aps	20	139	1	3	no	no
05	fmpc	aps	20	140	1	4	no	no
05	none	aps	20	141	1	1	no	no
05	none	aps	20	142	1	2	no	no
05	none	aps	20	143	1	3	no	no
05	none	has	21	144	-2	1	no	no
05	none	has	21	145	-2	2	no	no
05	none	has	21	146	-2	3	no	no
05	eba	has	21	147	-2	1	no	no
05	eba	has	21	148	-2	2	no	no
05	eba	has	21	149	-2	3	no	no
05	eba	las	21	150	2	1	no	no
05	eba	las	21	151	2	2	no	no
05	eba	las	21	152	2	3	no	no
05	none	las	21	153	2	1	no	no
05	none	las	21	154	2	2	no	no
05	none	las	21	155	2	3	no	no
05	none	has	20	156	-1	1	no	no
05	none	has	20	157	-1	2	no	no
05	none	has	20	158	-1	3	no	no
05	fmpc	has	20	159	-1	1	no	no
05	fmpc	has	20	160	-1	2	no	no
05	fmpc	has	20	161	-1	3	no	no
05	fmpc	las	20	162	1	1	no	no
05	fmpc	las	20	163	1	2	no	no
05	fmpc	las	20	164	1	3	no	no
05	none	las	20	165	1	1	no	no
05	none	las	20	166	1	2	no	no
05	none	las	20	167	1	3	no	no
05	none	lanus	21	168	-2	1	no	no
05	none	lanus	21	169	-2	2	no	no
05	none	lanus	21	170	-2	3	no	no
05	eba	lanus	21	171	-2	1	no	no
05	eba	lanus	21	172	-2	2	no	no
05	eba	lanus	21	173	-2	3	no	no
05	none	lanus	20	174	-1	1	no	no
05	none	lanus	20	175	-1	2	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
05	none	lanus	20	176	-1	3	no	no
05	fmpc	lanus	20	177	-1	1	no	no
05	fmpc	lanus	20	178	-1	2	no	no
05	fmpc	lanus	20	179	-1	3	no	no
06	eba	las	23	181	2	1	yes	yes
06	eba	las	23	182	2	2	yes	yes
06	eba	las	23	183	2	3	yes	yes
06	none	las	23	184	2	1	yes	yes
06	none	las	23	185	2	2	yes	yes
06	none	las	23	186	2	3	yes	yes
06	none	has	23	187	-2	1	yes	yes
06	none	has	23	188	-2	2	yes	yes
06	none	has	23	189	-2	3	yes	yes
06	eba	has	23	190	-2	1	yes	yes
06	eba	has	23	191	-2	2	yes	yes
06	eba	has	23	192	-2	3	yes	yes
06	fmpc	las	22	194	1	1	yes	yes
06	fmpc	las	22	195	1	2	yes	yes
06	fmpc	las	22	196	1	3	yes	yes
06	none	las	22	197	1	1	yes	yes
06	none	las	22	198	1	2	yes	yes
06	none	las	22	199	1	3	yes	yes
06	none	has	22	200	-1	1	yes	yes
06	none	has	22	201	-1	2	yes	yes
06	none	has	22	202	-1	3	yes	yes
06	fmpc	has	22	203	-1	1	yes	yes
06	fmpc	has	22	204	-1	2	yes	yes
06	fmpc	has	22	205	-1	3	yes	yes
06	eba	lanus	23	206	2	1	yes	yes
06	eba	lanus	23	207	2	2	yes	yes
06	eba	lanus	23	208	2	3	yes	yes
06	none	lanus	23	209	2	1	yes	yes
06	none	lanus	23	210	2	2	yes	yes
06	none	lanus	23	211	2	3	yes	yes
06	none	aps	23	212	-2	1	yes	yes
06	none	aps	23	213	-2	2	yes	yes
06	none	aps	23	214	-2	3	yes	yes
06	eba	aps	23	215	-2	1	yes	yes
06	eba	aps	23	216	-2	2	yes	yes
06	eba	aps	23	217	-2	3	yes	yes
06	fmpc	lanus	22	218	1	1	yes	yes
06	fmpc	lanus	22	219	1	2	yes	yes
06	fmpc	lanus	22	220	1	3	yes	yes
06	none	lanus	22	221	1	1	yes	yes
06	none	lanus	22	222	1	2	yes	yes
06	none	lanus	22	223	1	3	yes	yes
06	none	aps	22	224	-1	1	yes	yes
06	none	aps	22	225	-1	2	yes	yes
06	none	aps	22	226	-1	3	yes	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
06	fmpc	aps	22	227	-1	1	yes	yes
06	fmpc	aps	22	228	-1	2	yes	yes
06	fmpc	aps	22	229	-1	3	yes	yes
07	none	has	24	231	-1	1	no	no
07	none	has	24	232	-1	2	no	no
07	none	has	24	233	-1	3	no	no
07	fmpc	has	24	234	-1	1	no	no
07	fmpc	has	24	235	-1	2	no	no
07	fmpc	has	24	236	-1	3	no	no
07	fmpc	lanus	24	237	1	1	no	no
07	fmpc	lanus	24	238	1	2	no	no
07	fmpc	lanus	24	239	1	3	no	no
07	none	lanus	24	240	1	1	no	no
07	none	lanus	24	241	1	2	no	no
07	none	lanus	24	242	1	3	no	no
07	none	has	25	244	-2	1	no	no
07	none	has	25	245	-2	2	no	no
07	none	has	25	246	-2	3	no	no
07	eba	has	25	247	-2	1	no	no
07	eba	has	25	248	-2	2	no	no
07	eba	has	25	249	-2	3	no	no
07	eba	lanus	25	250	2	1	no	no
07	eba	lanus	25	251	2	2	no	no
07	eba	lanus	25	252	2	3	no	no
07	none	lanus	25	253	2	1	no	no
07	none	lanus	25	254	2	2	no	no
07	none	lanus	25	255	2	3	no	no
07	none	aps	24	256	-1	1	no	no
07	none	aps	24	257	-1	2	no	no
07	none	aps	24	258	-1	3	no	no
07	fmpc	aps	24	259	-1	1	no	no
07	fmpc	aps	24	260	-1	2	no	no
07	fmpc	aps	24	261	-1	3	no	no
07	fmpc	las	24	262	1	1	no	no
07	fmpc	las	24	263	1	2	no	no
07	fmpc	las	24	264	1	3	no	no
07	none	las	24	265	1	1	no	no
07	none	las	24	266	1	2	no	no
07	none	las	24	267	1	3	no	no
07	none	aps	25	268	-2	1	no	no
07	none	aps	25	269	-2	2	no	no
07	none	aps	25	270	-2	3	no	no
07	none	aps	25	271	-2	4	no	no
07	eba	aps	25	272	-2	1	no	no
07	eba	aps	25	273	-2	2	no	no
07	eba	aps	25	274	-2	3	no	no
07	eba	las	25	275	2	1	no	no
07	eba	las	25	276	2	2	no	no
07	eba	las	25	277	2	3	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
07	none	las	25	278	2	1	no	no
07	none	las	25	279	2	2	no	no
07	none	las	25	280	2	3	no	no
08	none	las	27	282	-1	1	no	yes
08	none	las	27	283	-1	2	no	yes
08	none	las	27	284	-1	3	no	yes
08	fmpc	las	27	285	-1	1	no	yes
08	fmpc	las	27	286	-1	2	no	yes
08	fmpc	las	27	287	-1	3	no	yes
08	fmpc	lanus	27	288	1	1	no	yes
08	fmpc	lanus	27	289	1	2	no	yes
08	fmpc	lanus	27	290	1	3	no	yes
08	none	lanus	27	291	1	1	no	yes
08	none	lanus	27	292	1	2	no	yes
08	none	lanus	27	293	1	3	no	yes
08	none	lanus	27	294	1	4	no	yes
08	none	lanus	27	295	1	5	no	yes
08	none	las	26	297	-2	1	no	yes
08	none	las	26	298	-2	2	no	yes
08	none	las	26	299	-2	3	no	yes
08	eba	las	26	300	-2	1	no	yes
08	eba	las	26	301	-2	2	no	yes
08	eba	las	26	302	-2	3	no	yes
08	eba	lanus	26	303	2	1	no	yes
08	eba	lanus	26	304	2	2	no	yes
08	eba	lanus	26	305	2	3	no	yes
08	none	lanus	26	306	2	1	no	yes
08	none	lanus	26	307	2	2	no	yes
08	none	lanus	26	308	2	3	no	yes
08	none	aps	27	309	-1	1	no	yes
08	none	aps	27	310	-1	2	no	yes
08	none	aps	27	311	-1	3	no	yes
08	fmpc	aps	27	312	-1	1	no	yes
08	fmpc	aps	27	313	-1	2	no	yes
08	fmpc	aps	27	314	-1	3	no	yes
08	fmpc	has	27	315	1	1	no	yes
08	fmpc	has	27	316	1	2	no	yes
08	fmpc	has	27	317	1	3	no	yes
08	none	has	27	318	1	1	no	yes
08	none	has	27	319	1	2	no	yes
08	none	has	27	320	1	3	no	yes
08	none	aps	26	321	-2	1	no	yes
08	none	aps	26	322	-2	2	no	yes
08	none	aps	26	323	-2	3	no	yes
08	eba	aps	26	324	-2	1	no	yes
08	eba	aps	26	325	-2	2	no	yes
08	eba	aps	26	326	-2	3	no	yes
08	eba	has	26	327	2	1	no	yes
08	eba	has	26	328	2	2	no	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
08	eba	has	26	329	2	3	no	yes
08	none	has	26	330	2	1	no	yes
08	none	has	26	331	2	2	no	yes
08	none	has	26	332	2	3	no	yes
09	fmpc	has	28	334	1	1	no	no
09	fmpc	has	28	335	1	2	no	no
09	fmpc	has	28	336	1	3	no	no
09	none	has	28	337	1	1	no	no
09	none	has	28	338	1	2	no	no
09	none	has	28	339	1	3	no	no
09	none	lanus	28	340	-1	1	no	no
09	none	lanus	28	341	-1	2	no	no
09	none	lanus	28	342	-1	3	no	no
09	fmpc	lanus	28	343	-1	1	no	no
09	fmpc	lanus	28	344	-1	2	no	no
09	fmpc	lanus	28	345	-1	3	no	no
09	fmpc	aps	28	346	1	1	no	no
09	fmpc	aps	28	347	1	2	no	no
09	fmpc	aps	28	348	1	3	no	no
09	none	aps	28	349	1	1	no	no
09	none	aps	28	350	1	2	no	no
09	none	aps	28	351	1	3	no	no
09	none	las	28	352	-1	1	no	no
09	none	las	28	353	-1	2	no	no
09	none	las	28	354	-1	3	no	no
09	fmpc	las	28	355	-1	1	no	no
09	fmpc	las	28	356	-1	2	no	no
09	fmpc	las	28	357	-1	3	no	no
10	fmpc	aps	10	359	1	1	yes	yes
10	fmpc	aps	10	360	1	2	yes	yes
10	fmpc	aps	10	361	1	3	yes	yes
10	none	aps	10	362	1	1	yes	yes
10	none	aps	10	363	1	2	yes	yes
10	none	aps	10	364	1	3	yes	yes
10	none	has	10	365	-1	1	yes	yes
10	none	has	10	366	-1	2	yes	yes
10	none	has	10	367	-1	3	yes	yes
10	fmpc	has	10	368	-1	1	yes	yes
10	fmpc	has	10	369	-1	2	yes	yes
10	fmpc	has	10	370	-1	3	yes	yes
10	eba	aps	30	372	2	1	yes	yes
10	eba	aps	30	373	2	2	yes	yes
10	eba	aps	30	374	2	3	yes	yes
10	none	aps	30	375	2	1	yes	yes
10	none	aps	30	376	2	2	yes	yes
10	none	aps	30	377	2	3	yes	yes
10	none	has	30	378	-2	1	yes	yes
10	none	has	30	379	-2	2	yes	yes
10	none	has	30	380	-2	3	yes	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
10	eba	has	30	381	-2	1	yes	yes
10	eba	has	30	382	-2	2	yes	yes
10	eba	has	30	383	-2	3	yes	yes
10	fmpc	las	10	384	1	1	yes	yes
10	fmpc	las	10	385	1	2	yes	yes
10	fmpc	las	10	386	1	3	yes	yes
10	none	las	10	387	1	1	yes	yes
10	none	las	10	388	1	2	yes	yes
10	none	las	10	389	1	3	yes	yes
10	none	lanus	10	390	-1	1	yes	yes
10	none	lanus	10	391	-1	2	yes	yes
10	none	lanus	10	392	-1	3	yes	yes
10	fmpc	lanus	10	393	-1	1	yes	yes
10	fmpc	lanus	10	394	-1	2	yes	yes
10	fmpc	lanus	10	395	-1	3	yes	yes
10	eba	las	30	396	2	1	yes	yes
10	eba	las	30	397	2	2	yes	yes
10	eba	las	30	398	2	3	yes	yes
10	none	las	30	399	2	1	yes	yes
10	none	las	30	400	2	2	yes	yes
10	none	las	30	401	2	3	yes	yes
10	none	lanus	30	402	-2	1	yes	yes
10	none	lanus	30	403	-2	2	yes	yes
10	none	lanus	30	404	-2	3	yes	yes
10	eba	lanus	30	405	-2	1	yes	yes
10	eba	lanus	30	406	-2	2	yes	yes
10	eba	lanus	30	407	-2	3	yes	yes
10	none	lanus	30	408	0	1	yes	yes
11	fmpc	las	32	410	1	1	no	yes
11	fmpc	las	32	411	1	2	no	yes
11	fmpc	las	32	412	1	3	no	yes
11	none	las	32	413	1	1	no	yes
11	none	las	32	414	1	2	no	yes
11	none	las	32	415	1	3	no	yes
11	none	lanus	32	416	-1	1	no	yes
11	none	lanus	32	417	-1	2	no	yes
11	none	lanus	32	418	-1	3	no	yes
11	fmpc	lanus	32	419	-1	1	no	yes
11	fmpc	lanus	32	420	-1	2	no	yes
11	fmpc	lanus	32	421	-1	3	no	yes
11	eba	las	31	423	2	1	no	no
11	eba	las	31	424	2	2	no	no
11	eba	las	31	425	2	3	no	no
11	none	las	31	426	2	1	no	no
11	none	las	31	427	2	2	no	no
11	none	las	31	428	2	3	no	no
11	none	lanus	31	429	-2	1	no	no
11	none	lanus	31	430	-2	2	no	no
11	none	lanus	31	431	-2	3	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
11	eba	lanus	31	432	-2	1	no	no
11	eba	lanus	31	433	-2	2	no	no
11	eba	lanus	31	434	-2	3	no	no
11	eba	aps	31	435	2	1	no	no
11	eba	aps	31	436	2	2	no	no
11	eba	aps	31	437	2	3	no	no
11	none	aps	31	438	2	1	no	no
11	none	aps	31	439	2	2	no	no
11	none	aps	31	440	2	3	no	no
11	none	has	31	441	-2	1	no	no
11	none	has	31	442	-2	2	no	no
11	none	has	31	443	-2	3	no	no
11	eba	has	31	444	-2	1	no	no
11	eba	has	31	445	-2	2	no	no
11	eba	has	31	446	-2	3	no	no
11	eba	has	31	447	-2	4	no	no
11	fmpc	aps	32	448	1	1	no	yes
11	fmpc	aps	32	449	1	2	no	yes
11	fmpc	aps	32	450	1	3	no	yes
11	none	aps	32	451	1	1	no	yes
11	none	aps	32	452	1	2	no	yes
11	none	aps	32	453	1	3	no	yes
11	none	has	32	454	-1	1	no	yes
11	none	has	32	455	-1	2	no	yes
11	none	has	32	456	-1	3	no	yes
11	fmpc	has	32	457	-1	1	no	yes
11	fmpc	has	32	458	-1	2	no	yes
11	fmpc	has	32	459	-1	3	no	yes
12	eba	lanus	33	461	2	1	no	yes
12	eba	lanus	33	462	2	2	no	yes
12	eba	lanus	33	463	2	3	no	yes
12	none	lanus	33	464	2	1	no	yes
12	none	lanus	33	465	2	2	no	yes
12	none	lanus	33	466	2	3	no	yes
12	none	aps	33	467	-2	1	no	yes
12	none	aps	33	468	-2	2	no	yes
12	none	aps	33	469	-2	3	no	yes
12	eba	aps	33	470	-2	1	no	yes
12	eba	aps	33	471	-2	2	no	yes
12	eba	aps	33	472	-2	3	no	yes
12	eba	has	33	473	2	1	no	yes
12	eba	has	33	474	2	2	no	yes
12	eba	has	33	475	2	3	no	yes
12	none	has	33	476	2	1	no	yes
12	none	has	33	477	2	2	no	yes
12	none	has	33	478	2	3	no	yes
12	none	las	33	479	-2	1	no	yes
12	none	las	33	480	-2	2	no	yes
12	none	las	33	481	-2	3	no	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
12	eba	las	33	482	-2	1	no	yes
12	eba	las	33	483	-2	2	no	yes
12	eba	las	33	484	-2	3	no	yes
13	none	lanus	34	486	-2	1	no	no
13	none	lanus	34	487	-2	2	no	no
13	none	lanus	34	488	-2	3	no	no
13	eba	lanus	34	489	-2	1	no	no
13	eba	lanus	34	490	-2	2	no	no
13	eba	lanus	34	491	-2	3	no	no
13	eba	aps	34	492	2	1	no	no
13	eba	aps	34	493	2	2	no	no
13	eba	aps	34	494	2	3	no	no
13	none	aps	34	495	2	1	no	no
13	none	aps	34	496	2	2	no	no
13	none	aps	34	497	2	3	no	no
13	none	lanus	36	499	-1	1	no	yes
13	none	lanus	36	500	-1	2	no	yes
13	none	lanus	36	501	-1	3	no	yes
13	fmpc	lanus	36	502	-1	1	no	yes
13	fmpc	lanus	36	503	-1	2	no	yes
13	fmpc	lanus	36	504	-1	3	no	yes
13	fmpc	aps	36	505	1	1	no	yes
13	fmpc	aps	36	506	1	2	no	yes
13	fmpc	aps	36	507	1	3	no	yes
13	none	aps	36	508	1	1	no	yes
13	none	aps	36	509	1	2	no	yes
13	none	aps	36	510	1	3	no	yes
13	none	has	34	511	-2	1	no	no
13	none	has	34	512	-2	2	no	no
13	none	has	34	513	-2	3	no	no
13	eba	has	34	514	-2	1	no	no
13	eba	has	34	515	-2	2	no	no
13	eba	has	34	516	-2	3	no	no
13	eba	las	34	517	2	1	no	no
13	eba	las	34	518	2	2	no	no
13	eba	las	34	519	2	3	no	no
13	none	las	34	520	2	1	no	no
13	none	las	34	521	2	2	no	no
13	none	las	34	522	2	3	no	no
13	none	has	36	523	-1	1	no	yes
13	none	has	36	524	-1	2	no	yes
13	none	has	36	525	-1	3	no	yes
13	fmpc	has	36	526	-1	1	no	yes
13	fmpc	has	36	527	-1	2	no	yes
13	fmpc	has	36	528	-1	3	no	yes
13	fmpc	las	36	529	1	1	no	yes
13	fmpc	las	36	530	1	2	no	yes
13	fmpc	las	36	531	1	3	no	yes
13	none	las	36	532	1	1	no	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
13	none	las	36	533	1	2	no	yes
13	none	las	36	534	1	3	no	yes
14	fmpc	lanus	35	536	1	1	no	yes
14	fmpc	lanus	35	537	1	2	no	yes
14	fmpc	lanus	35	538	1	3	no	yes
14	none	lanus	35	539	1	1	no	yes
14	none	lanus	35	540	1	2	no	yes
14	none	lanus	35	541	1	3	no	yes
14	none	aps	35	542	-1	1	no	yes
14	none	aps	35	543	-1	2	no	yes
14	none	aps	35	544	-1	3	no	yes
14	fmpc	aps	35	545	-1	1	no	yes
14	fmpc	aps	35	546	-1	2	no	yes
14	fmpc	aps	35	547	-1	3	no	yes
14	fmpc	has	35	548	1	1	no	yes
14	fmpc	has	35	549	1	2	no	yes
14	fmpc	has	35	550	1	3	no	yes
14	none	has	35	551	1	1	no	yes
14	none	has	35	552	1	2	no	yes
14	none	has	35	553	1	3	no	yes
14	none	las	35	554	-1	1	no	yes
14	none	las	35	555	-1	2	no	yes
14	none	las	35	556	-1	3	no	yes
14	fmpc	las	35	557	-1	1	no	yes
14	fmpc	las	35	558	-1	2	no	yes
14	fmpc	las	35	559	-1	3	no	yes
14	fmpc	las	35	560	-1	4	no	yes
15	none	aps	37	562	-2	1	yes	yes
15	none	aps	37	563	-2	2	yes	yes
15	none	aps	37	564	-2	3	yes	yes
15	eba	aps	37	565	-2	1	yes	yes
15	eba	aps	37	566	-2	2	yes	yes
15	eba	aps	37	567	-2	3	yes	yes
15	eba	has	37	568	2	1	yes	yes
15	eba	has	37	569	2	2	yes	yes
15	eba	has	37	570	2	3	yes	yes
15	none	has	37	571	2	1	yes	yes
15	none	has	37	572	2	2	yes	yes
15	none	has	37	573	2	3	yes	yes
15	none	aps	38	575	-1	1	yes	yes
15	none	aps	38	576	-1	2	yes	yes
15	none	aps	38	577	-1	3	yes	yes
15	fmpc	aps	38	578	-1	1	yes	yes
15	fmpc	aps	38	579	-1	2	yes	yes
15	fmpc	aps	38	580	-1	3	yes	yes
15	fmpc	has	38	581	1	1	yes	yes
15	fmpc	has	38	582	1	2	yes	yes
15	fmpc	has	38	583	1	3	yes	yes
15	none	has	38	584	1	1	yes	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
15	none	has	38	585	1	2	yes	yes
15	none	has	38	586	1	3	yes	yes
15	none	las	37	587	-2	1	yes	yes
15	none	las	37	588	-2	2	yes	yes
15	none	las	37	589	-2	3	yes	yes
15	eba	las	37	590	-2	1	yes	yes
15	eba	las	37	591	-2	2	yes	yes
15	eba	las	37	592	-2	3	yes	yes
15	eba	lanus	37	593	2	1	yes	yes
15	eba	lanus	37	594	2	2	yes	yes
15	eba	lanus	37	595	2	3	yes	yes
15	none	lanus	37	596	2	1	yes	yes
15	none	lanus	37	597	2	2	yes	yes
15	none	lanus	37	598	2	3	yes	yes
15	none	las	38	599	-1	1	yes	yes
15	none	las	38	600	-1	2	yes	yes
15	none	las	38	601	-1	3	yes	yes
15	fmpc	las	38	602	-1	1	yes	yes
15	fmpc	las	38	603	-1	2	yes	yes
15	fmpc	las	38	604	-1	3	yes	yes
15	fmpc	lanus	38	605	1	1	yes	yes
15	fmpc	lanus	38	606	1	2	yes	yes
15	fmpc	lanus	38	607	1	3	yes	yes
15	none	lanus	38	608	1	1	yes	yes
15	none	lanus	38	609	1	2	yes	yes
15	none	lanus	38	610	1	3	yes	yes
16	none	has	40	612	-1	1	no	no
16	none	has	40	613	-1	2	no	no
16	none	has	40	614	-1	3	no	no
16	fmpc	has	40	615	-1	1	no	no
16	fmpc	has	40	616	-1	2	no	no
16	fmpc	has	40	617	-1	3	no	no
16	fmpc	las	40	618	1	1	no	no
16	fmpc	las	40	619	1	2	no	no
16	fmpc	las	40	620	1	3	no	no
16	none	las	40	621	1	1	no	no
16	none	las	40	622	1	2	no	no
16	none	las	40	623	1	3	no	no
16	none	has	39	625	-2	1	no	no
16	none	has	39	626	-2	2	no	no
16	none	has	39	627	-2	3	no	no
16	eba	has	39	628	-2	1	no	no
16	eba	has	39	629	-2	2	no	no
16	eba	has	39	630	-2	3	no	no
16	eba	las	39	631	2	1	no	no
16	eba	las	39	632	2	2	no	no
16	eba	las	39	633	2	3	no	no
16	eba	las	39	634	2	4	no	no
16	none	las	39	635	2	1	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
16	none	las	39	636	2	2	no	no
16	none	las	39	637	2	3	no	no
16	none	lanus	40	638	-1	1	no	no
16	none	lanus	40	639	-1	2	no	no
16	none	lanus	40	640	-1	3	no	no
16	fmpc	lanus	40	641	-1	1	no	no
16	fmpc	lanus	40	642	-1	2	no	no
16	fmpc	lanus	40	643	-1	3	no	no
16	fmpc	lanus	40	644	-1	4	no	no
16	fmpc	aps	40	645	1	1	no	no
16	fmpc	aps	40	646	1	2	no	no
16	fmpc	aps	40	647	1	3	no	no
16	none	aps	40	648	1	1	no	no
16	none	aps	40	649	1	2	no	no
16	none	aps	40	650	1	3	no	no
16	none	lanus	39	651	-2	1	no	no
16	none	lanus	39	652	-2	2	no	no
16	none	lanus	39	653	-2	3	no	no
16	none	lanus	39	654	-2	4	no	no
16	eba	lanus	39	655	-2	1	no	no
16	eba	lanus	39	656	-2	2	no	no
16	eba	lanus	39	657	-2	3	no	no
16	eba	aps	39	658	2	1	no	no
16	eba	aps	39	659	2	2	no	no
16	eba	aps	39	660	2	3	no	no
16	none	aps	39	661	2	1	no	no
16	none	aps	39	662	2	2	no	no
16	none	aps	39	663	2	3	no	no
16	eba	lanus	11	665	2	1	yes	yes
16	eba	lanus	11	666	2	2	yes	yes
16	eba	lanus	11	667	2	3	yes	yes
16	none	lanus	11	668	2	1	yes	yes
16	none	lanus	11	669	2	2	yes	yes
16	none	lanus	11	670	2	3	yes	yes
16	none	lanus	11	671	2	4	yes	yes
16	none	aps	11	672	-2	1	yes	yes
16	none	aps	11	673	-2	2	yes	yes
16	none	aps	11	674	-2	3	yes	yes
16	eba	aps	11	675	-2	1	yes	yes
16	eba	aps	11	676	-2	2	yes	yes
16	eba	aps	11	677	-2	3	yes	yes
16	fmpc	lanus	43	679	1	1	yes	yes
16	fmpc	lanus	43	680	1	2	yes	yes
16	fmpc	lanus	43	681	1	3	yes	yes
16	none	lanus	43	682	1	1	yes	yes
16	none	lanus	43	683	1	2	yes	yes
16	none	lanus	43	684	1	3	yes	yes
16	none	aps	43	685	-1	1	yes	yes
16	none	aps	43	686	-1	2	yes	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
16	none	aps	43	687	-1	3	yes	yes
16	fmpc	aps	43	688	-1	1	yes	yes
16	fmpc	aps	43	689	-1	2	yes	yes
16	fmpc	aps	43	690	-1	3	yes	yes
16	eba	las	11	691	2	1	yes	yes
16	eba	las	11	692	2	2	yes	yes
16	eba	las	11	693	2	3	yes	yes
16	eba	las	11	694	2	4	yes	yes
16	none	las	11	695	2	1	yes	yes
16	none	las	11	696	2	2	yes	yes
16	none	las	11	697	2	3	yes	yes
16	none	has	11	698	-2	1	yes	yes
16	none	has	11	699	-2	2	yes	yes
16	none	has	11	700	-2	3	yes	yes
16	eba	has	11	701	-2	1	yes	yes
16	eba	has	11	702	-2	2	yes	yes
16	eba	has	11	703	-2	3	yes	yes
16	fmpc	las	43	704	1	1	yes	yes
16	fmpc	las	43	705	1	2	yes	yes
16	fmpc	las	43	706	1	3	yes	yes
16	none	las	43	707	1	1	yes	yes
16	none	las	43	708	1	2	yes	yes
16	none	las	43	709	1	3	yes	yes
16	none	has	43	710	-1	1	yes	yes
16	none	has	43	711	-1	2	yes	yes
16	none	has	43	712	-1	3	yes	yes
16	fmpc	has	43	713	-1	1	yes	yes
16	fmpc	has	43	714	-1	2	yes	yes
16	fmpc	has	43	715	-1	3	yes	yes
17	eba	las	44	717	2	1	no	no
17	eba	las	44	718	2	2	no	no
17	eba	las	44	719	2	3	no	no
17	none	las	44	720	2	1	no	no
17	none	las	44	721	2	2	no	no
17	none	las	44	722	2	3	no	no
17	none	has	44	723	-2	1	no	no
17	none	has	44	724	-2	2	no	no
17	none	has	44	725	-2	3	no	no
17	eba	has	44	726	-2	1	no	no
17	eba	has	44	727	-2	2	no	no
17	eba	has	44	728	-2	3	no	no
17	eba	lanus	44	729	2	1	no	no
17	eba	lanus	44	730	2	2	no	no
17	eba	lanus	44	731	2	3	no	no
17	none	lanus	44	732	2	1	no	no
17	none	lanus	44	733	2	2	no	no
17	none	lanus	44	734	2	3	no	no
17	none	lanus	44	735	2	4	no	no
17	none	aps	44	736	-2	1	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
17	none	aps	44	737	-2	2	no	no
17	none	aps	44	738	-2	3	no	no
17	eba	aps	44	739	-2	1	no	no
17	eba	aps	44	740	-2	2	no	no
17	eba	aps	44	741	-2	3	no	no
18	fmpc	has	42	743	1	1	no	no
18	fmpc	has	42	744	1	2	no	no
18	fmpc	has	42	745	1	3	no	no
18	none	has	42	746	1	1	no	no
18	none	has	42	747	1	2	no	no
18	none	has	42	748	1	3	no	no
18	none	las	42	749	-1	1	no	no
18	none	las	42	750	-1	2	no	no
18	none	las	42	751	-1	3	no	no
18	fmpc	las	42	752	-1	1	no	no
18	fmpc	las	42	753	-1	2	no	no
18	fmpc	las	42	754	-1	3	no	no
18	eba	has	41	756	2	1	no	no
18	eba	has	41	757	2	2	no	no
18	eba	has	41	758	2	3	no	no
18	none	has	41	759	2	1	no	no
18	none	has	41	760	2	2	no	no
18	none	has	41	761	2	3	no	no
18	none	las	41	762	-2	1	no	no
18	none	las	41	763	-2	2	no	no
18	none	las	41	764	-2	3	no	no
18	eba	las	41	765	-2	1	no	no
18	eba	las	41	766	-2	2	no	no
18	eba	las	41	767	-2	3	no	no
18	fmpc	lanus	42	768	1	1	no	no
18	fmpc	lanus	42	769	1	2	no	no
18	fmpc	lanus	42	770	1	3	no	no
18	none	lanus	42	771	1	1	no	no
18	none	lanus	42	772	1	2	no	no
18	none	lanus	42	773	1	3	no	no
18	none	aps	42	774	-1	1	no	no
18	none	aps	42	775	-1	2	no	no
18	none	aps	42	776	-1	3	no	no
18	fmpc	aps	42	777	-1	1	no	no
18	fmpc	aps	42	778	-1	2	no	no
18	fmpc	aps	42	779	-1	3	no	no
18	eba	lanus	41	780	2	1	no	no
18	eba	lanus	41	781	2	2	no	no
18	eba	lanus	41	782	2	3	no	no
18	none	lanus	41	783	2	1	no	no
18	none	lanus	41	784	2	2	no	no
18	none	lanus	41	785	2	3	no	no
18	none	aps	41	786	-2	1	no	no
18	none	aps	41	787	-2	2	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
18	none	aps	41	788	-2	3	no	no
18	eba	aps	41	789	-2	1	no	no
18	eba	aps	41	790	-2	2	no	no
18	eba	aps	41	791	-2	3	no	no
19	none	las	46	793	-1	1	no	no
19	none	las	46	794	-1	2	no	no
19	none	las	46	795	-1	3	no	no
19	fmpc	las	46	796	-1	1	no	no
19	fmpc	las	46	797	-1	2	no	no
19	fmpc	las	46	798	-1	3	no	no
19	fmpc	has	46	799	1	1	no	no
19	fmpc	has	46	800	1	2	no	no
19	fmpc	has	46	801	1	3	no	no
19	none	has	46	802	1	1	no	no
19	none	has	46	803	1	2	no	no
19	none	has	46	804	1	3	no	no
19	none	las	45	806	-2	1	no	no
19	none	las	45	807	-2	2	no	no
19	none	las	45	808	-2	3	no	no
19	none	las	45	809	-2	4	no	no
19	eba	las	45	810	-2	1	no	no
19	eba	las	45	811	-2	2	no	no
19	eba	las	45	812	-2	3	no	no
19	eba	has	45	813	2	1	no	no
19	eba	has	45	814	2	2	no	no
19	eba	has	45	815	2	3	no	no
19	none	has	45	816	2	1	no	no
19	none	has	45	817	2	2	no	no
19	none	has	45	818	2	3	no	no
19	none	lanus	46	819	-1	1	no	no
19	none	lanus	46	820	-1	2	no	no
19	none	lanus	46	821	-1	3	no	no
19	fmpc	lanus	46	822	-1	1	no	no
19	fmpc	lanus	46	823	-1	2	no	no
19	fmpc	lanus	46	824	-1	3	no	no
19	fmpc	aps	46	825	1	1	no	no
19	fmpc	aps	46	826	1	2	no	no
19	fmpc	aps	46	827	1	3	no	no
19	none	aps	46	828	1	1	no	no
19	none	aps	46	829	1	2	no	no
19	none	aps	46	830	1	3	no	no
19	none	lanus	45	831	-2	1	no	no
19	none	lanus	45	832	-2	2	no	no
19	none	lanus	45	833	-2	3	no	no
19	eba	lanus	45	834	-2	1	no	no
19	eba	lanus	45	835	-2	2	no	no
19	eba	lanus	45	836	-2	3	no	no
19	eba	aps	45	837	2	1	no	no
19	eba	aps	45	838	2	2	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
19	eba	aps	45	839	2	3	no	no
19	none	aps	45	840	2	1	no	no
19	none	aps	45	841	2	2	no	no
19	none	aps	45	842	2	3	no	no
20	eba	aps	48	844	2	1	no	no
20	eba	aps	48	845	2	2	no	no
20	eba	aps	48	846	2	3	no	no
20	none	aps	48	847	2	1	no	no
20	none	aps	48	848	2	2	no	no
20	none	aps	48	849	2	3	no	no
20	none	las	48	850	-2	1	no	no
20	none	las	48	851	-2	2	no	no
20	none	las	48	852	-2	3	no	no
20	eba	las	48	853	-2	1	no	no
20	eba	las	48	854	-2	2	no	no
20	eba	las	48	855	-2	3	no	no
20	fmpc	aps	47	857	1	1	no	yes
20	fmpc	aps	47	858	1	2	no	yes
20	fmpc	aps	47	859	1	3	no	yes
20	none	aps	47	860	1	1	no	yes
20	none	aps	47	861	1	2	no	yes
20	none	aps	47	862	1	3	no	yes
20	none	las	47	863	-1	1	no	yes
20	none	las	47	864	-1	2	no	yes
20	none	las	47	865	-1	3	no	yes
20	fmpc	las	47	866	-1	1	no	yes
20	fmpc	las	47	867	-1	2	no	yes
20	fmpc	las	47	868	-1	3	no	yes
20	eba	has	48	869	2	1	no	no
20	eba	has	48	870	2	2	no	no
20	eba	has	48	871	2	3	no	no
20	none	has	48	872	2	1	no	no
20	none	has	48	873	2	2	no	no
20	none	has	48	874	2	3	no	no
20	none	lanus	48	875	-2	1	no	no
20	none	lanus	48	876	-2	2	no	no
20	none	lanus	48	877	-2	3	no	no
20	eba	lanus	48	878	-2	1	no	no
20	eba	lanus	48	879	-2	2	no	no
20	eba	lanus	48	880	-2	3	no	no
20	fmpc	has	47	881	1	1	no	yes
20	fmpc	has	47	882	1	2	no	yes
20	fmpc	has	47	883	1	3	no	yes
20	none	has	47	884	1	1	no	yes
20	none	has	47	885	1	2	no	yes
20	none	has	47	886	1	3	no	yes
20	none	lanus	47	887	-1	1	no	yes
20	none	lanus	47	888	-1	2	no	yes
20	none	lanus	47	889	-1	3	no	yes

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
20	fmpc	lanus	47	890	-1	1	no	yes
20	fmpc	lanus	47	891	-1	2	no	yes
20	fmpc	lanus	47	892	-1	3	no	yes
21	fmpc	las	53	894	1	1	no	no
21	fmpc	las	53	895	1	2	no	no
21	fmpc	las	53	896	1	3	no	no
21	none	las	53	897	1	1	no	no
21	none	las	53	898	1	2	no	no
21	none	las	53	899	1	3	no	no
21	none	has	53	900	-1	1	no	no
21	none	has	53	901	-1	2	no	no
21	none	has	53	902	-1	3	no	no
21	fmpc	has	53	903	-1	1	no	no
21	fmpc	has	53	904	-1	2	no	no
21	fmpc	has	53	905	-1	3	no	no
21	none	lanus	53	906	-1	1	no	no
21	none	lanus	53	907	-1	2	no	no
21	none	lanus	53	908	-1	3	no	no
21	fmpc	lanus	53	909	-1	1	no	no
21	fmpc	lanus	53	910	-1	2	no	no
21	fmpc	lanus	53	911	-1	3	no	no
21	none	aps	53	912	-1	1	no	no
21	none	aps	53	913	-1	2	no	no
21	none	aps	53	914	-1	3	no	no
21	fmpc	aps	53	915	-1	1	no	no
21	fmpc	aps	53	916	-1	2	no	no
21	fmpc	aps	53	917	-1	3	no	no
22	none	aps	50	919	-2	1	no	yes
22	none	aps	50	920	-2	2	no	yes
22	none	aps	50	921	-2	3	no	yes
22	eba	aps	50	922	-2	1	no	yes
22	eba	aps	50	923	-2	2	no	yes
22	eba	aps	50	924	-2	3	no	yes
22	eba	las	50	925	2	1	no	yes
22	eba	las	50	926	2	2	no	yes
22	eba	las	50	927	2	3	no	yes
22	none	las	50	928	2	1	no	yes
22	none	las	50	929	2	2	no	yes
22	none	las	50	930	2	3	no	yes
22	none	aps	49	932	-1	1	no	no
22	none	aps	49	933	-1	2	no	no
22	none	aps	49	934	-1	3	no	no
22	fmpc	aps	49	935	-1	1	no	no
22	fmpc	aps	49	936	-1	2	no	no
22	fmpc	aps	49	937	-1	3	no	no
22	fmpc	las	49	938	1	1	no	no
22	fmpc	las	49	939	1	2	no	no
22	fmpc	las	49	940	1	3	no	no
22	none	las	49	941	1	1	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
22	none	las	49	942	1	2	no	no
22	none	las	49	943	1	3	no	no
22	none	has	50	944	-2	1	no	yes
22	none	has	50	945	-2	2	no	yes
22	none	has	50	946	-2	3	no	yes
22	eba	has	50	947	-2	1	no	yes
22	eba	has	50	948	-2	2	no	yes
22	eba	has	50	949	-2	3	no	yes
22	eba	lanus	50	950	2	1	no	yes
22	eba	lanus	50	951	2	2	no	yes
22	eba	lanus	50	952	2	3	no	yes
22	none	lanus	50	953	2	1	no	yes
22	none	lanus	50	954	2	2	no	yes
22	none	lanus	50	955	2	3	no	yes
22	none	has	49	956	-1	1	no	no
22	none	has	49	957	-1	2	no	no
22	none	has	49	958	-1	3	no	no
22	fmpc	has	49	959	-1	1	no	no
22	fmpc	has	49	960	-1	2	no	no
22	fmpc	has	49	961	-1	3	no	no
22	fmpc	lanus	49	962	1	1	no	no
22	fmpc	lanus	49	963	1	2	no	no
22	fmpc	lanus	49	964	1	3	no	no
22	none	lanus	49	965	1	1	no	no
22	none	lanus	49	966	1	2	no	no
22	none	lanus	49	967	1	3	no	no
23	none	lanus	51	969	-2	1	no	yes
23	none	lanus	51	970	-2	2	no	yes
23	none	lanus	51	971	-2	3	no	yes
23	none	lanus	51	972	-2	4	no	yes
23	eba	lanus	51	973	-2	1	no	yes
23	eba	lanus	51	974	-2	2	no	yes
23	eba	lanus	51	975	-2	3	no	yes
23	eba	aps	51	976	2	1	no	yes
23	eba	aps	51	977	2	2	no	yes
23	eba	aps	51	978	2	3	no	yes
23	none	aps	51	979	2	1	no	yes
23	none	aps	51	980	2	2	no	yes
23	none	aps	51	981	2	3	no	yes
23	fmpc	lanus	52	983	1	1	no	no
23	fmpc	lanus	52	984	1	2	no	no
23	fmpc	lanus	52	985	1	3	no	no
23	none	lanus	52	986	1	1	no	no
23	none	lanus	52	987	1	2	no	no
23	none	lanus	52	988	1	3	no	no
23	fmpc	aps	52	989	1	1	no	no
23	fmpc	aps	52	990	1	2	no	no
23	fmpc	aps	52	991	1	3	no	no
23	none	aps	52	992	1	1	no	no

Day	Alg.	Scn.	Pilot	Run	Seq	Itr.	Test Pilot	Mil. Trained
23	none	aps	52	993	1	2	no	no
23	none	aps	52	994	1	3	no	no
23	none	las	51	995	-2	1	no	yes
23	none	las	51	996	-2	2	no	yes
23	none	las	51	997	-2	3	no	yes
23	eba	las	51	998	-2	1	no	yes
23	eba	las	51	999	-2	2	no	yes
23	eba	las	51	1000	-2	3	no	yes
23	eba	has	51	1001	2	1	no	yes
23	eba	has	51	1002	2	2	no	yes
23	eba	has	51	1003	2	3	no	yes
23	none	has	51	1004	2	1	no	yes
23	none	has	51	1005	2	2	no	yes
23	none	has	51	1006	2	3	no	yes
23	none	las	52	1007	-1	1	no	no
23	none	las	52	1008	-1	2	no	no
23	none	las	52	1009	-1	3	no	no
23	fmpc	las	52	1010	-1	1	no	no
23	fmpc	las	52	1011	-1	2	no	no
23	fmpc	las	52	1012	-1	3	no	no
23	fmpc	has	52	1013	1	1	no	no
23	fmpc	has	52	1014	1	2	no	no
23	fmpc	has	52	1015	1	3	no	no
23	none	has	52	1016	1	1	no	no
23	none	has	52	1017	1	2	no	no
23	none	has	52	1018	1	3	no	no

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14. ABSTRACT

A stall recovery guidance system was designed to help pilots improve their stall recovery performance when the current aircraft state may be unrecognized under various complicating operational factors. Candidate guidance algorithms were connected to the split-cue pitch and roll flight directors that are standard on large transport commercial aircraft. A new thrust guidance algorithm and cue was also developed to help pilots prevent the combination of excessive thrust and nose-up stabilizer trim. The overall system was designed to reinforce the current FAA recommended stall recovery procedure. A general transport aircraft model, similar to a Boeing 757, with an extended aerodynamic database for improved stall dynamics simulation fidelity was integrated into the Vertical Motion Simulator at NASA Ames Research Center. A detailed study of the guidance system was then conducted across four stall scenarios with 30 commercial and 10 research test pilots, and the results are reported.

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