CONTEXT DEPENDENT TOTAL ENERGY ALERTING SYSTEM FOR THE DETECTION OF LOW ENERGY UNSTABILIZED APPROACHES

A Thesis
Presented to
The Academic Faculty

by

Michael Portman

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in the
School of Aerospace Engineering

Georgia Institute of Technology
August, 2019

CONTEXT DEPENDENT TOTAL ENERGY ALERTING SYSTEM FOR THE DETECTION OF LOW ENERGY UNSTABILIZED APPROACHES

Approved by:

Dr. Amy R. Pritchett, Advisor and Co-Chair
Department of Aerospace Engineering
Pennsylvania State University

Dr. Brian German, Co-Chair
School of Aerospace Engineering
Georgia Institute of Technology

Dr. John-Paul Clarke
School of Aerospace Engineering
Georgia Institute of Technology

Date Approved: June 28, 2019

ACKNOWLEDGEMENTS

First, I'd like to thank my thesis committee, Co-Chairs Dr. Amy Pritchett and Dr. Brian German, as well as Dr. John-Paul Clarke. Their insight, experience, questions, and feedback have made this endeavor fascinating, challenging, and inspiring, and I consider my thesis much stronger thanks to their influence. Special thanks go to Dr. Pritchett who has been my advisor and mentor for both my undergraduate and graduate career. She has truly shaped the academician, engineer, and safety professional that I am today. I have had the incredible fortune of having several other mentors throughout my life and education. Captain Buddy Roberts, Dr. Mark Rosekind, and too many others to name have each helped me in unique and invaluable ways. Each of these mentors, for their time, passion, and interest in me, deserve great thanks.

A big thanks to my commercial aviation safety colleagues for providing me with the platform upon which I ran my thesis, and for exposing me to the amazing world of commercial aviation. I'd like to thank my colleagues in the Cognitive Engineering Center. Special thanks go to my thesis partner Martijn IJtsma for copy editing everything I wrote, no matter how painful, suggesting edits, and keeping me on task. Bedank hem namens mij, voor al zijn hulp en vriendschap. A big thanks to all my other friends and family, Celine, Katie, Logan, Ajmal, Zach and Aria, SK, Kevin, and many more, for supporting me through this thesis.

I'd like to thank Yafa Portman for the unconditional love and support throughout the writing process. Lastly, I'd like to thank my mother, Dr. Sandra Portman. From the inspiration to pursue academic achievement, to pushing me through the tough times and believing in me the entire way, I will forever owe a great debt of gratitude.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AFE	Above Field Elevation
ALA	Approach and Landing Accidents
ALAR	Approach and Landing Accident Reduction task force
A/T	Autothrottle
CVR	Cockpit Voice Recorder
D	Drag
EGPWS	Enhanced Ground Proximity Warning System
FAA	Federal Aviation Administration
FAF	Final Approach Fix
F/D	Flight Director
FDR	Flight Data Recorder
FLCH	Flight Level Change
FOQA	Flight Operations Quality Assurance
FSF	Flight Safety Foundation
GPWS	Ground Proximity Warning System
GS	Glide Slope
h	Height
HAT	Height Above Touchdown
HF	Human Factors
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
LAA	Low Airspeed Alert
NASA	National Aeronautics and Space Administration

NTSB	National Transportation Safety Board
PAPI	Precision Approach Path Indicator
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility and Sustainability
PF	Pilot Flying
PM	Pilot Monitoring
SAFO	Safety Alert for Operators
T	Thrust
TAWS	Terrain Awareness Warning System
TCAS	Traffic Collision Avoidance System
TE	Total Energy
TEA	Total Energy Alert
V	Airspeed
VMC	Visual Meteorological Conditions
V_{REF}	Reference Approach Airspeed
VS	Vertical Speed
$\dot{z}$	Vertical Speed

SUMMARY

This thesis examines context dependent total energy alerting to protect against low energy unstable approaches in commercial aviation operations. Currently, many individual states are monitored independently to identify unstable approaches, rather than an integrated single assessment of total energy. An alert would also have to be context dependent, integrating the individual states with awareness of phase of flight, approach profile modeling, and expected pilot response to individualize the alert's activation threshold for each approach. This thesis details a design of such a context dependent total energy alerting system. First, a preliminary analysis examines when such an alert would have been given in a case study of Asiana Airlines Flight 214. This flight's crash on approach into San Francisco International Airport was attributed to lack of pilot situational awareness and understanding of the aircraft's autoflight systems, leading to the aircraft having sufficiently low total energy that it stalled into the seawall just before the runway threshold. Analysis shows the total energy alert would have sounded roughly 14-41 seconds before impact, earlier than any currently installed system and potentially early enough for corrective action. Next, the context dependent total energy alert is analyzed to assess its performance in real flight as captured by Flight Operations Quality Assurance (FOQA) data. The analysis examines how alerting parameters impact when and how often the alert is triggered, and the thesis concludes with recommendations for the design and application of a context dependent total energy alert, along with recommendations for future work.

CHAPTER 1. INTRODUCTION

1.1 Problem Statement

Currently, the literature defines unstable approaches according to a range of conditions including improper airspeed, altitude, deviation from the proper approach path, and incorrect aircraft configuration. Many cockpit alerting systems exist which warn pilots of some of these conditions individually. These systems include low altitude alerts and low airspeed alerts, in addition to several additional systems which each independently display or warn of the conditions collectively defining unstable approaches. Nonetheless, no system exists which combines these criteria to alert pilots to low total energy conditions.

These unstable approaches, and corresponding lack of alerting, have led to catastrophic outcomes. Notably, in July of 2013, Asiana Airlines Flight 214 crashed on approach into San Francisco International Airport, resulting in the total loss of the aircraft and death of three passengers. In its final report, the National Transportation Safety Board (NTSB) cited, as contributing to the accident, a lack of pilot familiarity with and inappropriate use of the autopilot system, and lack of pilot situational awareness, collectively leading to an unstable vertical profile and speed on approach (NTSB, 2013). To enhance the safety of commercial aviation, the NTSB recommended, among other rectifications, the development of a context dependent total energy alerting system.

This thesis introduces such a context dependent low total energy alerting system. The alert integrates data already available via sensors onboard air transport aircraft to estimate both the aircraft's current energy state and the trend in total energy. The system projects whether the aircraft's total energy will become too low within an immediate future time horizon and, if so, alerts the pilot to the danger. The future time horizon is intended to be long enough to allow pilots ample time to recover or abort the approach.

Much research has taken place to evaluate energy metrics for use in aviation, from applications in education and post-flight analysis to design of autoflight systems. However, little emphasis has been placed on developing alerts, particularly for situations in which pilots are manually flying the aircraft. Additionally, little research has taken place evaluating the real-world utility of such an alert. To be truly useful, the alert should be able to detect low energy unstable approach conditions with a correct detection rate similar to or greater than current technology and provide more advanced warning.

1.2 Contributions

Multiple research projects and accident investigations have demonstrated the need for total energy alerting systems in modern commercial aviation cockpits. Especially of need is the ability to alert pilots engaged in both hand flying as well as interacting with autoflight systems. Through the evaluation of such an alert in its basic form, this thesis will determine the alert's ability to effectively discriminate stable versus unstable approaches as compared to current day technology. This includes developing the algorithms which will improve pilot awareness of the aircraft's energy state. Subsequently, the work will evaluate how alerting parameters impact alert effectiveness, thereby providing recommendations for the practical design and application considerations needed for this type of alert. Unique to the work completed in this thesis is the analysis of the alerting algorithm by evaluating its performance in real flights as captured by Flight Operations Quality Assurance (FOQA) data. This application allows for a larger-scale analysis of the design metrics of such an energy alert that, previously, was only performed on either small sets of flight data or in simulations with pilots actively flying.

1.3 Overview of Thesis

Chapter 2 presents a literature review by first posing several fundamental questions to better define the required attributes of a context dependent total energy alert: What is the function of an alert? What is total energy? What is context dependency? Why would we need a total energy alert? What are the attributes of a good total energy alert? Next, a review of current technology and research is provided, to detail areas of current industry interest and progress, and to demonstrate opportunities for further research and development.

In chapter 3, the context dependent total energy alert's algorithm is presented. In summary, the algorithm creates a sum of energy from both kinetic and potential energy sources, and additionally calculates the rate of change of this total energy. The algorithm then predicts the energy state of the aircraft at a given time in the future, as well as calculating some minimum required energy at that time. If the predicted energy is less than that which is required, the alert is triggered.

Chapter 4 evaluates the alerting algorithm across a range of potential alerting thresholds. First, the alert is applied in an analysis of Asiana 214, to determine if the alert would have sounded, and if it would have sounded early enough for the pilots to take corrective action. Next, the alert is applied to the digital flight data records of several hundred thousand flights provided by a major air carrier. This analysis highlights important considerations in determining the alert's threshold. From this, a series of case studies detail these considerations.

This thesis concludes in chapter 5 by re-evaluating the findings from the thesis, discussing the limitations of the analysis, and providing recommendations for the design of the alert. The thesis concludes with the future work required to further validate the alerting algorithm and to extend it into the design of a complete alerting system.

CHAPTER 2. LITERATURE REVIEW

Several key principles are important to a context dependent total energy alert. First, this chapter defines what an alert is, what properties it holds and what functions it can accomplish. Next, this chapter discusses the idea of total energy, the components of total energy important during an approach to landing, and how energy flows from one form to another and increases or decays during an approach. This chapter continues with a discussion of context dependency and, finally, highlights the need for a total energy alert over alerts currently in use.

2.1 What is the Function of an Alert?

First, it is critical to understand the function, purpose, and limitations of an alert. For the purposes of this thesis, Pritchett (2001) provided this definition:

"An alerting system is an electro-mechanical system capable of monitoring for, detecting and announcing conditions anticipated (by the operator or the system designer) to impact the operator's near-term activities."

This definition leads to some important properties of alerts. First, the alert must be capable of properly detecting certain conditions requiring input data from sensors capable of observing relevant states of the aircraft. Second, the alert must be capable of announcing the presence of these conditions through aural, visual, or tactile annunciators, or a combination of such forms. Lastly, the alert must be given at an appropriate time sufficiently early enough to allow the pilot to resolve the condition or abort the approach. This consideration should therefore also include whether the operator should be given time to analyze the information to synthesize the best course of action or the timing requires immediate action without much thought on the operator's part.

2.2 What is Total Energy?

In the context of this research, total energy is defined as the sum of the aircraft's kinetic and gravitational potential energies, as defined by its velocity and position, and measured relative to the elevation of the runway the aircraft is approaching. In the course of a normal approach, some minimum amount of energy is "maintained" in both airspeed (kinetic energy), and altitude (above ground gravitational potential energy). If one energy store becomes too high or low, the pilot can correct via a pitching action, effectively "transferring" energy from one store to another. Energy is added to the system by increasing thrust.

Low total energy, in this context, occurs when there is not sufficient energy in the system as a whole for a pitching action alone to correct the insufficiency in one store without causing insufficiency in the other. Thus, the only appropriate response to a low energy state is to add energy to the system by means of increasing the thrust. It should be noted that this definition is consistent with NTSB recommendations for a context dependent low energy alert (NTSB, 2013).

2.3 What is Context Dependency?

Context dependency is also key in the design of modern cockpit alerts. Context dependency includes awareness of the aircraft's state in ways that would impact the threshold for alerting. For example, in airspeed alerting, the phase of flight, as well as the aircraft's configuration, including gear and flaps, affects the flying characteristics of the aircraft and thus affects its stall speed. Factoring these aspects into the airspeed alert is crucial so that pilots are effectively warned in a timely fashion.

Many early designs of cockpit alerting systems were plagued by lack of context dependency. In particular, early versions of what is now EGPWS (enhanced ground proximity warning system) had infamously high false alarm rates (Pritchett, 2001). These were often caused by the system relying solely on radar altitude, rather than incorporating a terrain database, thus erroneously detecting excessive terrain closure during approaches over terrain that rises up to the runway threshold.

It is important, therefore, to ensure modern cockpit alerting systems account for context dependencies. In this way, the system can better model and monitor the aircraft's performance. This allows for alerts to be customized to each scenario, modifying the alerting threshold according to important contextual clues including phase of flight, vertical approach profile, aircraft weight and thrust setting, as well as flap and landing gear configuration.

2.4 Why Would We Need a Total Energy Alert?

2.4.1 Asiana 214 Overview and Crash Data

The following section presents a high-level overview and timeline of the events leading to the Asiana 214 crash (NTSB, 2013). Particular emphasis is taken to show the evolution of total energy as apparently resulted from the pilot's actions and lack of situational awareness, demonstrating the need for a total energy alert. Beginning very early on in the descent, the pilots were advised to prepare for a visual approach rather than the instrument approach they typically would fly. Shortly before crossing the Final Approach Fix (FAF), the Instructor Pilot noted that the aircraft was too high, and the vertical speed was subsequently set to -1500 feet per minute (fpm). The aircraft crossed the FAF approximately 500ft above the minimum altitude (1,800ft), maintaining a descent rate of -1,000 fpm. At this point of the approach, this aircraft was in a very high energy state, being slightly fast, well above the glide slope, and at a high rate of descent. Typically, to maintain an approach, descent rates are maintained closer to -500 fpm.

The aircraft continued into the final approach still in a high energy state, both high and fast. In an effort to quickly decrease the altitude of the aircraft, at 1,600ft altitude, the Pilot Flying erroneously put the aircraft in Flight Level Change (FLCH) mode presumably to rapidly descend. This is not the intended use of the system, and because the Pilot Monitoring had already input the go around altitude of 3,000ft, the aircraft instead began to pitch and throttle to increase its altitude to 3,000ft. In response to this action, the PF retarded the throttles into the idle position. At this point, one of the Flight Director switches remained on. As a consequence of the design logic for the autothrottle, having a F/D switch on caused the autothrottle to remain in HOLD mode, holding the throttles in the idle position without a safety "wakeup" function active, seemingly without crew awareness. Holding the throttles at idle essentially eliminates the addition of energy into the system as a whole, and, when combined with the rapid descent rate, resulted in the aircraft losing energy very rapidly.

By the decision height of 500ft, flight data recorder data shows that, by coincidence, most basic parameters (glide slope, airspeed, etc.) were on target; however, the aircraft was still showing a very rapid decay in energy because of the throttles being held at idle and the aircraft was maintaining its high descent rate. Transcripts of the cockpit voice recorder show the pilots checking these basic parameters and deciding to continue the approach.

At slightly above 400ft, as the aircraft descended below the glideslope, the PF pulled back on the control column to correct the aircraft's vertical profile through pitching. This had the consequence of further draining the airspeed of the aircraft.

Interestingly, the approach continued without any apparent crew awareness of the deteriorating airspeed until, at approximately 11 seconds before impact, a Low Airspeed Alert quad-chime sounded. A go around was then initiated. However, there was not enough time for the engines spool up to provide sufficient thrust, and the aircraft impacted the seawall just short of the runway threshold.

During the analysis of the accident, the NTSB referenced previous calls for low airspeed alerting, in which systems have already been designed and implemented, as having made progress but insufficient to avoid an accident such as this. As stated in the NTSB final report, as well as Boeing submissions during the investigation, the low airspeed alert is designed as a caution rather than a warning, designed to direct pilots' attention to the decreasing airspeed, but not as a last-minute warning designed to provoke an immediate response. Therefore, the alert is insufficient in both its ability to provoke immediate action and in its ability to convey the type of action needed. Additionally, the Board cautioned that the low airspeed alert by itself "may not be adequately tailored to alert pilots to an impending hazard due to a combination of conditions (i.e., low airspeed combined with low altitude).” (NTSB, 2013) Thus, the Board recognized the need for an alert that would allow the pilots to be aware of a synthesis of potential and kinetic energy states.

2.4.2 Unstabilized Approaches and Stabilized Approach Criteria

The Flight Safety Foundation notes that unstabilized approaches are common in approach-and-landing accidents (ALAs). (Flight Safety Foundation, 2000) Their Approach-and-Landing Accident Reduction (ALAR) task force identified unstable approaches as causal in 66% of approach-and-landing accidents and serious incidents studied between 1984 and 1997. Though a concise, broad definition of unstabilized approaches is difficult to find, they can be roughly defined as approaches that violate either energy or configuration approach requirements in such a way that may significantly increase the risk of continuing the approach to landing.

In association their ALAR task force, the Flight Safety Foundation published criteria to officially determine whether or not an approach is stable. From their manual, the following conditions define a stable approach:

- The aircraft is on the correct flight path as published on the approach plate, and also reflected by displays such as glide slope indicators and PAPI.
- Only small changes in heading/pitch are required to maintain the correct flight path
- The aircraft speed is not more than V_{REF} + 20 knots indicated airspeed and not less than $V_{REF.}$
- The aircraft is in the correct landing configuration.
- Sink rate is no greater than 1,000 feet per minute; if an approach requires a sink rate greater than 1,000 feet per minute, a special briefing should be conducted.

- Power setting is appropriate for the aircraft configuration and is not below the minimum power for approach as defined by the aircraft operating manual.
- All briefings and checklists have been conducted.
- Specific types of approaches are stabilized if they also fulfil the following: instrument landing system (ILS) approaches must be flown within the expanded localizer band; during a circling approach, wings should be level on final when the aircraft reaches 300 feet above airport elevation.
- Unique approach procedures or abnormal conditions requiring a deviation from the above elements of a stabilized approach require a special briefing.

If any of these conditions are not met, or broken, below 1,000 feet above airport elevation in IMC or below 500 feet in VMC, the approach is considered unstable, and the FSF calls for an immediate go around.

Airlines have operationalized these conditions in pilot training, flight operations, and in-flight safety analyses. In practice, these conditions are taught to the pilots, who are then instructed to go around if any of the conditions are broken. Additionally, airline Flight Operations Quality Assurance (FOQA) programs track these conditions in post flight analyses, with triggers in place to automatically flag a flight for further analysis if a certain number of the above described conditions are broken. (McFadden, et al., 1999)

Given that the Flight Safety Foundation criteria can reflect high or low kinetic energy alone, or high or low potential energy alone, an alternative approach uses a total energy perspective. The criteria referencing flight path and sink rate could be thought of as assessing for a proper potential energy reduction profile. Similarly, having proper speeds through the approach could be thought of as having a proper kinetic energy profile. As such, particular emphasis on the distance to runway, speed, and altitude metrics are those primarily used in this thesis, as they help to define the desired energy state of the aircraft. To operationalize this perspective, the number of conditions defining an unstable approach could be theoretically reduced from nine to roughly four (proper energy state, and three other configuration and briefing conditions).

2.4.3 Summary

Implementing a total energy alert would provide an additional safeguard against low energy unstable approaches. As mentioned above, pilots currently have to track several different metrics to determine the stability of the approach. This can not only be a cumbersome task in the midst of hand flying an approach, but also leads to missing a perspective on the overall state of the aircraft from an energy perspective. Alerting based on total energy and trends in total energy can combine many of these metrics together to provide a more comprehensive picture of the aircraft's state and provide an earlier alert for the pilots to act upon.

2.5 What are the Attributes of a Good Total Energy Alert?

Summing together the previous sections, we can define which attributes make a good context dependent total energy alert. The alert should direct the pilot's attention to the predicted unstable approach. As a total energy alert, the measure of approach stability should be based on a combination of both altitude and airspeed metrics. Being context dependent, the alert should reference the approach being flown and be aware of the aircraft's configuration and state to ensure the calculations are as specific to each scenario as possible.

In theory, the alert should minimize both Type I and II errors (false alarm and missed detection). However, in practice, there is usually some trade-off between the two. A later warning will help to reduce false alarms but may result in more missed detections and give less time for pilots to react; an earlier warning will reduce missed detections, but will increase false alarms, potentially becoming a nuisance alarm and leading to pilots disregarding it, even in cases of correct detection. Further, there is no exact standard determining when an alert should be given.

2.6 Review of Current Technology

There are currently many technologies already installed and in operation aboard commercial aircraft today that display and/or alert on conditions contributing to low energy on approach (NTSB, 2013; Boeing, 2014). These include an autothrottle with an A/T Wakeup feature, Enhanced Ground Proximity Warning System (EGPWS), and Low Airspeed Alerting (LAA). These systems add crucial safety features to the aircraft, and yet there is still room for improvement.

- A/T Wakeup: The A/T wakeup is a system built in to the autothrottle that monitors the aircraft's speed. When the airspeed is too low, the autothrottle will "wakeup," automatically advancing the throttles. However, the wakeup feature will only activate if the autothrottle is in BLANK mode (i.e. not engaged); where the autothrottle is engaged and actively tracking low thrust or airspeed at the apparent command of the flight crew, autothrottle will not engage. (In Asiana 214, the autothrottle was effectively placed into HOLD mode, deactivating the A/T wakeup.)

- Enhanced Ground Proximity Warning System (EGPWS): In addition to monitoring excessive closure on terrain EGPWS monitors the aircraft's location with respect to the glide slope (which was inactive for Asiana 214) and will sound an alert if the aircraft has an excessive vertical speed or an excessive deviation from the glide slope. A critical disadvantage of the EGPWS is that when the aircraft is below 150ft radar altitude, the system is desensitized.

- Low Airspeed Alerting (LAA): The Low Airspeed Alerting (LAA) system activates a quadruple chime alarm when the airspeed of the aircraft reaches 30% into amber band. (The amber band is a range of airspeed between the minimum maneuvering speed and the stick shaker activation speed.) This allows for pilots who are cognizant of the situation to operate the aircraft close to and slightly inside the amber band without the nuisance of an unneeded alarm.

In summary, there are several systems currently in place in air transport aircraft. However, there are significant corner conditions in which an alarm is needed, yet no current one would sound. An unavoidable issue with most onboard warning technologies is that, to reduce the likelihood of false alarms, these systems are either inactivated or desensitized when certain conditions are met, such as distance from an airport during an approach. While this does help to reduce nuisance alarms, it does not protect the aircraft against low energy conditions close to the airport. Additionally, because the systems are not interlinked, altitude or airspeed alerts may go off too late, when there is too little energy for the pilot to respond.

2.7 Review of Current and Historical Research

Significant research has examined energy-based metrics for use in aviation. These research activities include the use of energy-based metrics for applications other than alerting (such as vehicle performance analysis and design, flight training and education, as well as flight controls) and energy state awareness without energy prediction. Historically, energy modeling was used as early as the 1940's in the determining of aircraft performance characteristics (Rutowski, 1954; Merritt, et al., 1985). This modeling, whereupon an aircraft's flight characteristics were evaluated as a sum of potential and kinetic energies, was useful in determining climb and cruise range characteristics, especially of high speed aircraft.

More recently, a prominent source of research into the field of energy metrics for flight has been FAA's Center of Excellence titled Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS). Projects conducted within PEGASAS have examined the use of energy monitoring for general aviation training and education, such as energy metrics to evaluate the safety of a flight (Puranik, et al., 2016). Several different types of energy were tracked throughout the flight, rather than solely for approach, and visualized for post-flight analysis.

Separately, Dutch researchers have applied energy metrics to commercial aviation post-flight analysis. In The Automatic Identification of Unstable Approaches from Flight Data, researchers used data from a sample of commercial flights to evaluate the usefulness of the FSF's Stabilized Approach criteria (de Boer, et al., 2014). The basis of this analysis is somewhat similar to that proposed in this thesis in that it builds off first principles examining state of energy. However, this analysis only evaluates total energy state, rather than evaluating energy decay. In this way, the system is not useful to give a look ahead that would be a hallmark early warning feature of the system proposed in this thesis. As a result, the researchers' arguments are more directed towards advocating for a correction to the FSF criteria, rather than proposing an onboard warning system.

In addition to flight training and flight safety efforts, there has also been work to develop flight control systems which operate on the basis of monitoring energy. In patent filings, Boeing engineers proposed an autoflight system which can, through the use of energy metrics, purportedly reduce the complexity of such systems and increase reliability (Lambregts, 1985). It is argued that many of the flight control systems certified for use in commercial aviation applications result from years of evolutionary development, steadily increasing capability, but also complexity. Therefore, this clean sheet design would allow for simpler effective control over the aircraft. However, this system was not designed to incorporate alerting features for manual flying and was designed for nearly completely automated flight.

Separately, researchers at Delft University of Technology investigated the use of energy management in the application to flight path displays (van den Hoven, etc., 2010). In this analysis, researchers developed a total energy-based flight path display and conducted simulator trials to evaluate the effect of such a display on pilot situational awareness of energy state and workload in several approach scenarios. While it was found that this display type increased energy state awareness of the pilots tested, workload also increased with energy display, and further research was recommended to reduce the workload resulting from such a display. Research has also taken place to apply energy metrics to optimize approach profiles to reduce noise (Williams, 2004). This research, a part of NASA's Quiet Aircraft Technology (QAT) project, worked to reduce the noise impact of aircraft operations without making aircraft design changes. To accomplish this, the aircraft's potential energy is maintained, and flaps and gear are held up as long as reasonably possible. In simulator studies, it was found that, on most types of approaches tested, pilots were able to fly the approach path given, resulting in fuel and noise reductions. It is not known to what degree these systems have been implemented in modern commercial aviation.

Additionally, work has been done to develop energy-based alerting during approach. Researchers at NASA Ames have designed an alert similar to that proposed in this thesis (Shish et al., 2015; Shish et al., 2016). Their alert incorporates data from airspeed and altitude, as well as knowledge of autopilot states and mode transition logic. In this way, the Ames system aims to address issues of pilot mode confusion and automation error as contributing to low energy state approaches. As stated in their 2015 paper, their system seeks to "make the behavior of the automation more transparent to the fight crew, while enhancing their energy state awareness, and alerting pilots of problematic autoflight inputs or conditions." (Shish et al., 2015) While the alert did appear to improve both reaction time and outcome in simulator studies, it is still designed for pilots interacting with autoflight systems, rather than alerting pilots during manual flying scenarios. Multiple official recommendations, including FAA SAFOs (Safety Alert for Operators), have been issued to promote manual flying (FAA, 2013; FAA, 2017), especially in approach and landing phases of flight. Thus, any alert designed to protect against unstable approaches must include protections in manual flight regimes. Additionally, as their system was not applied to a large set of real flight data, it was unclear how the system would perform in real world application.

CHAPTER 3. ALERTING ALGORITHM DESIGN

This algorithm is designed to alert pilots to impending low energy unstable approaches. Thus, it is only active during the approach-to-landing phase of flight. This algorithm, similar in principal to that described in "Aircraft Mode and Energy-State Prediction, Assessment, and Alerting," (Shish et al., 2016) monitors and synthesizes information from multiple sources, including airspeed and altitude, but is designed to be effective in both manual and automatic flight. These data, when combined, help paint a broader picture of the aircraft's current energy state.

This is accomplished by, first, summing the aircraft's current kinetic and potential energies and calculating the rate of change of this energy state. Next, given some safe time with which to look ahead, the predicted energy is calculated by accounting for the predicted loss of energy by that time. To establish an alert threshold, a minimum allowable total energy profile is then constructed at that future point, with some predetermined minimum allowable potential and kinetic energies based on the vertical profile and airspeed expected during the approach, respectively. If the predicted energy falls below the required energy, the alert sounds. This alert will identify situations where added thrust is required because a pitching movement would either be ineffective or ill-advised. This should help reduce false alarms based on either low potential or low kinetic energy alone.

It should be noted that loss of energy due to pitching actions was neglected. This energy loss due to pitching actions account for an energy loss approximately six orders of magnitude smaller than other energy sinks accounted for in this analysis and therefore is negligible (Carbaugh, 2007).

The calculations are mathematically described as follows:

1) $TE = mgz + \frac{1}{2}mV^2$. Total Energy (TE) is calculated as the sum of potential (mgz) and kinetic $\left(\frac{1}{2}mV^2\right)$ energies, where z is the height above touchdown, and V is the airspeed of the aircraft.

2) The rate of change of total energy is calculated as $\frac{dTE}{dt} = m(g\dot{z} + Va)$ or $mg\dot{z} + FV$, where $\dot{z}$ = vertical speed (taking a three second average to eliminate the possibility of turbulence and eddies falsely triggering an alarm), a = the forward acceleration of the aircraft, and F = the net longitudinal force on the aircraft (T-D), otherwise known as excess thrust.

3) In order to determine how far the system should look predict the aircraft's energy state, a safe time is calculated as $t_{safe} = t_{spool}\ (+\ t_{reaction})$. $t_{reaction}$ is an optional reaction time needed for the pilots to react (maximum of approximately 4-5 seconds (Boeing, 2014)). t_{spool} is the engine spool up time, where $t_{spool} = -4.55 \ln\left(1 - \left(\frac{D}{\delta T}\right)\right)$ where D is the current drag of the aircraft, and δT is the difference between T_{Max} and the current thrust setting. 4.55s is the rise time calculated for the engine used on Asiana outfitted Boeing 777-200ER's, which Boeing states will achieve full thrust, from idle, in approximately 10 seconds (Boeing, 2014).

4) $TE_{minimum} = mgz_{req} + \frac{1}{2}mV_{req}^2$. The minimum allowable total energy ($TE_{minimum}$) is a dynamic threshold calculated at the future time point using the same equation (1) as is used for TE but with V_{req} as some multiplier of V_{stall}. On modern aircraft, V_{stall} is known onboard the aircraft as a function of aircraft weight and

aircraft configuration such gear and flaps setting. z_{req} is a linear function of predicted lateral distance away from the airport at time $t_{current} + t_{safe}$ (d) calculated by using the vertical profile of the approach in question, $z_{req} = n * d * h(approach)$ (where n is again some multiplier to allow for minor glideslope deviation). Although almost all approaches use a standard 3 º glideslope, this additionally allows for non-standard approaches with glideslopes other than 3º, or other approach profiles such as step-down profiles.

5) The estimated energy change (ΔTE) after the minimum safe time has elapsed is approximated by $\left(\frac{dTE}{dt}\right) * t_{safe}$. Summing the originally calculated TE with the (presumably negative) ΔTE gives the approximate TE_{final}. From this equation, the importance of t_{safe} can be seen in that t_{safe} affects the calculation of both the required energy and predicted energy. The effects of t_{safe} are magnified in cases where energy is dissipating from the aircraft quickly, for example when the aircraft is fully configured for landing (high drag) and at a very low power setting (low thrust). In these cases, energy loss from the aircraft is magnified and longer t_{safe} results in larger changes in energy.

6) If $TE_{final} \leq TE_{minimum}$, the system sounds an alarm.

CHAPTER 4. ANALYSIS

4.1 Introduction

There are two major components to the analysis performed in this thesis. First, the alert is evaluated within the evolution of aircraft state in the Asiana 214 accident. This is accomplished by estimating flight data as obtained from documents submitted by Boeing to the NTSB during the accident investigation (Boeing, 2014). Second, the alert is applied to FOQA data to evaluate the alert's performance across a broad range of flights, including those which have previously been labeled as either stable or unstable by current industry analyses. To evaluate the proper alerting threshold, 96 variants of the alert were implemented with varying combinations of required safe time, minimum allowable potential energy (as determined by a glide slope deviation multiplier), and minimum allowable kinetic energy (as determined by a stall speed multiplier). The specific values implemented are shown in Table 1.

Table 1. Variants of Alerting Parameters Analyzed.

t_{safe}	GSx	V_{stall}x
10	1	1.3
9	0.9	1.2
8	0.8	1.1
7	0.7	1
6		
5		

It should be noted for context that a nominal approach will typically fly on the glide slope (GS multiplier of 1) and will fly at $1.3V_{stall}$, otherwise known as the reference approach speed or V_{ref}. Minimum required energy thresholds in excess of a glide slope multiplier of 1 and a stall speed multiplier 1.3 were initially analyzed, but not used in this analysis as these parameters made the alerting algorithm too sensitive, resulting in a very large number of undisputedly stable flights to be erroneously flagged as unstable. Deviations below a glide slope multiplier of 0.7 or a stall speed multiplier of 1 were not analyzed as they are so low energy that the aircraft would have triggered other alerts independently. Finally, safe times are dictated by a combination of federal requirements and human factors analysis, with a 5 second minimum per federal requirements of engine spool time, up to 10 seconds to allow for an additional 5 seconds of reaction time.

For this analysis, the vertical profile was assumed to be 3 degrees, as specific vertical profiles for each approach were not available for the vast majority of the flights analyzed; an onboard system, once implemented, would typically have this information allowing for a more contextualized definition of required altitude than possible here.

Analysis of approaches begins at 2,000 feet Height Above Touchdown (HAT) and ends at 50 feet HAT. This range should begin early enough to detect low energy approaches (earlier than current post-flight analysis metrics, which begin at 1,000 feet HAT), but late enough to avoid the risk of false alarms caused by the aircraft not yet intercepting the approach and starting its vertical profile. Similarly, variance in the altitude measurement close to the ground and during transition to flare can lead to false alarms, therefore the analysis is suspended below 50 feet HAT.

4.2 Application of the Alerting Algorithm to Asiana 214

A first step to validate the design of the alert is to apply it to the case of Asiana 214. The analysis is based on the time history of aircraft state given in the publicly available NTSB docket. Unfortunately, digital flight data recorder data was not provided in a useable format, and so this analysis was estimated from the graphical time history. Visually examining the published information, it is clear to see that the flight clearly violated several Flight Safety Foundation Stabilized Approach Criteria. These include excessive descent rate (at times in excess of 2000 feet/min), excessive glide slope deviation (both in excess of two dots high and low), and excessive deviation from V_{REF} with speeds below 110kts (V_{REF} in this case was published as 137kts, and 110kts is approximately $1.04V_{stall}$). Additionally, as previously mentioned, the aircraft flew for more than a minute with the throttles held at idle, significantly lower than the standard approach thrust.

Boeing's analysis of the final approach of the aircraft is shown in Figure 1 (Boeing, 2014). For the final 40 seconds of the flight, the figure also highlights the moments in the timeline at which the aircraft violated FSF criteria. Additionally, a red vertical line at 12 seconds prior to impact is shown, indicating the point at which the low airspeed quadruple chime sounded. Lastly, a blue bar is superimposed on the timeline at the bottom, indicating the range of times that the low energy alert detailed in this thesis triggers across the 96 different variants defining the alerting threshold for minimum required total energy.

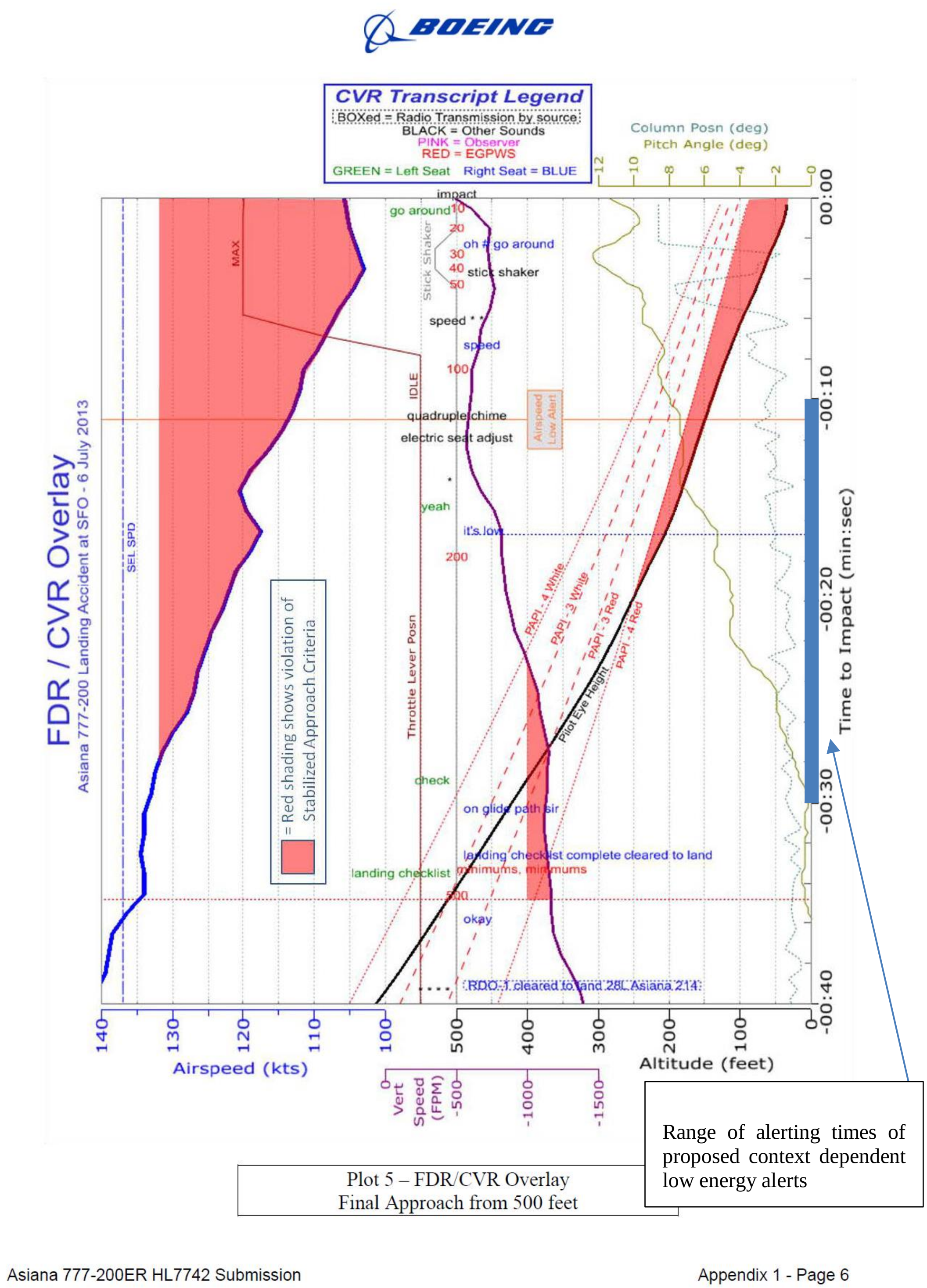

Figure 1. Asiana 214 Final Approach Timeline.

As an example, shown in detail, the alert variant examined in Figure 2 employed a 7 second safe time, along with a glide slope multiplier of 1 and a stall speed multiplier of 1.2. The total energy predicted and required by the alerting algorithm are shown through time in Figure 2. This alert variant alerts approximately 29 seconds before impact, approximately 17 seconds earlier than the low speed quadruple chime in the accident. The time at which the quadruple chime sounded is shown by the red vertical line. Additionally, the alert variant sounded approximately 6 seconds after the aircraft was considered to be in an unstable state by Boeing post-accident analysis, as shown by the orange vertical line. However, since no system exists to warn against unstable approaches, no alert sounded at that point.

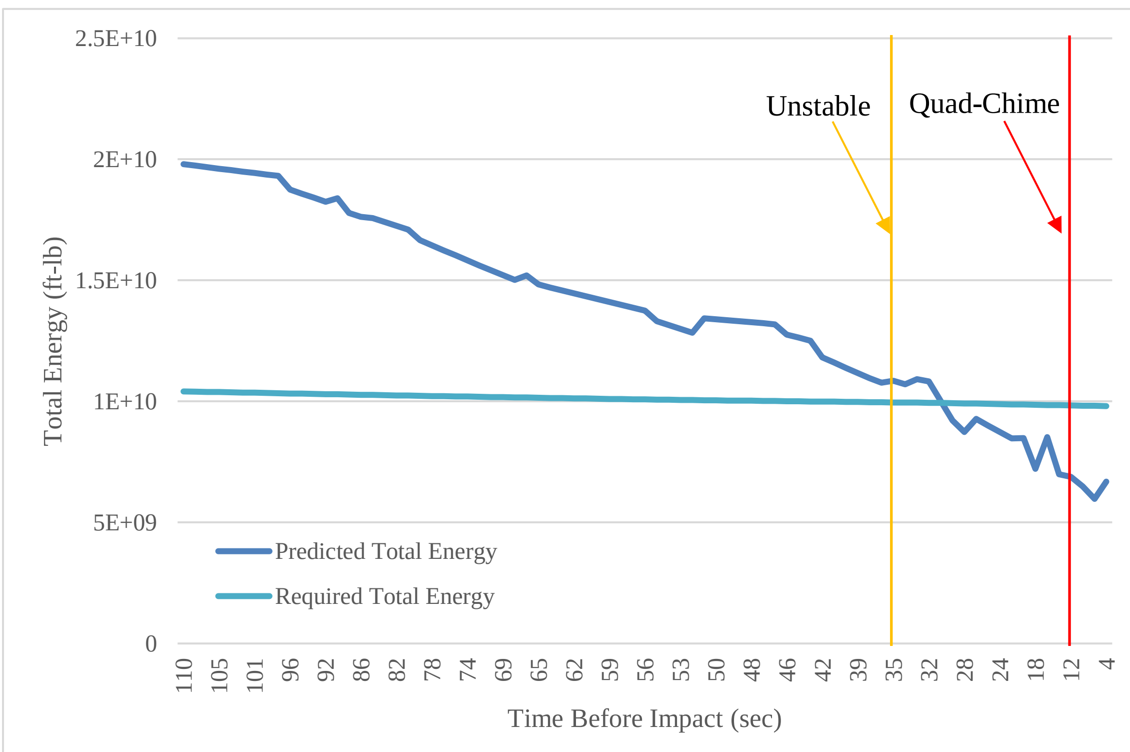

Figure 2. Time History of Asiana 214 Compared to Alerting Threshold Defined by t_{safe} = 7 seconds, Potential Energy Multiplier = 1.0, and Kinetic Energy Multiplier = 1.2.

Varying the safe time or minimum required potential energy does not change the time at which the alert sounds by more than 1 second. Rather, changes in minimum required kinetic energy has the most significant impacts on the timing of the alert. Several alert variants requiring progressively lower kinetic energy from $1.3V_{stall}$ to V_{stall} are shown in Figure 3. (All variants maintained a safe time of 7 seconds and a vertical profile multiplier of 1.0.)

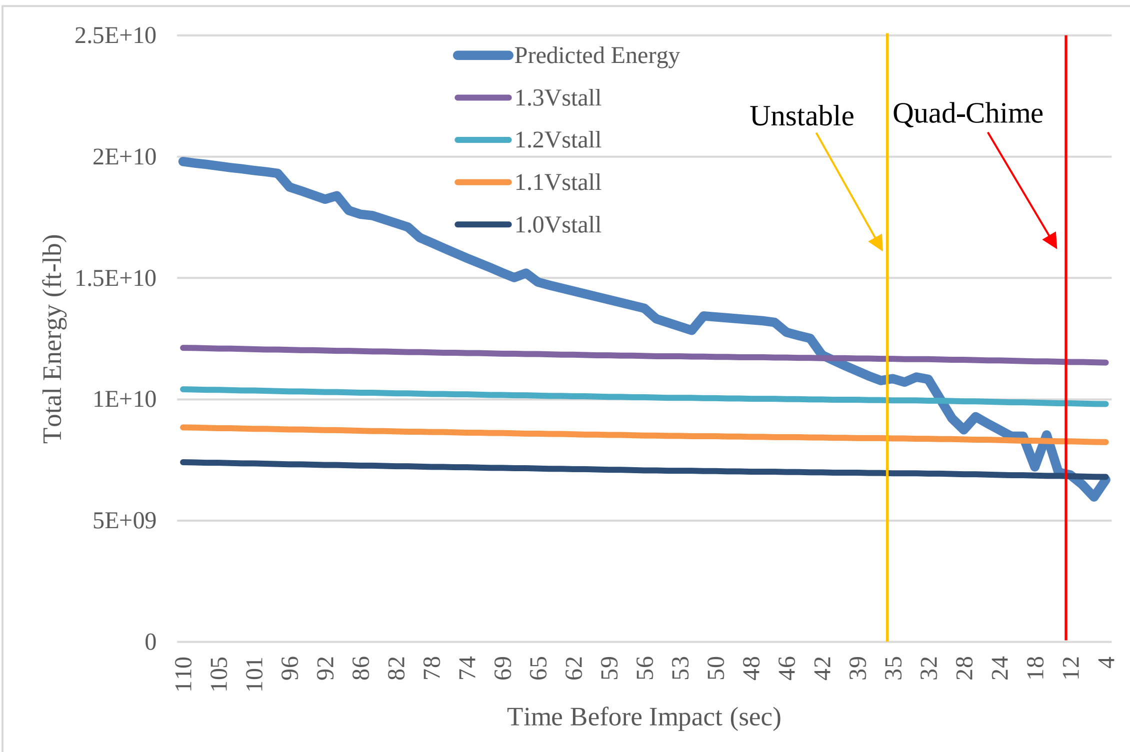

Figure 3. Time History of Total Energy in Asiana 214 Compared to Alerting Thresholds Defined by t_{safe} = 7 seconds, Potential Energy Multiplier = 1.0, and Varying Kinetic Energy Multiplier from 1.5 to 1.

The alert variant with a kinetic energy multiplier of 1.1 triggered the closest to the quadruple chime at 14 seconds before impact. Only the alert variant with a kinetic energy multiplier of 1.0 alerted after the quadruple chime, at 10 seconds before impact. These results are numerically presented in Table 2. Clearly, changes in kinetic energy have a dominant effect on the alert as a whole. Changing other parameters within the alert only modify the alert time by a couple seconds, while the alerting time with varying kinetic energy changed much more significantly.

Table 2. Asiana 214 Kinetic Energy Variation Results.

V_{stall}x	Seconds Before Impact	Seconds Before Quad Chime
1.3	41	29
1.2	29	17
1.1	14	2
1	10	-2

Next, the impact of changing safe time in Asiana 214 is analyzed. It should be noted that, as the safe time parameter is used in calculation of both the minimum required energy, as well as the predicted energy, it is not possible to plot the different safe time varying required energy plots in the same chart. Nonetheless, results will be shown in tabular format. In this analysis, the safe time was varied between 5 and 10 seconds (with safe times of 0 to 4 seconds shown in Table 3 to help demonstrate the effect of changing safe time on alerting time) while holding the glide slope multiplier constant at 1 and the stall speed multiplier constant at 1.2. The specific results of this analysis are detailed in Table 3.

Table 3. Impact of t_{safe} on the Time an Alert Would Be Given in the Asiana 214 Flight Profile.

t_{safe}	Seconds Before Impact	Seconds Before Quad Chime	Predicted Energy (ft-lb)	Required Energy (ft-lb)	Difference (ft-lb)
10	30	18	8413167574	9912283281	-1499115707
9	30	18	8680641890	9917392138	-1236750248
8	30	18	8948116206	9922500995	-974384788
7	29	17	9215590522	9927609851	-712019329
6	29	17	9483064838	9932718708	-449653870
5	29	17	9750539154	9937827565	-187288410
4	28	16	9614490018	9933291762	-318801743
3	25	13	9665614252	9918920997	-253306745
2	25	13	9830789389	9923816300	-93026911
1	24	12	9713507556	9918857410	-205349854
0	24	12	9876242252	9923685376	-47443125

Comparing these alert variants, it is clear to see that differences in safe time do indeed affect the minimum allowable total energy. As safe time increases, both the predicted and required energy decrease. However, when the aircraft thrust is low, predicted energy decreases much faster than required energy, and thus, with a large enough increase in safe time, the alert will sound significantly earlier.

Overall, most variants of this alert trigger early enough to allow useful pilot action. This alert comes much earlier than the FSF stable approach criteria and current onboard alerts (In this case, the low airspeed quadruple chime sounded merely 11-12 seconds before impact), mainly because this alert evaluates the decay of both altitude and airspeed combined. This extra time would have allowed the pilots to recognize the situation, increase the throttle and successfully execute a go around.

4.3 FOQA Analysis

Application of the alerting algorithm to the Flight Operations Quality Assurance (FOQA) data for a large number of flights assesses its functioning over a wide range of 'real' flights. More than 500,000 flights were collected from a major American carrier over a six-month time frame between July and December 2018. A variety of aircraft were included, including both larger widebody aircraft and smaller narrowbody aircraft. Some fleets of older aircraft were excluded from the analysis due to the onboard recorders not having the necessary parameters to complete the analysis. A variety of airports were included.

The data analysis began by applying the 96 variants of the alerting algorithm to the flights collected. When the algorithm triggered, i.e., predicted the energy state of the aircraft would fall below its minimum required energy state threshold, the flight was flagged, and the times when the low energy event was active were recorded. Simultaneously, any flights that triggered the FSF stable approach criteria were also flagged. Full details are provided in the results table in Appendix A.

For the purposes of compliance with a non-disclosure agreement, the data that follows is presented in a de-identified fashion, with specific numbers referring to the alert rate relative to the rate of detection using the FSF stable approach criteria currently used in FOQA analysis that are specific to the energy metrics used in this thesis. For example, if a variant of the alerting algorithm triggers on half as many flights as the FSF stable approach criteria, its measure is "50%", and if an alert triggers on twice as many flights as the FSF stable approach criteria, its measure is "200%." These measures for the 96 different alert variants are plotted in Figure 4.

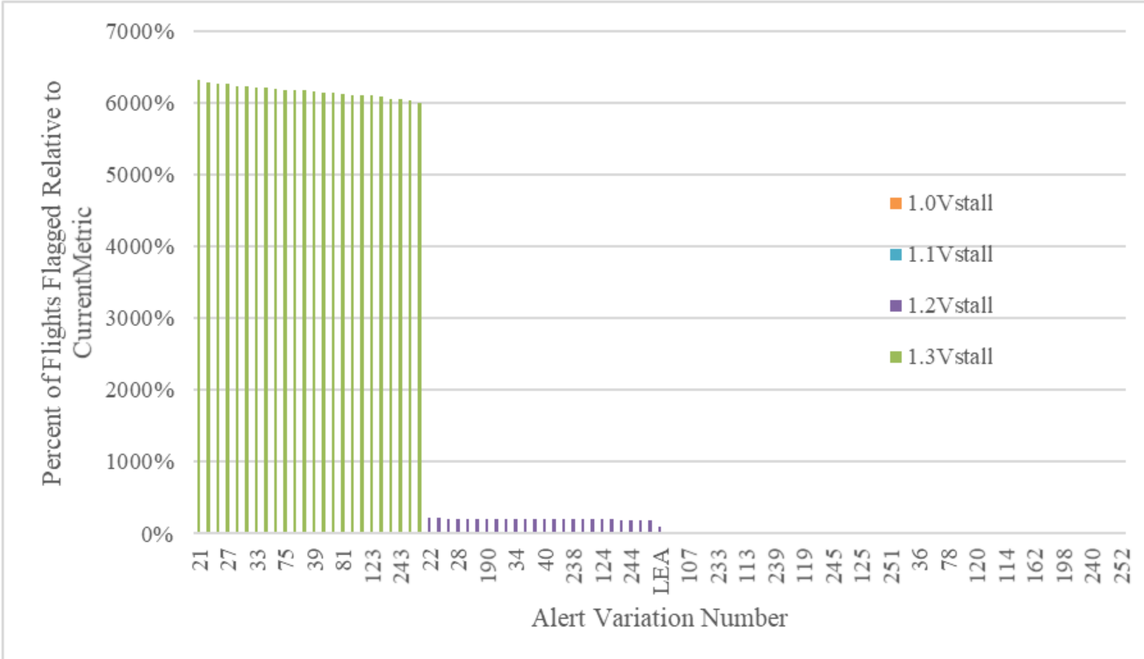

Figure 4. Comparison of Number of Flights Triggering an Alert, Compared to Those Violating FSF Stable approach criteria for Each Variant of the Kinetic Energy Alerting Threshold.

The highest minimum allowable energy threshold (with a 10 second safe time, minimum potential energy associated with a glide slope multiplier of 1, and minimum kinetic energy associated with a speed of 1.3 times V_{stall}) flags 6,312% as many flights as the currently-used FSF stable approach criteria. The lowest minimum allowable energy threshold (with a 5 second safe time, minimum altitude of 0.7 times the glideslope calculated altitude, and minimum speed of 1 times V_{stall}) flags 12% as many flights as the currently-used FSF stable approach criteria.

The clusters of alerts in Figure 4 correspond to different specifications of minimum allowable airspeed in the alerting threshold. A stall speed multiplier of 1.3 results in very large numbers of flights being flagged as "low energy", approximately 6,000% higher than currently-used FSF stable approach criteria, which would undoubtedly result in a large number of nuisance alerts. Focusing on low kinetic energy thresholds of $1.2V_{stall}$ and lower, a more detailed view of the results is shown in Figure 5.

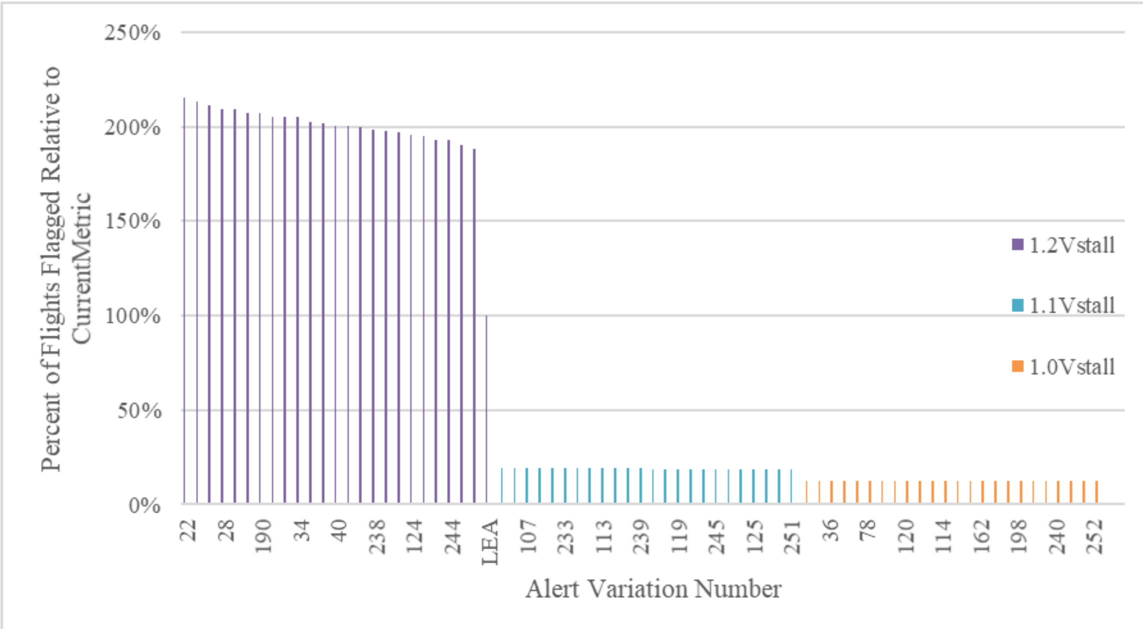

Figure 5. Comparison of Number of Flights Triggering an Alert, Compared to Those Violating FSF Stable Approach Criteria for Each Variant of Low Kinetic Energy Alerting Threshold.

Again, three distinct groups of alerts correspond to the lower three stall speed multipliers, 1.2, 1.1, and 1.0. For reference, the currently used FSF stable approach criteria detection rate is 100%. Variation within each minimum kinetic energy cluster are due to a mix of minimum potential energy and safe time parameters (see Appendix A for full results).

As previously discussed, the 96 different permutations of the alert algorithm were constructed by varying three different parameters: minimum allowable airspeed (a kinetic energy term), minimum allowable altitude or glide slope deviation (a potential energy term), and safe time. By holding two of the parameters constant, and varying the third, it is possible to observe the significance with which each parameter influences the detection rate of the algorithm. First, an evaluation of varying minimum allowable kinetic energy is presented. In Figure 6, the stall speed multiplier is varied, while holding the safe time constant at 7 seconds and the glide slope multiplier constant at 1.

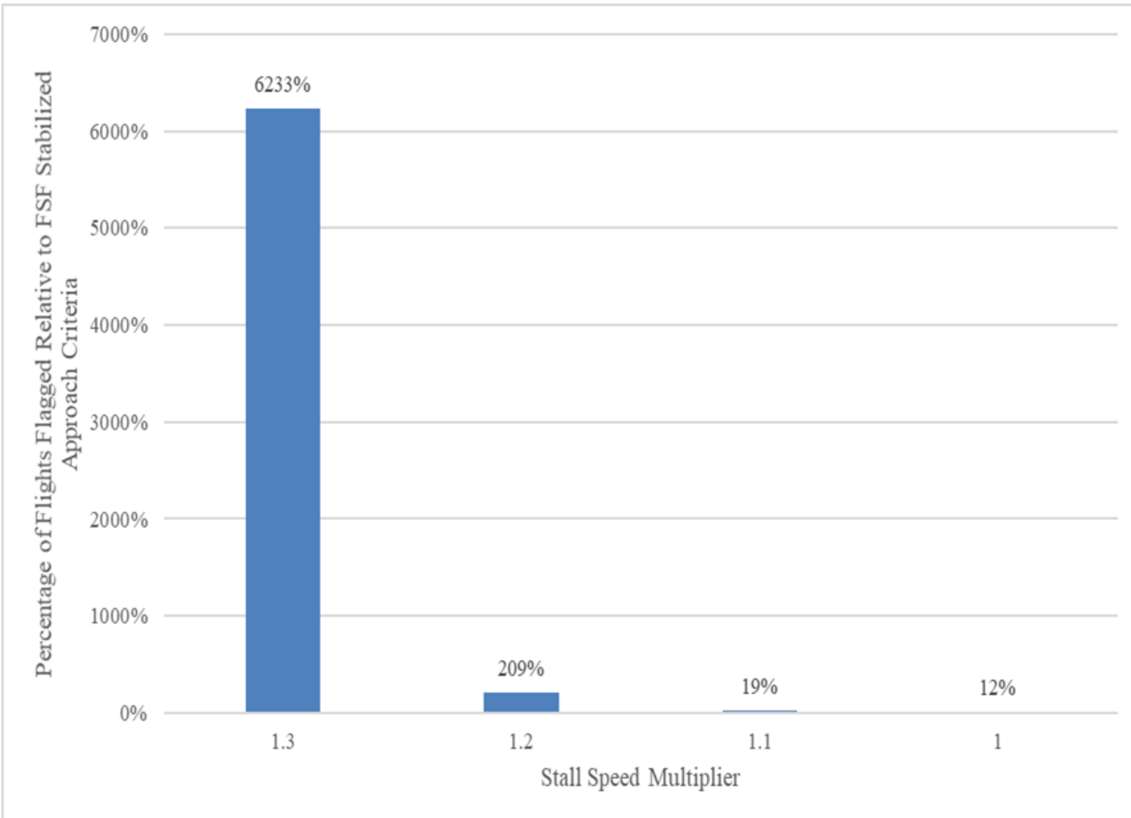

Figure 6. Comparison of Number of Flights Triggering an Alert, Compared to Those Violating FSF Stable Approach Criteria for A Variety of Low Kinetic Energy Alerting Thresholds.

From this breakdown, it is clear to see how significantly varying the minimum required kinetic energy affects the number of flights flagged. There are several theories for the reason of this significance. First, as the kinetic energy term is based on some velocity squared, any changes in that velocity term are quadratic, rather than linear. On a related note, aircraft are very sensitive to changes in airspeed on approach, and pilots attempt to fly an approach at as constant an airspeed as possible. As previously discussed, aircraft generally approach at approximately $1.3V_{stall}$. Thus, most flights flown will be at or slightly above this airspeed for nearly the entire approach, hence why variants of the algorithm with minimum kinetic energies based on airspeeds of $1.3V_{stall}$ or greater produce very large results.

Next, Figure 7 shows the detection rate as a function of potential energy requirements. In this analysis, the glide slope deviation multiplier is varied, while holding the stall speed multiplier constant at 1.2 and the safe time constant at 7 seconds.

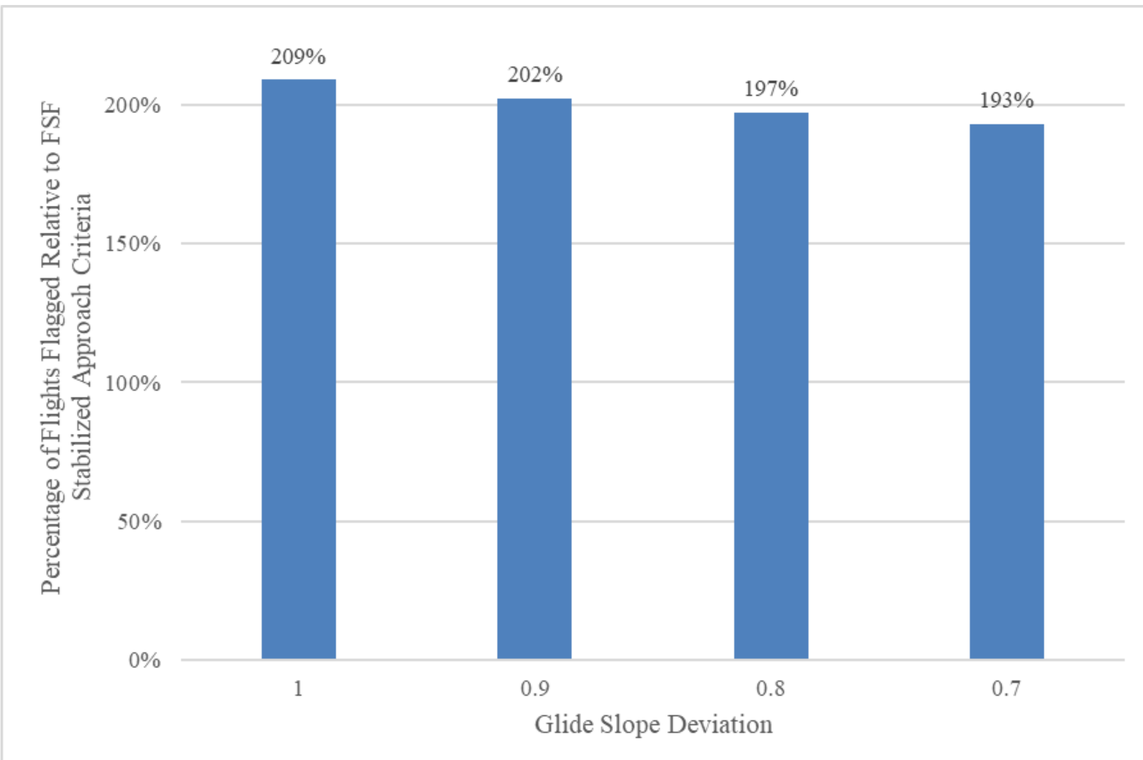

Figure 7. Comparison of Number of Flights Triggering an Alert, Compared to Those Violating FSF Stable Approach Criteria for A Variety of Potential Energy Alerting Thresholds.

For context, a 10% change in the altitude corresponds to an approximately 0.3 degree change or slightly less than one dot on a glide slope indicator (approximately 0.5 degrees within a half scale deviation). Therefore, the full deviation from 1 to 0.7 that was performed in this analysis roughly corresponds to two dots low on the glide slope. FSF stable approach criteria only define being "on the correct flight path" as stable, and there seems to be no official definition for maximum deviation allowed. From this analysis, it is shown that the change in flights flagged by the algorithm is roughly linear with respect to changing minimum allowable potential energy. Compared to the previous analysis looking at kinetic energy, these results are also to be expected, as altitude is more variable during approaches than airspeed.

Finally, an analysis of variation of safe time is performed as seen below in Figure 8. For this analysis, the stall speed multiplier was held constant at 1.2 and the glide slope multiplier was held constant at 1.0.

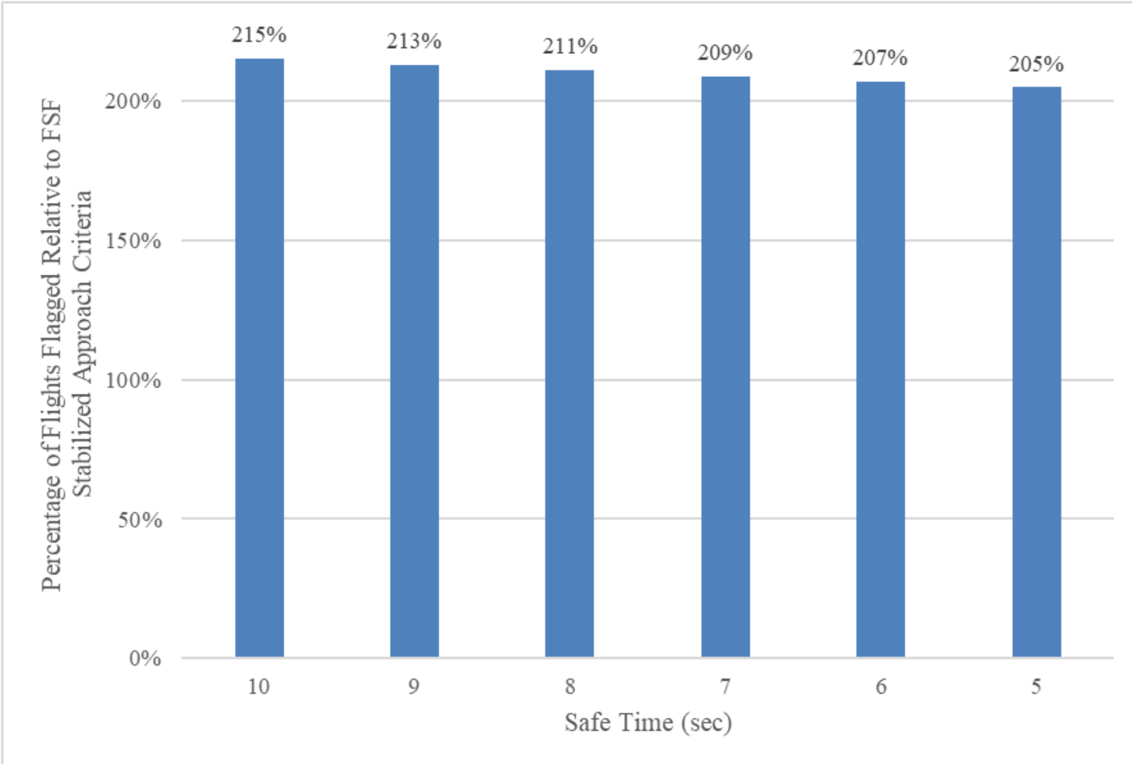

Figure 8. Comparison of Number of Flights Triggering an Alert, Compared to Those Violating FSF Stable Approach Criteria for A Variety of Safe Time Alerting Thresholds

Similar to the variation in minimum allowable potential energy, there is a fairly linear slope in terms of number of flights flagged by the algorithm as the t_{safe} parameter is varied. As all the look-ahead terms in the algorithm are linear, this linear variation is consistent with expectations. Increasing the look ahead time means that aircraft that are decreasing in total energy too fast will have a larger correction to their predicted energy. Therefore, greater look ahead time does indeed correlate with higher rates of detection. Nonetheless, it should be noted that the increases in detection rates due to increased alerting time are much smaller than for other variations (a 10% range of detection rates across the evaluated safe time parameters, compared to approximately 40% for the evaluated glide slope variations and over 200% for minimum speed variations between V_{stall} and $1.2V_{stall}$).

Therefore, it is hypothesized that increasing the safe time by a few seconds could enable pilots to have more time to respond without necessarily increasing the alerting rate to untenable levels.

Lastly, detection rates as a function of both glide slope multiplier and safe time is presented in Figure 9. These results show the detection rate of all alerts with a stall speed multiplier held constant at 1.2.

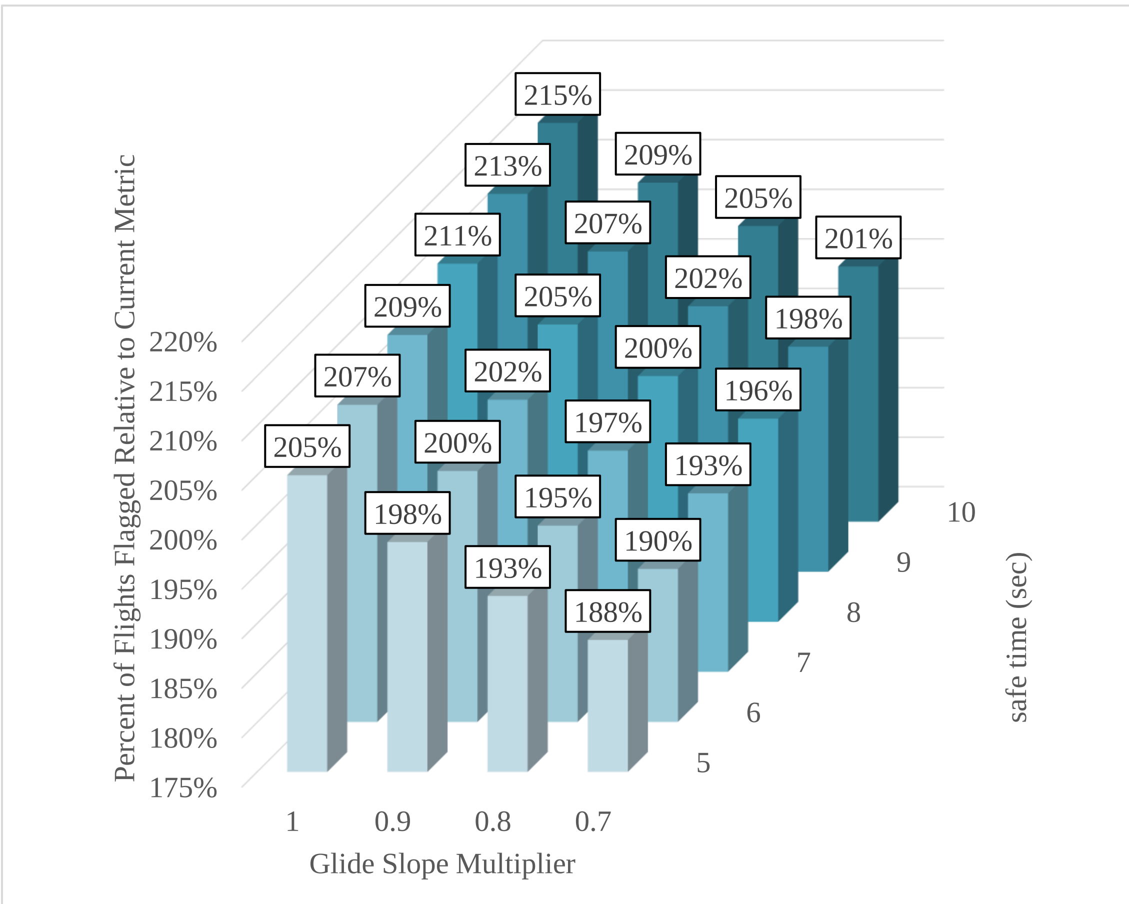

Figure 9. Comparison of Number of Flights Triggering an Alert, Compared to Those Violating FSF Stable Approach Criteria, for A Variety of Potential Energy and Safe Time Alerting Thresholds.

4.4 FOQA Case Studies

To further validate the alert with several exemplars, approaches out of the FOQA data set were analyzed to determine exactly when the alert triggered, especially as compared to the current FSF stable approach criteria. Specific variants of the alert parameters were applied to these flights to demonstrate how they change when the alert would be triggered, as shown in Table 4.

Table 4. Alert Variants Used in FOQA Case Studies.

t_{safe}	GSx	V_{stall}x
10	1	1.2
10	0.9	1.2
9	1	1.2
8	1	1.2
7	1	1.3
7	1	1.2
7	1	1.1
7	1	1
7	0.9	1.2
7	0.8	1.2
7	0.7	1.2
6	1	1.2
5	1	1.2
5	0.7	1

This section presents three case studies. The first is a stable approach in which no alerts were triggered except for the most sensitive variant of the proposed alert. The second is a low energy approach in which all variants of the alert as well as the current FSF stable approach criteria were triggered. Lastly, a case is presented which violated the current FSF stable approach criteria but not the low energy alert. It should be noted that, in accordance with the non-disclosure agreement covering this thesis' use of FOQA data, the analyses that follow are presented in a de-identified fashion with the vertical axis labels removed.

4.4.1 Stable Approach Case Study

An analysis of the aircraft's performance with regards to speed and vertical profile is first presented in a non-energy-based method. Figure 10 displays the aircraft's airspeed during the final approach with reference to the approach speed and stall speed. Figure 11 displays the aircraft's vertical profile in reference to the true glideslope on this approach.

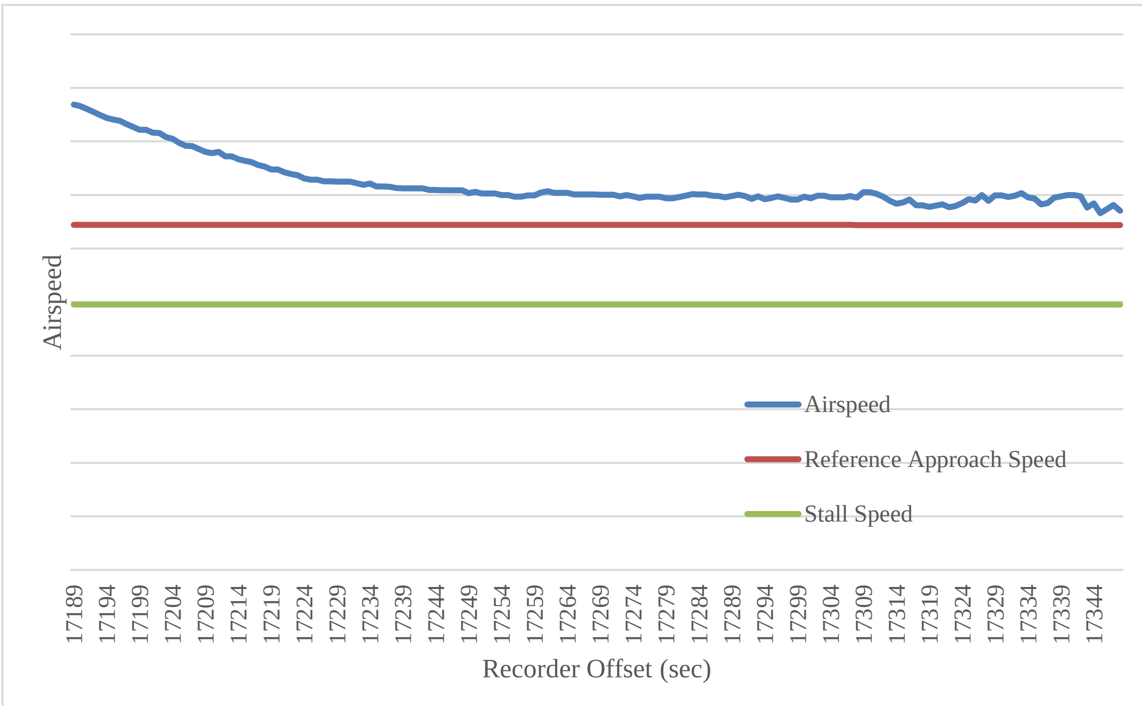

Figure 10. Time History of Airspeed During a Stable Approach.

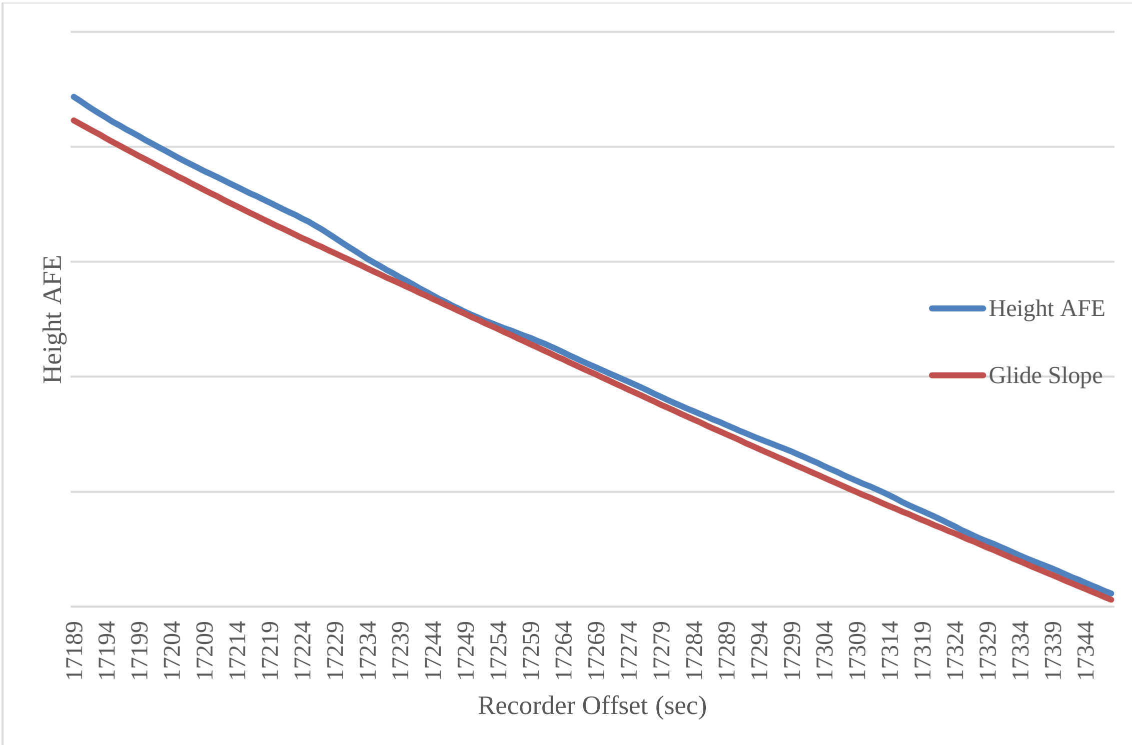

Figure 11. Time History of Vertical Profile During a Stable Approach.

As can be seen, the aircraft maintains a proper approach profile throughout the analyzed period. Additionally, there appear to be no significant periods of excessive vertical speed or airspeed changes. Thus, it is expected that this approach will be considered stable and should not trigger any variants of the total energy alert.

Applying the low energy algorithm to the flight, the following results are obtained. Figure 12 displays the time history of the alerting algorithm's predicted total energy and minimum total energy required with each variant of the alerting algorithm's thresholds.

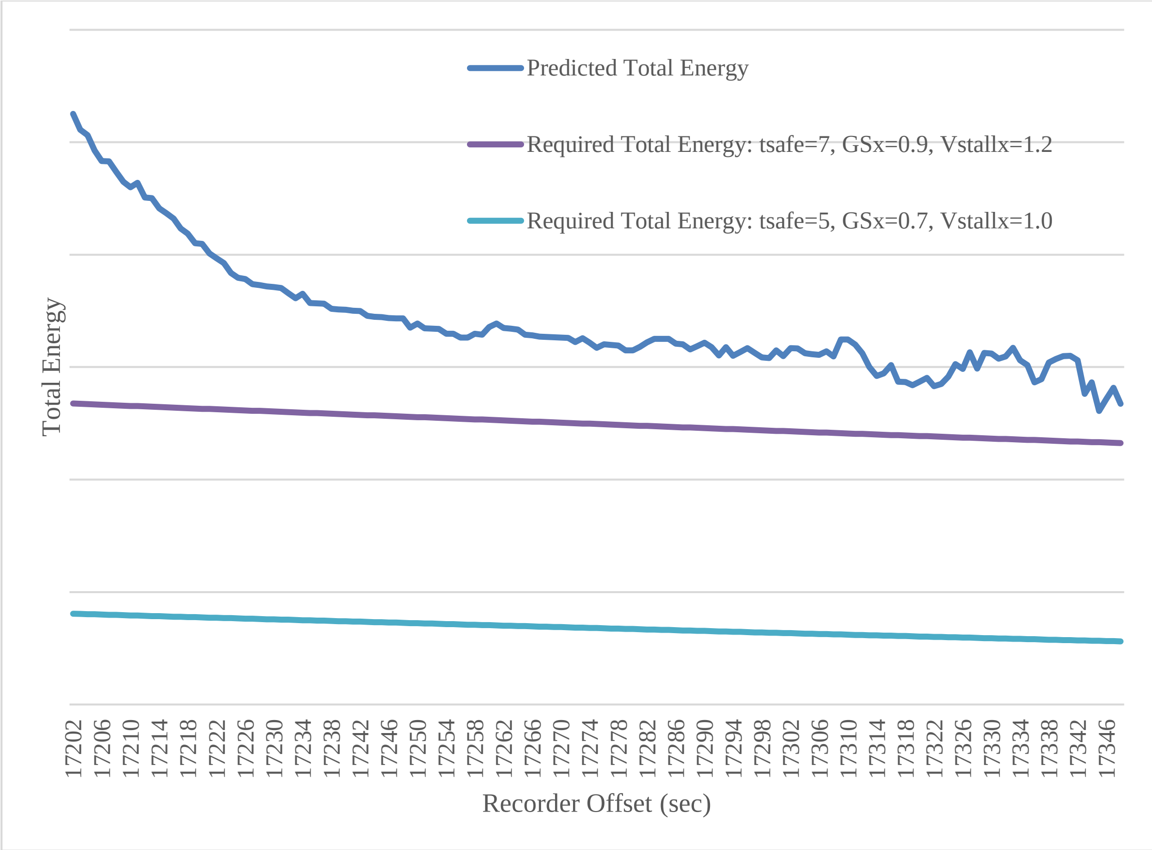

Figure 12. Time History of Predicted and Required Total Energy During a Stable Approach with Exemplar Alert Variants.

For this flight, no variant of the alert was triggered, nor was any current FSF stable approach criteria triggered. The alert with the lowest required energy of all variants analyzed is well below the predicted energy state of the aircraft for the entire approach. For context, alerts with the $1.2V_{stall}$ kinetic energy threshold were much more similar to each other than other variants.

4.4.2 Low Energy Approach Case Study

This section presents a flight in which both the proposed alert is triggered and the current FSF stable approach criteria are violated. First, an analysis of the aircraft's performance with regards speed and vertical profile is presented in a non-energy-based method. Figure 13 displays the aircraft's airspeed during the final approach with reference to the approach speed and stall speed. Figure 14 displays the aircraft's vertical profile in reference to the true glideslope on this approach. The point at which the FSF stable approach criteria flag the flight as unstable is denoted by the vertical red line.

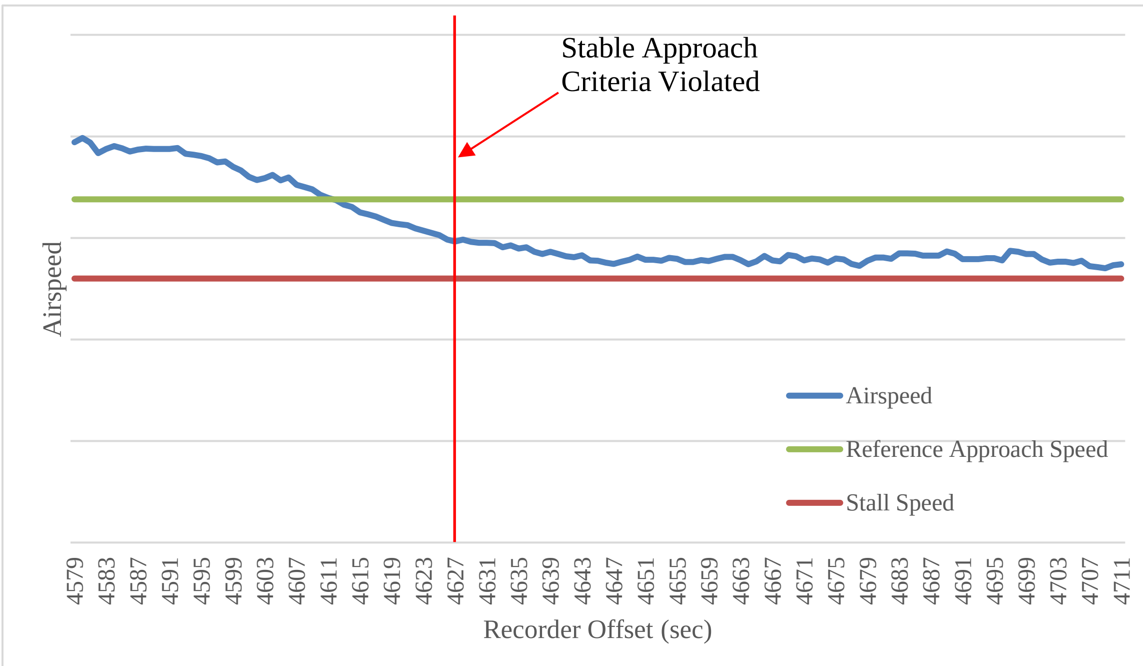

Figure 13. Time History of Airspeed During a Low Energy Approach.

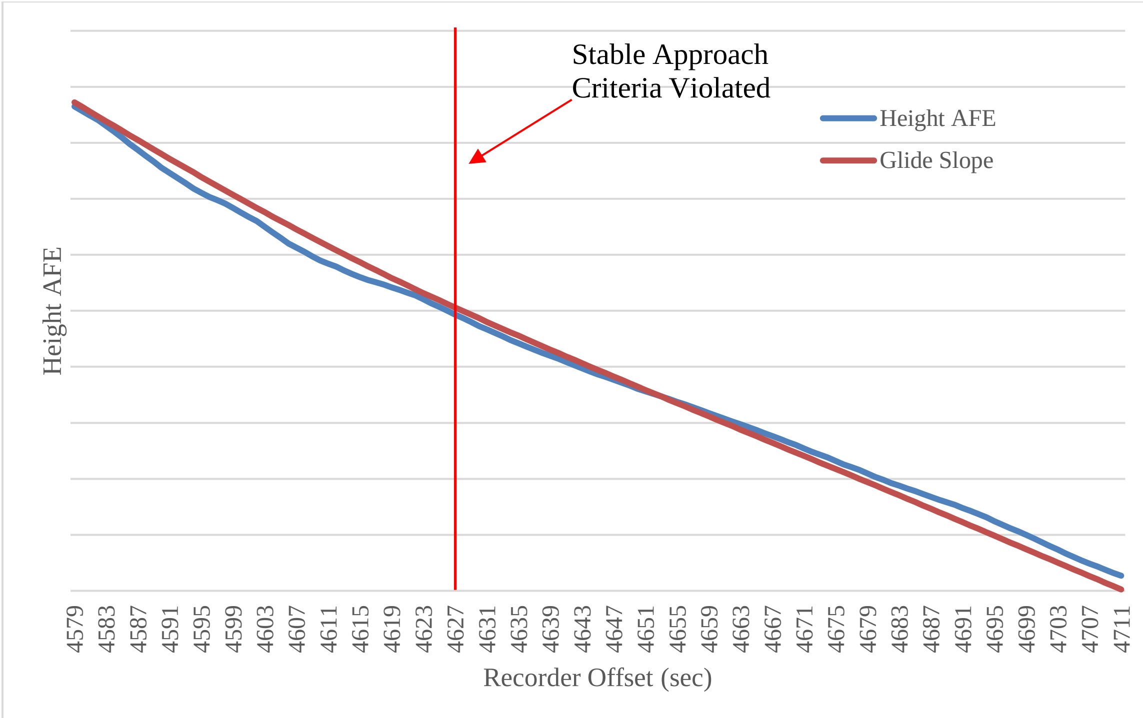

Figure 14. Time History of Vertical Profile During a Low Energy Approach.

As can be seen, the aircraft begins the final approach slightly below the glide slope but above the reference approach airspeed. It appears as if the pilot flying corrected by pitching the aircraft to lose airspeed and recover the glide slope, and in doing so, triggered the unstable approach in the FOQA system. For the remainder of the approach, the aircraft remained on or slightly above glide slope, but at a lower speed than required. Thus, it is predicted that the aircraft will have adequate potential energy, but lower than required kinetic energy.

Next, Figure 15 shows the alerting time as a function of minimum required kinetic energy. Plotted are alert variants with the stall speed multiplier varying between 1.3 and 1.0, the glide slope multiplier constant at 1.0, and the safe time at 7 seconds. For this flight, the FSF stable approach criteria triggered at a recorder offset timestamp of 4627 seconds, as is indicated by the red vertical line.

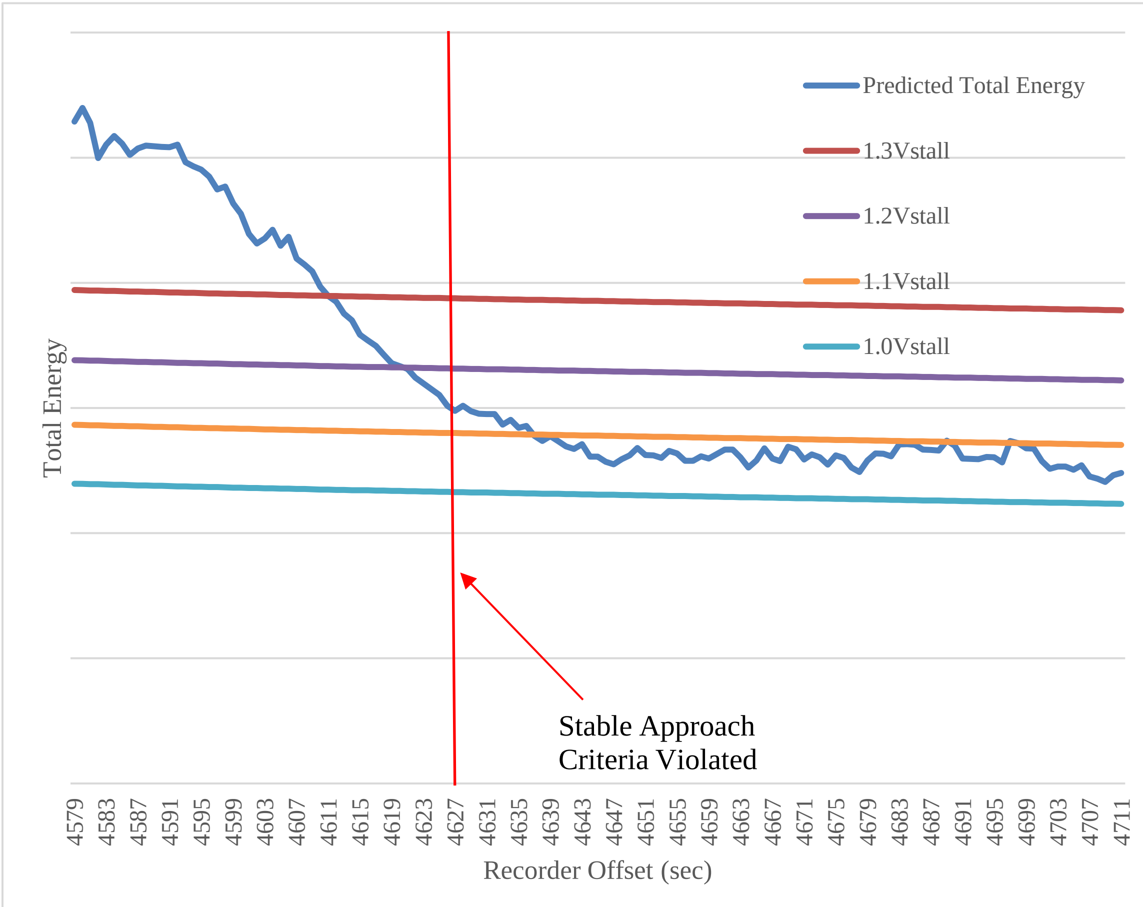

Figure 15. Time History of Predicted and Required Total Energy During a Low Energy Approach with Changing Kinetic Energy Requirements with a Glide Slope Multiplier of 1.0 and a Safe Time of 7 seconds.

Comparing these alert variants, significant differences are observed. The alert variant with a stall speed multiplier of 1.2 triggered 6 seconds before the FSF stable approach criteria; the alert variant with a stall speed multiplier of 1.1 triggered 10 seconds after the FSF stable approach criteria; and the alert variant with a stall speed multiplier of just 1.0 did not trigger at all. This large spread of results highlights how significantly the kinetic energy multiplier influences the behavior of the alert, and the importance of correctly selecting a proper speed with which to base the alert.

Next, to analyze the effect of varying minimum allowable potential energy, the same flight was used, and all alerting thresholds held the safe time at 7 seconds and the stall speed multiplier at 1.2, while varying the glide slope multiplier between 1.3 and 0.7. The time history of the entire final approach is shown in Figure 16 and a detail view at the time which the predicted energy crosses the various required energy thresholds is shown in Figure 17, with the red vertical line denoting the time at which the FSF stable approach criteria flagged the approach as unstable.

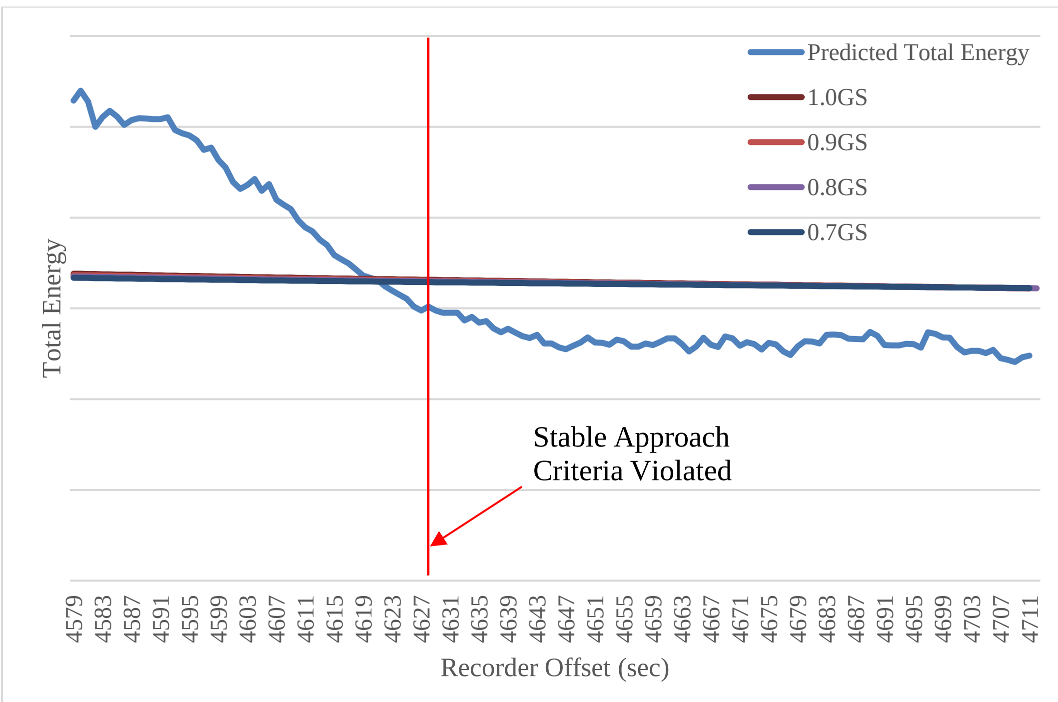

Figure 16. Time History of Predicted and Required Total Energy During a Low Energy Approach with Changing Potential Energy Requirements.

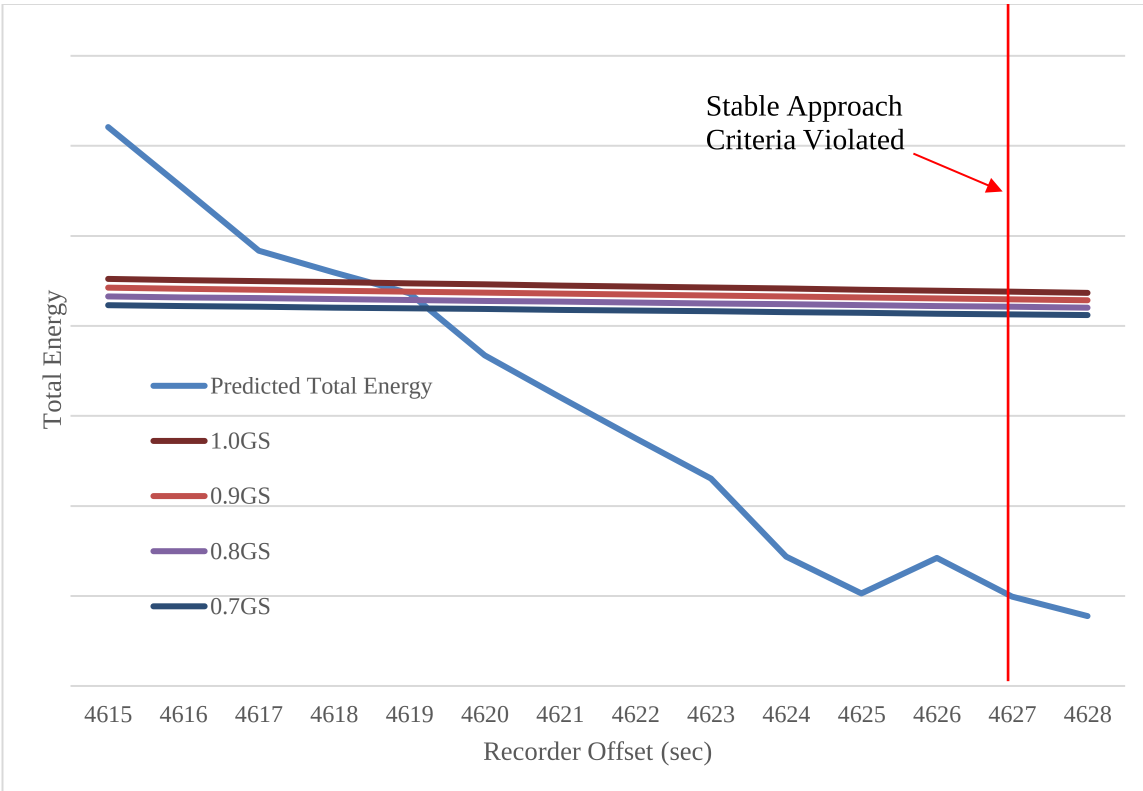

Figure 17. Time History of Predicted and Required Total Energy During a Low Energy Approach with Changing Potential Energy Requirements Expanded to Focus on the Time of Alerts.

Much smaller differences in alerting time are found with these different thresholds on potential energy, compared to the earlier different kinetic energy thresholds. Nonetheless, it can be seen that higher glide slope multipliers (and thus higher potential energy requirements) do indeed lead to higher total energy requirements and, consequentially, a slightly earlier alert. Alert variants with the highest required potential energy alerted 7 seconds earlier than the FSF stable approach criteria, whereas alert variants with lower potential energy requirements only alert 5 seconds earlier than the FSF stable approach criteria. The red highlighted line, denoting where the FSF stable approach criteria triggered an unstable approach, appears to be in an area where the total energy drops temporarily, associated with a decrease in airspeed.

Lastly, an analysis of variation in safe time is presented. This analysis is similar to that performed on varying safe time in evaluating the alert's performance on Asiana 214. Again, it should be noted that, as the safe time parameter is used in calculation of both the minimum required energy, as well as the predicted energy, it is not possible to plot the different safe time varying required energy plots in the same chart. Mathematical comparisons will instead be performed to evaluate the difference in energy required at a given time point, as was performed in the stable approach case study. In this analysis, the safe time was varied between 5 and 10 seconds while holding the glide slope multiplier constant at 1 and the stall speed multiplier constant at 1.2. The specific results of this analysis are detailed in Table 5. Due to the similarity of the results, an additional comparison is provided in the three right columns of data, presented in a de-identified fashion, again, due to compliance with a non-disclosure agreement. Each row shows the percent difference in predicted and required energy compared to the alert variant with a safe time of 10 seconds. These values were taken at the point in the approach at which the alert triggered, 6 seconds prior to the FSF stable approach criteria in each case. Values in excess of 100% indicate that the algorithm predicted or required higher energy for that alert variant than for the alert variant with a 10 second safe time. In the right most column, the difference between the predicted and required energy changes is shown.

Table 5. Low Energy Case Study Safe Time Variation Results.

t_{safe}	Seconds Before FSF Criteria	% Change in Predicted Energy	% Change in Required Energy	Difference
10	6	100.000%	100.000%	0.000%
9	6	100.118%	100.039%	0.079%
8	6	100.236%	100.078%	0.159%
7	6	100.355%	100.116%	0.238%
6	6	100.473%	100.155%	0.317%
5	6	100.591%	100.194%	0.397%

Comparing these alert variants, it is clear to see that differences in safe time result in less change in the minimum allowable total energy, as was previously demonstrated in the stable Asiana 214 study, however these results show a much smaller change. Reducing the safe time by 1 second results in a roughly 0.1% increase in the predicted energy, and a roughly 0.04% increase in required energy. Due to this flight's maintaining some throttle input above idle, the aircraft was not losing total energy at a rate comparable to Asiana 214, reducing the predicted loss of total energy scaled by t_{safe}. These slight variations are further displayed in Figure 18, showing a plot of the change in required energy compared to the change in predicted energy with decreasing safe time.

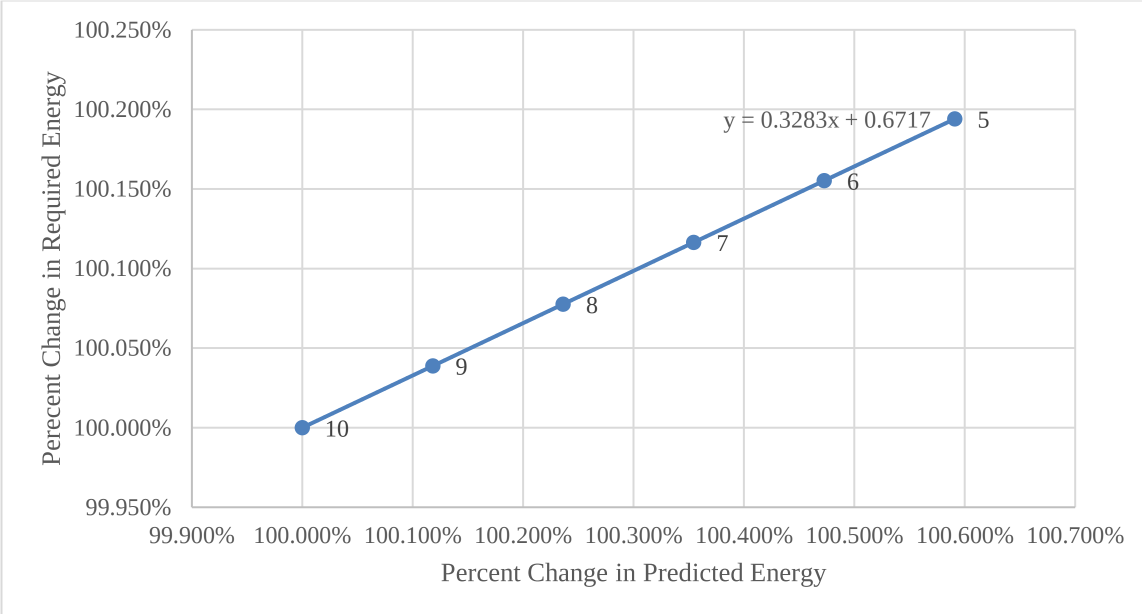

Figure 18. Change in Required and Predicted Energies with Varying Safe Time.

4.4.3 General Unstable Approach Case Study

In this case study, a flight was selected which triggered the FSF stable approach criteria, but which did not trigger any but the most sensitive of the low energy alert variants. Again, this case study begins with an analysis of the aircraft's performance with regards to speed and vertical profile as presented in a non-energy-based method. Figure 19 displays the aircraft's airspeed during the final approach with reference to the approach speed and stall speed. Figure 20 displays the aircraft's vertical profile in reference to the true glide slope on this approach. The point at which the FSF stable approach criteria flag the flight as unstable is denoted by the vertical red line.

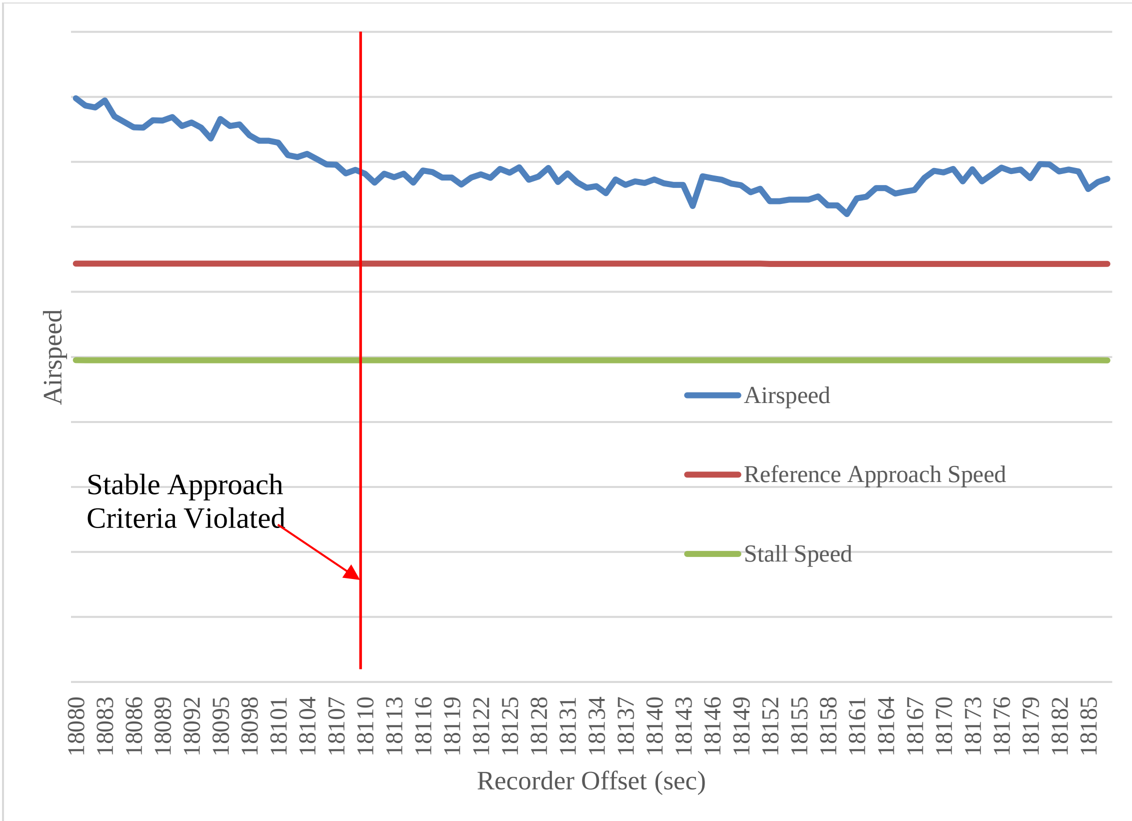

Figure 19. Time History of Airspeed During an Unstable but not Low Energy Unstable Approach.

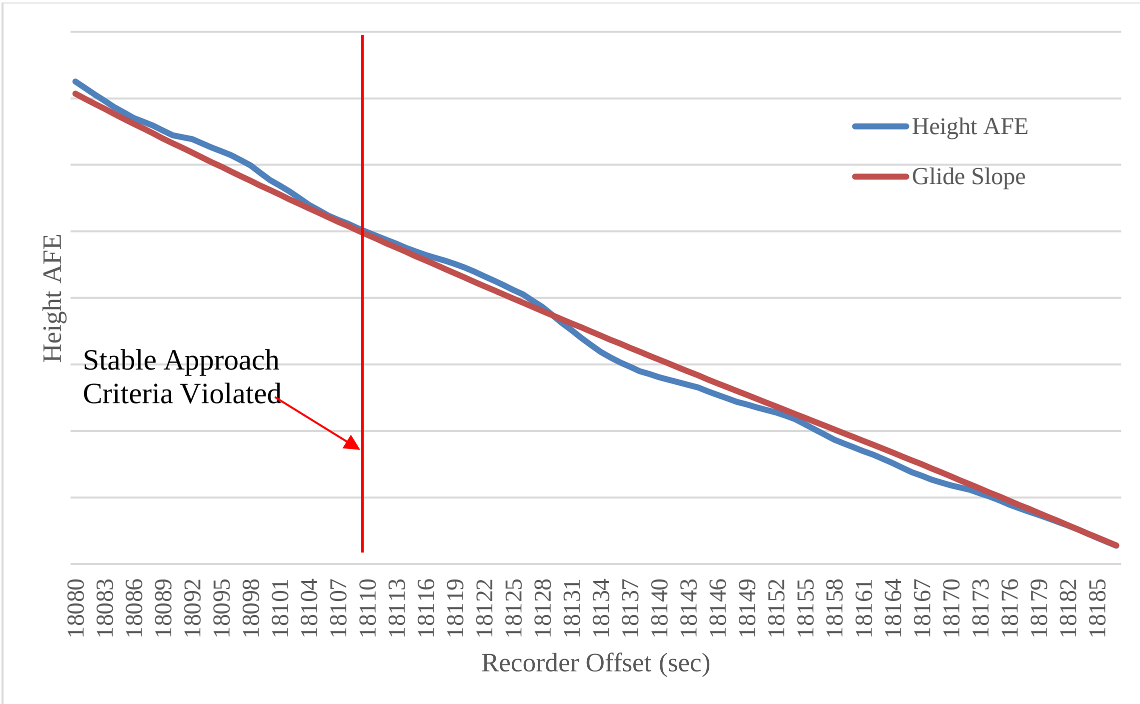

Figure 20. Time History of Vertical Profile During an Unstable but not Low Energy Approach.

As can be seen, the aircraft begins the final approach slightly above the glide slope and very much above the reference approach airspeed. Later in the approach, the aircraft appears to drop below the glide slope; however, the aircraft maintains a high airspeed throughout the approach. This is an interesting example as the aircraft will therefore have low potential energy but high kinetic energy. Given the dominance of the kinetic energy term in the previous case studies, it is expected that this term will again ensure the aircraft has an overall acceptable level of total energy.

To demonstrate the range of required energy used in the alert threshold, a plot of minimum total energy as calculated with varying minimum required kinetic energy is shown in Figure 21. The point at which the FSF stable approach criteria flags the approach as unstable is at a recorder timestamp of 18110, as shown by the vertical red line.

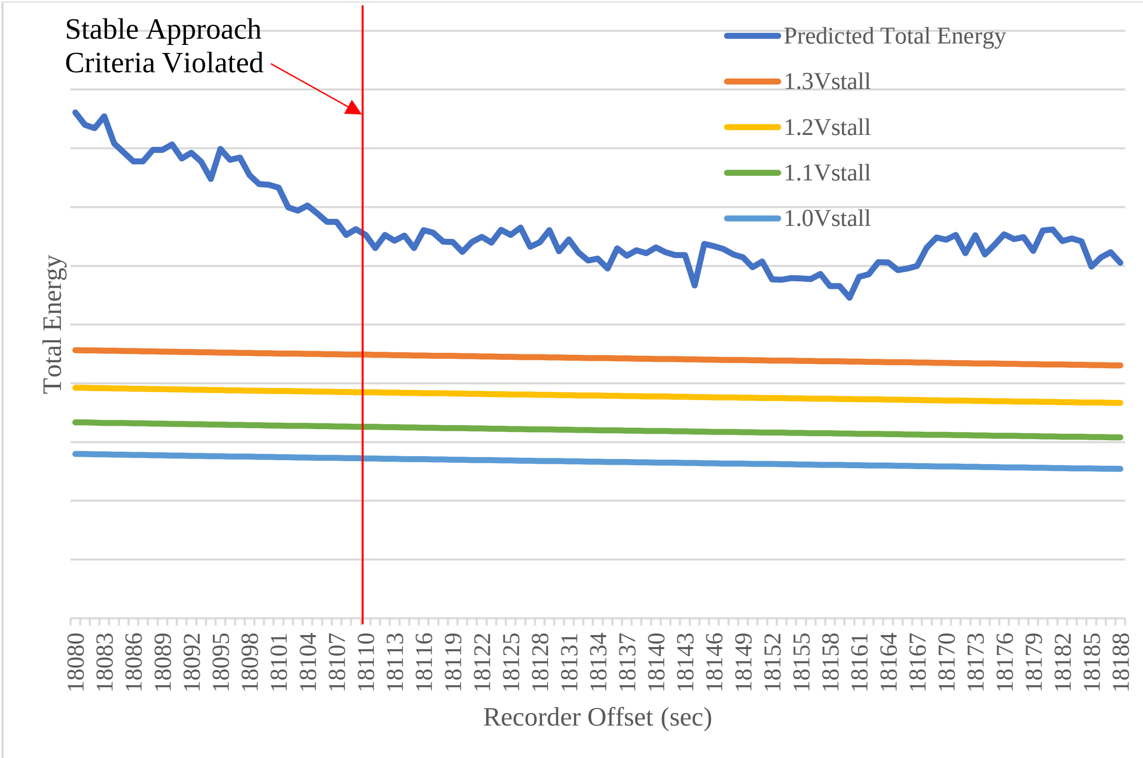

Figure 21. Time History of Predicted and Required Total Energy During an Unstable but not Low Energy Approach with Changing Kinetic Energy Requirements.

In this case, the flight was flagged according to the FSF stable approach criteria as unstable due to a high rate of descent. This can be seen in Figure 21 with the significant reduction in total energy seen just before the current FSF stable approach criteria flags the approach. This high rate of descent translates into a faster reduction in potential energy. However, in addition to a high rate of descent, the flight was also noticeable for maintaining a high airspeed throughout the approach. If so, the high airspeed offset the rate of descent and maintained the total energy at a level which did not trigger any low energy alerts. It is hypothesized that the algorithm was correct in not alerting, as the aircraft maintained enough total energy for the instability to have been corrected through a pitching action, rather than necessitating the addition of thrust.

4.5 Summary and Recommendations

From analysis of the approach of flight Asiana 214, it is clear that a low energy alert would likely have sounded earlier than the alerts onboard the aircraft where the total energy is low. This result was also demonstrated in the FOQA case studies, which also found that, with appropriate threshold settings, the alert will not trigger when total energy is not too low.

The timing of the alert is dominated by the kinetic energy threshold, with large variations in the alert time based on varying the minimum required kinetic energy. Minimum kinetic energy requirements based on a stall speed multiplier greater than 1.2 led to very large numbers of flights flagged. This is due to a $1.3V_{stall}$ being the optimal airspeed at which most approaches are intended to be flown. Thus, from a design perspective, it can be argued that the alert should be designed with a minimum kinetic energy of no greater than that associated with a speed of $1.3V_{stall}$, and more likely, closer to $1.2V_{stall}$. Additionally, it is suspected, though not confirmed, that stall speed multipliers of 1.1 and 1 are too low to generate timely alerts; more research is warranted in this regard.

The variations in minimum required potential energy and safe time were comparatively smaller in their effect in the cases analyzed. Nonetheless, these parameters do affect the alerting time, and alerting even a few seconds earlier could have a significant impact on the safety of flight operations. Therefore, the glide slope multiplier used should be greater than 0.7 or 0.8, as having a higher minimum required potential energy would likely alert slightly earlier. However, given that the approach is intended to be flown on the glide slope (glide slope multiplier of 1), flying any higher would indicate the aircraft still had energy that could be transferred from the potential store to the kinetic. Alerting in this regime is better suited to the individual criteria alerts, and thus it is recommended that the total energy alert be designed with a glide slope multiplier of 1 or 0.9.

Variation of safe time did not yield as significant changes in alerting time for the case studies analyzed as those found in the study of the Asiana 214 accident. This is likely due to the dominance of the other terms in the algorithm during these case studies, none of which had significantly lower throttle settings leading to significant loss of total energy over the interval defined by t_{safe}. In the case of Asiana 214, as the throttle remained at idle with the aircraft fully configured for landing, the aircraft was in a state which maximized drag and minimized thrust, magnifying the effect of t_{safe} on the change in predicted energy. It is suspected that a safe time of between 7 and 10 seconds is likely to yield meaningful results in cases such as the Asiana 214 accident, where these conditions are present.

CHAPTER 5. CONCLUSIONS

5.1 Summary of Findings

This thesis detailed the design of an algorithm for a context dependent total energy alerting system for commercial aviation operations. First, a background into the need for such an alert was described, including a detailed look into Asiana 214, an accident which directly inspired this design, and an overview of currently available technologies used to identify unstable approaches. Much research has taken place to evaluate energy metrics for use in aviation, from applications in pilot training and post-flight analysis to design of autoflight systems. However, little emphasis has been placed on developing alerts, particularly for situations in which pilots are manually flying the aircraft. Additionally, little research has taken place evaluating the real-world utility of such an alert.

The alert integrates data already available via sensors onboard air transport aircraft to estimate both the aircraft's current energy state and the trend in total energy. The algorithm creates a sum of energy from both kinetic and potential energy sources, and additionally calculates the rate of change of this total energy. The algorithm then predicts the energy state of the aircraft at a given time in the future, as well as calculating minimum required energy at that time. If the predicted energy is less than that which is required, the alert is triggered. The future time horizon is intended to be long enough to allow pilots ample time to recover or abort the approach.

Variants of the algorithm were applied to FOQA data for over 500,000 real flights to assess the parameters that define its alerting threshold. Based on this analysis, it was determined that the alert should be based on a minimum allowable kinetic energy defined by a stall speed multiplier of less than 1.3, as well as a minimum allowable potential energy defined by a glide slope multiplier of 0.9 or 1.0. The safe time parameter, though found to be less impactful than the other variables in the FOQA case studies presented in this thesis, still affected the required and predicted energy in a meaningful way. In cases where throttles are held at idle and the aircraft is fully configured for landing, variation of safe time may lead to earlier alerting times. Thus, to allow extra reaction time, the safe time could be set between 7 and 10 seconds.

5.2 Contributions

While significant research in the area of stabilized approaches and energy metrics for flight path evaluation has been conducted, much of the research has been focused on autoflight systems, post flight evaluation, or pilot training. The alert proposed herein is the first which has been designed to assist pilots by specifically warning against low energy approaches with both automatically flown approaches and those flown manually.

Additionally, the alert was evaluated using a large set of real time flight data. This application allows for a larger-scale analysis of the design metrics of such an energy alert that, previously, was only performed on either small sets of flight data or in simulations with pilots actively flying. This thesis showed the utility of such a total energy alert, and that the algorithm would predict the trend toward an unstable approach earlier than FSF stable approach criteria detect such approaches.

5.3 Limitations

A major limitation in the analysis is that the comparison of current FSF stable approach criteria to the system proposed provides an imperfect benchmark. As noted as the start of this thesis, the current day FSF stable approach criteria are univariate, each looking at different components of total energy. This comparison does nonetheless help to gain an understanding of how the proposed system would work in practice. Another fundamental difference between the two systems is that the current FSF stable approach criteria look at immediate conditions, whereas the alert proposed in this thesis is designed to be predictive. The predictive component should lead to earlier alerts when total energy is decreasing, allowing for earlier pilot responses; however, a safe time that looks too far ahead may generate false alarms.

Additionally, true evaluation of false alarm or missed detection rates would be impossible to make, again because there is no standard for determining the best alerting threshold. The criteria to which this alert could be compared, namely the FSF Stable approach criteria, though based on statistical analysis of accident data, can alert on any of several conditions that may not collectively indicate a problem with total energy requiring, at least, increased throttle.

Additional limitations are also present in the algorithm proposed here. Other real-world factors are present that were not taken into account in this thesis, which assumes a somewhat idealized model of an approach profile. Also, crosswind components typically require an aircraft to fly an approach at a higher than normal speed, and thus may be low total energy, but would not necessarily activate an alert due to the higher than normal speed.

Additionally, while different aircraft configurations are currently implicitly factored into the algorithm by their effect on an aircraft's stall speed, other effects of these configuration changes were not taken into account, such as the increased response time a pilot may need to raise flaps and gear to execute a go-around.

5.4 Future Work

Further data analysis of this alert could be completed with more robust data and further terms added to the algorithm. One such example is the explicit incorporation of configuration changes into the algorithm, such as improper gear or flap setting. Additionally, factoring in some of the other above-mentioned limitations, such as crosswind components, would allow for a more robust alert. Less crucially, while it is predicted that reducing assumptions such as a five second t_{spool} or a three-degree glide slope have minimal effect on the analysis, since the variations between the assumed and likely actual values are minimal, this addition would technically allow greater resolution into and specificity of the alerting advance time.

Additionally, as the alert was tested in a flight data post-processing environment, there is the opportunity to further the validation of this alert in real time tests, including simulator trials and flight testing to help add the human element, better specify the alerting characteristics, especially advanced alerting time, and help uncover real world influencing factors that have not yet been considered.

In addition to the mathematical criteria put forth in this thesis, consideration must be made for additional factors that can influence the effectiveness of the alert. Broadly speaking, these factors include sensor characteristics, aircraft performance and human factors. For the purposes of this thesis analysis, sensor metrics similar to those of current day technology, including LAA, EGPWS, and the like, were assumed. This is to emulate the most likely implementation scenario wherein the alert is programmed into the aircraft's computers without adding additional sensor hardware. Potential further research would evaluate, characterize, and recommend an optimal suite of sensors to be implemented natively in new aircraft designs.

Aircraft performance must also be considered in the design of the alert. In the alerting algorithm, engine spool time is factored into the advance warning time, t_{safe}. Due to the large moment of inertia of modern turbofan engines, this is a non-insignificant time that must be factored into the overall equations. Additionally, given that the aircraft is likely established on a certain descent profile, as the engines begin to power up, it will take a certain amount of time to arrest the descent; in other words, stop the energy decay and begin adding net energy. This is a parameter that is commonly tracked on modern commercial aircraft and could be added as another contextual factor when implemented onboard aircraft.

As previously mentioned, consideration must also be taken for human factors. Reaction time, at a minimum, dictates how much additional advanced warning is needed simply for pilots to hear an alert and react as trained. This number, as presented in the alert algorithm as a component of t_{safe}, is somewhat variable and dependent on many factors including workload, attention, and the current mental and physical state of the pilot. During approach, the aircraft is approaching a low total energy state and the pilot's work load is somewhat high; however, given that the pilot is likely to be actively engaged in flying the approach, their attention is already primed for such an alert. Therefore, consideration must also be taken for allowing the pilot to be involved in the decision-making process. Giving the pilots advanced warning may allow them to diagnose and potentially correct the situation. However, this will also surely lead to a larger number of alerts (as the system is predictive, and uncertainty increases the further from the event the prediction is made), many of them potentially false. Stemming from this concern is the potential for false alarms which may cause pilots to disregard the alert entirely, even when the alert properly predicts a dangerous situation.

Thus, the potential for a phased alert seems appealing. The aim of phased alerting would be to give enough advanced warning to pilots to allow them to correct the approach rather than simply go-around, but also reduce the severity of the alert early in the approach, so as to reduce the nuisance of such an alert. This design could provide a minimally distracting notification early on and increase in severity and prominence should the aircraft progress toward a low total energy state. As seen by the initial FOQA results, there is a clear quadratic curve in the number of flights flagged with different minimum energy requirements, with several groupings of alert threshold variants that have similar detection rates. These groupings could be further evaluated for their utility as phases of an alert.

Additionally, it should be noted that this system evaluated an aircraft's energy state up to 2,000 feet HAT. Because of this, many of the alert variants with very high minimum energy requirements alerted on flights where the captured "low energy states" were resolved before 1,000 feet HAT, the altitude at which the FSF stable approach criteria would begin evaluating. This may or may not be considered a false detection, but situations like these could be seen as warranting such a lower priority "information only" alert rather than a caution or warning, especially given the number of flights which were flagged with these higher minimum energy requirement alerts.

Lastly, one must examine the factors surrounding human knowledge of an event. If a pilot is already aware of a problem, and is taking steps to correct it, the alert could be seen as a nuisance. As an easily implemented additional parameter, to avoid nuisance alerts, the system could also track the commanded thrust. Significantly increasing commanded thrust values can be interpreted as pilot awareness of the low energy state and engagement in corrective action. If the commanded thrust is sufficiently high, indicating such pilot awareness, the alert could be silenced.

Alternatively, if a pilot is suspicious of a problem, or is unsure of how to act, given inadequate training or concerns over command structure, an alert may help to give that pilot the needed assurance that their belief is correct and can justify their action calling for a go-around, or mandate a go-around even when the pilot was attempting to salvage the approach. Indeed, when reviewing the Cockpit Voice Recorder (CVR) of Asiana 214, one of the junior pilots noted the unstable appearance of the approach before any alarms sound but did not call for a go-around when his suspicions were initially aroused, and the trainee captain continued to attempt to salvage the approach even when suspicions were first raised, until the quad-chime low airspeed alert clearly indicated a problem warranting action (Boeing, 2014).

APPENDIX A: FOQA ANALYSIS RESULTS TABLE

The following is the full list of results from the FOQA analysis for each variant of the alert, ranked by number of flights flagged. Included for context, is the FSF stable approach criteria, at a rank of 170. This analysis initially also evaluated alert variants with glide slope multipliers up to 1.3, and stall speed multipliers up to 1.5. These high energy results were not considered valid for the analysis presented in this thesis but are shown here for completeness. The data is presented organized in two versions. First, the alert variants are ranked by number of flights flagged by each. Second, alert variants are numbered in the order in which they were built and labeled, for easier reference.

Rank	Alert #	t_{safe}	GSx	V_{stall}x	Ratio of flights flagged to FSF stable approach criteria flights flagged
1	1	10	1.3	1.5	13217%
2	43	9	1.3	1.5	13217%
3	85	8	1.3	1.5	13217%
4	127	7	1.3	1.5	13216%
5	7	10	1.2	1.5	13216%
6	49	9	1.2	1.5	13215%
7	169	6	1.3	1.5	13215%
8	91	8	1.2	1.5	13215%
9	211	5	1.3	1.5	13215%
10	133	7	1.2	1.5	13215%
11	175	6	1.2	1.5	13214%
12	13	10	1.1	1.5	13214%
13	55	9	1.1	1.5	13213%
14	217	5	1.2	1.5	13213%
15	97	8	1.1	1.5	13213%
16	139	7	1.1	1.5	13212%
17	19	10	1	1.5	13212%
18	61	9	1	1.5	13211%

19	181	6	1.1	1.5	13211%
20	223	5	1.1	1.5	13211%
21	103	8	1	1.5	13211%
22	145	7	1	1.5	13210%
23	25	10	0.9	1.5	13209%
24	187	6	1	1.5	13209%
25	67	9	0.9	1.5	13209%
26	229	5	1	1.5	13209%
27	31	10	0.8	1.5	13208%
28	109	8	0.9	1.5	13208%
29	151	7	0.9	1.5	13208%
30	73	9	0.8	1.5	13207%
31	37	10	0.7	1.5	13207%
32	193	6	0.9	1.5	13207%
33	115	8	0.8	1.5	13207%
34	79	9	0.7	1.5	13206%
35	235	5	0.9	1.5	13206%
36	157	7	0.8	1.5	13206%
37	199	6	0.8	1.5	13205%
38	121	8	0.7	1.5	13205%
39	241	5	0.8	1.5	13205%
40	163	7	0.7	1.5	13204%
41	205	6	0.7	1.5	13204%
42	247	5	0.7	1.5	13203%
43	2	10	1.3	1.4	12417%
44	44	9	1.3	1.4	12412%
45	86	8	1.3	1.4	12408%
46	8	10	1.2	1.4	12403%
47	128	7	1.3	1.4	12403%
48	170	6	1.3	1.4	12399%
49	50	9	1.2	1.4	12395%
50	92	8	1.2	1.4	12390%
51	134	7	1.2	1.4	12385%
52	14	10	1.1	1.4	12384%
53	176	6	1.2	1.4	12379%
54	56	9	1.1	1.4	12378%
55	218	5	1.2	1.4	12374%
56	98	8	1.1	1.4	12372%

57	20	10	1	1.4	12368%
58	140	7	1.1	1.4	12366%
59	62	9	1	1.4	12361%
60	182	6	1.1	1.4	12359%
61	212	5	1.3	1.4	12359%
62	104	8	1	1.4	12354%
63	224	5	1.1	1.4	12353%
64	26	10	0.9	1.4	12352%
65	146	7	1	1.4	12347%
66	68	9	0.9	1.4	12345%
67	188	6	1	1.4	12340%
68	32	10	0.8	1.4	12338%
69	110	8	0.9	1.4	12336%
70	230	5	1	1.4	12332%
71	74	9	0.8	1.4	12328%
72	152	7	0.9	1.4	12328%
73	38	10	0.7	1.4	12323%
74	194	6	0.9	1.4	12320%
75	116	8	0.8	1.4	12320%
76	80	9	0.7	1.4	12314%
77	236	5	0.9	1.4	12313%
78	158	7	0.8	1.4	12311%
79	122	8	0.7	1.4	12306%
80	200	6	0.8	1.4	12302%
81	164	7	0.7	1.4	12296%
82	242	5	0.8	1.4	12294%
83	206	6	0.7	1.4	12286%
84	248	5	0.7	1.4	12276%
85	3	10	1.3	1.3	6502%
86	45	9	1.3	1.3	6483%
87	87	8	1.3	1.3	6465%
88	129	7	1.3	1.3	6446%
89	9	10	1.2	1.3	6431%
90	171	6	1.3	1.3	6430%
91	213	5	1.3	1.3	6413%
92	51	9	1.2	1.3	6412%
93	93	8	1.2	1.3	6392%
94	135	7	1.2	1.3	6371%

95	15	10	1.1	1.3	6370%
96	177	6	1.2	1.3	6353%
97	57	9	1.1	1.3	6347%
98	219	5	1.2	1.3	6333%
99	99	8	1.1	1.3	6324%
100	21	10	1	1.3	6312%
101	141	7	1.1	1.3	6301%
102	63	9	1	1.3	6285%
103	183	6	1.1	1.3	6278%
104	105	8	1	1.3	6259%
105	27	10	0.9	1.3	6258%
106	225	5	1.1	1.3	6255%
107	147	7	1	1.3	6233%
108	69	9	0.9	1.3	6229%
109	33	10	0.8	1.3	6210%
110	189	6	1	1.3	6207%
111	111	8	0.9	1.3	6201%
112	75	9	0.8	1.3	6181%
113	231	5	1	1.3	6181%
114	153	7	0.9	1.3	6172%
115	39	10	0.7	1.3	6167%
116	117	8	0.8	1.3	6148%
117	195	6	0.9	1.3	6142%
118	81	9	0.7	1.3	6133%
119	159	7	0.8	1.3	6116%
120	237	5	0.9	1.3	6114%
121	123	8	0.7	1.3	6099%
122	201	6	0.8	1.3	6083%
123	165	7	0.7	1.3	6062%
124	243	5	0.8	1.3	6051%
125	207	6	0.7	1.3	6027%
126	249	5	0.7	1.3	5992%
128	4	10	1.3	1.2	238%
129	46	9	1.3	1.2	236%
130	88	8	1.3	1.2	235%
131	130	7	1.3	1.2	234%
132	172	6	1.3	1.2	232%
133	214	5	1.3	1.2	230%

134	10	10	1.2	1.2	230%
135	52	9	1.2	1.2	227%
136	94	8	1.2	1.2	225%
137	136	7	1.2	1.2	224%
138	178	6	1.2	1.2	223%
139	16	10	1.1	1.2	222%
140	220	5	1.2	1.2	221%
141	58	9	1.1	1.2	220%
142	100	8	1.1	1.2	218%
143	142	7	1.1	1.2	216%
144	22	10	1	1.2	215%
145	184	6	1.1	1.2	214%
146	64	9	1	1.2	213%
147	226	5	1.1	1.2	212%
148	106	8	1	1.2	211%
149	28	10	0.9	1.2	209%
150	148	7	1	1.2	209%
151	70	9	0.9	1.2	207%
152	190	6	1	1.2	207%
153	112	8	0.9	1.2	205%
154	232	5	1	1.2	205%
155	34	10	0.8	1.2	205%
156	154	7	0.9	1.2	202%
157	76	9	0.8	1.2	202%
158	40	10	0.7	1.2	201%
159	196	6	0.9	1.2	200%
160	118	8	0.8	1.2	200%
161	238	5	0.9	1.2	198%
162	82	9	0.7	1.2	198%
163	160	7	0.8	1.2	197%
164	124	8	0.7	1.2	196%
165	202	6	0.8	1.2	195%
166	166	7	0.7	1.2	193%
167	244	5	0.8	1.2	193%
168	208	6	0.7	1.2	190%
169	250	5	0.7	1.2	188%
170	Current	Current	Current	Current	100%
171	5	10	1.3	1.1	20%

172	47	9	1.3	1.1	20%
173	89	8	1.3	1.1	20%
174	131	7	1.3	1.1	20%
175	173	6	1.3	1.1	20%
176	215	5	1.3	1.1	20%
177	11	10	1.2	1.1	20%
178	53	9	1.2	1.1	20%
179	95	8	1.2	1.1	20%
180	137	7	1.2	1.1	20%
181	179	6	1.2	1.1	20%
182	221	5	1.2	1.1	20%
183	101	8	1.1	1.1	20%
184	143	7	1.1	1.1	20%
185	17	10	1.1	1.1	20%
186	59	9	1.1	1.1	20%
187	185	6	1.1	1.1	20%
188	227	5	1.1	1.1	20%
189	23	10	1	1.1	19%
190	65	9	1	1.1	19%
191	107	8	1	1.1	19%
192	149	7	1	1.1	19%
193	191	6	1	1.1	19%
194	233	5	1	1.1	19%
195	29	10	0.9	1.1	19%
196	71	9	0.9	1.1	19%
197	113	8	0.9	1.1	19%
198	155	7	0.9	1.1	19%
199	197	6	0.9	1.1	19%
200	239	5	0.9	1.1	19%
201	35	10	0.8	1.1	19%
202	77	9	0.8	1.1	19%
203	119	8	0.8	1.1	19%
204	161	7	0.8	1.1	19%
205	203	6	0.8	1.1	19%
206	245	5	0.8	1.1	19%
207	41	10	0.7	1.1	19%
208	83	9	0.7	1.1	19%
209	125	8	0.7	1.1	19%

210	167	7	0.7	1.1	19%
211	209	6	0.7	1.1	19%
212	251	5	0.7	1.1	19%
213	6	10	1.3	1	13%
214	48	9	1.3	1	13%
215	90	8	1.3	1	13%
216	132	7	1.3	1	13%
217	174	6	1.3	1	13%
218	216	5	1.3	1	13%
219	12	10	1.2	1	12%
220	24	10	1	1	12%
221	18	10	1.1	1	12%
222	30	10	0.9	1	12%
223	36	10	0.8	1	12%
224	66	9	1	1	12%
225	72	9	0.9	1	12%
226	78	9	0.8	1	12%
227	42	10	0.7	1	12%
228	54	9	1.2	1	12%
229	84	9	0.7	1	12%
230	96	8	1.2	1	12%
231	120	8	0.8	1	12%
232	126	8	0.7	1	12%
233	138	7	1.2	1	12%
234	60	9	1.1	1	12%
235	108	8	1	1	12%
236	114	8	0.9	1	12%
237	180	6	1.2	1	12%
238	102	8	1.1	1	12%
239	150	7	1	1	12%
240	156	7	0.9	1	12%
241	222	5	1.2	1	12%
242	144	7	1.1	1	12%
243	162	7	0.8	1	12%
244	168	7	0.7	1	12%
245	192	6	1	1	12%
246	198	6	0.9	1	12%
247	186	6	1.1	1	12%

248	204	6	0.8	1	12%
249	210	6	0.7	1	12%
250	240	5	0.9	1	12%
251	246	5	0.8	1	12%
252	228	5	1.1	1	12%
253	234	5	1	1	12%
254	252	5	0.7	1	12%

Alert variants ordered as evaluated:

Alert #	Rank	t_{safe}	GSx	$V_{stall}x$	Ratio of flights flagged to FSF stable approach criteria flights flagged
1	1	10	1.3	1.5	13217%
2	43	10	1.3	1.4	12417%
3	85	10	1.3	1.3	6502%
4	128	10	1.3	1.2	238%
5	171	10	1.3	1.1	20%
6	213	10	1.3	1	13%
7	5	10	1.2	1.5	13216%
8	46	10	1.2	1.4	12403%
9	89	10	1.2	1.3	6431%
10	134	10	1.2	1.2	230%
11	177	10	1.2	1.1	20%
12	219	10	1.2	1	12%
13	12	10	1.1	1.5	13214%
14	52	10	1.1	1.4	12384%
15	95	10	1.1	1.3	6370%
16	139	10	1.1	1.2	222%
17	185	10	1.1	1.1	20%
18	221	10	1.1	1	12%
19	17	10	1	1.5	13212%
20	57	10	1	1.4	12368%
21	100	10	1	1.3	6312%
22	144	10	1	1.2	215%

23	189	10	1	1.1	19%
24	220	10	1	1	12%
25	23	10	0.9	1.5	13209%
26	64	10	0.9	1.4	12352%
27	105	10	0.9	1.3	6258%
28	149	10	0.9	1.2	209%
29	195	10	0.9	1.1	19%
30	222	10	0.9	1	12%
31	27	10	0.8	1.5	13208%
32	68	10	0.8	1.4	12338%
33	109	10	0.8	1.3	6210%
34	155	10	0.8	1.2	205%
35	201	10	0.8	1.1	19%
36	223	10	0.8	1	12%
37	31	10	0.7	1.5	13207%
38	73	10	0.7	1.4	12323%
39	115	10	0.7	1.3	6167%
40	158	10	0.7	1.2	201%
41	207	10	0.7	1.1	19%
42	227	10	0.7	1	12%
43	2	9	1.3	1.5	13217%
44	44	9	1.3	1.4	12412%
45	86	9	1.3	1.3	6483%
46	129	9	1.3	1.2	236%
47	172	9	1.3	1.1	20%
48	214	9	1.3	1	13%
49	6	9	1.2	1.5	13215%
50	49	9	1.2	1.4	12395%
51	92	9	1.2	1.3	6412%
52	135	9	1.2	1.2	227%
53	178	9	1.2	1.1	20%
54	228	9	1.2	1	12%
55	13	9	1.1	1.5	13213%
56	54	9	1.1	1.4	12378%
57	97	9	1.1	1.3	6347%
58	141	9	1.1	1.2	220%
59	186	9	1.1	1.1	20%
60	234	9	1.1	1	12%

61	18	9	1	1.5	13211%
62	59	9	1	1.4	12361%
63	102	9	1	1.3	6285%
64	146	9	1	1.2	213%
65	190	9	1	1.1	19%
66	224	9	1	1	12%
67	25	9	0.9	1.5	13209%
68	66	9	0.9	1.4	12345%
69	108	9	0.9	1.3	6229%
70	151	9	0.9	1.2	207%
71	196	9	0.9	1.1	19%
72	225	9	0.9	1	12%
73	30	9	0.8	1.5	13207%
74	71	9	0.8	1.4	12328%
75	112	9	0.8	1.3	6181%
76	157	9	0.8	1.2	202%
77	202	9	0.8	1.1	19%
78	226	9	0.8	1	12%
79	34	9	0.7	1.5	13206%
80	76	9	0.7	1.4	12314%
81	118	9	0.7	1.3	6133%
82	162	9	0.7	1.2	198%
83	208	9	0.7	1.1	19%
84	229	9	0.7	1	12%
85	3	8	1.3	1.5	13217%
86	45	8	1.3	1.4	12408%
87	87	8	1.3	1.3	6465%
88	130	8	1.3	1.2	235%
89	173	8	1.3	1.1	20%
90	215	8	1.3	1	13%
91	8	8	1.2	1.5	13215%
92	50	8	1.2	1.4	12390%
93	93	8	1.2	1.3	6392%
94	136	8	1.2	1.2	225%
95	179	8	1.2	1.1	20%
96	230	8	1.2	1	12%
97	15	8	1.1	1.5	13213%
98	56	8	1.1	1.4	12372%

99	99	8	1.1	1.3	6324%
100	142	8	1.1	1.2	218%
101	183	8	1.1	1.1	20%
102	238	8	1.1	1	12%
103	21	8	1	1.5	13211%
104	62	8	1	1.4	12354%
105	104	8	1	1.3	6259%
106	148	8	1	1.2	211%
107	191	8	1	1.1	19%
108	235	8	1	1	12%
109	28	8	0.9	1.5	13208%
110	69	8	0.9	1.4	12336%
111	111	8	0.9	1.3	6201%
112	153	8	0.9	1.2	205%
113	197	8	0.9	1.1	19%
114	236	8	0.9	1	12%
115	33	8	0.8	1.5	13207%
116	75	8	0.8	1.4	12320%
117	116	8	0.8	1.3	6148%
118	160	8	0.8	1.2	200%
119	203	8	0.8	1.1	19%
120	231	8	0.8	1	12%
121	38	8	0.7	1.5	13205%
122	79	8	0.7	1.4	12306%
123	121	8	0.7	1.3	6099%
124	164	8	0.7	1.2	196%
125	209	8	0.7	1.1	19%
126	232	8	0.7	1	12%
127	4	7	1.3	1.5	13216%
128	47	7	1.3	1.4	12403%
129	88	7	1.3	1.3	6446%
130	131	7	1.3	1.2	234%
131	174	7	1.3	1.1	20%
132	216	7	1.3	1	13%
133	10	7	1.2	1.5	13215%
134	51	7	1.2	1.4	12385%
135	94	7	1.2	1.3	6371%
136	137	7	1.2	1.2	224%

137	180	7	1.2	1.1	20%
138	233	7	1.2	1	12%
139	16	7	1.1	1.5	13212%
140	58	7	1.1	1.4	12366%
141	101	7	1.1	1.3	6301%
142	143	7	1.1	1.2	216%
143	184	7	1.1	1.1	20%
144	242	7	1.1	1	12%
145	22	7	1	1.5	13210%
146	65	7	1	1.4	12347%
147	107	7	1	1.3	6233%
148	150	7	1	1.2	209%
149	192	7	1	1.1	19%
150	239	7	1	1	12%
151	29	7	0.9	1.5	13208%
152	72	7	0.9	1.4	12328%
153	114	7	0.9	1.3	6172%
154	156	7	0.9	1.2	202%
155	198	7	0.9	1.1	19%
156	240	7	0.9	1	12%
157	36	7	0.8	1.5	13206%
158	78	7	0.8	1.4	12311%
159	119	7	0.8	1.3	6116%
160	163	7	0.8	1.2	197%
161	204	7	0.8	1.1	19%
162	243	7	0.8	1	12%
163	40	7	0.7	1.5	13204%
164	81	7	0.7	1.4	12296%
165	123	7	0.7	1.3	6062%
166	166	7	0.7	1.2	193%
167	210	7	0.7	1.1	19%
168	244	7	0.7	1	12%
169	7	6	1.3	1.5	13215%
170	48	6	1.3	1.4	12399%
171	90	6	1.3	1.3	6430%
172	132	6	1.3	1.2	232%
173	175	6	1.3	1.1	20%
174	217	6	1.3	1	13%

175	11	6	1.2	1.5	13214%
176	53	6	1.2	1.4	12379%
177	96	6	1.2	1.3	6353%
178	138	6	1.2	1.2	223%
179	181	6	1.2	1.1	20%
180	237	6	1.2	1	12%
181	19	6	1.1	1.5	13211%
182	60	6	1.1	1.4	12359%
183	103	6	1.1	1.3	6278%
184	145	6	1.1	1.2	214%
185	187	6	1.1	1.1	20%
186	247	6	1.1	1	12%
187	24	6	1	1.5	13209%
188	67	6	1	1.4	12340%
189	110	6	1	1.3	6207%
190	152	6	1	1.2	207%
191	193	6	1	1.1	19%
192	245	6	1	1	12%
193	32	6	0.9	1.5	13207%
194	74	6	0.9	1.4	12320%
195	117	6	0.9	1.3	6142%
196	159	6	0.9	1.2	200%
197	199	6	0.9	1.1	19%
198	246	6	0.9	1	12%
199	37	6	0.8	1.5	13205%
200	80	6	0.8	1.4	12302%
201	122	6	0.8	1.3	6083%
202	165	6	0.8	1.2	195%
203	205	6	0.8	1.1	19%
204	248	6	0.8	1	12%
205	41	6	0.7	1.5	13204%
206	83	6	0.7	1.4	12286%
207	125	6	0.7	1.3	6027%
208	168	6	0.7	1.2	190%
209	211	6	0.7	1.1	19%
210	249	6	0.7	1	12%
211	9	5	1.3	1.5	13215%
212	61	5	1.3	1.4	12359%

213	91	5	1.3	1.3	6413%
214	133	5	1.3	1.2	230%
215	176	5	1.3	1.1	20%
216	218	5	1.3	1	13%
217	14	5	1.2	1.5	13213%
218	55	5	1.2	1.4	12374%
219	98	5	1.2	1.3	6333%
220	140	5	1.2	1.2	221%
221	182	5	1.2	1.1	20%
222	241	5	1.2	1	12%
223	20	5	1.1	1.5	13211%
224	63	5	1.1	1.4	12353%
225	106	5	1.1	1.3	6255%
226	147	5	1.1	1.2	212%
227	188	5	1.1	1.1	20%
228	252	5	1.1	1	12%
229	26	5	1	1.5	13209%
230	70	5	1	1.4	12332%
231	113	5	1	1.3	6181%
232	154	5	1	1.2	205%
233	194	5	1	1.1	19%
234	253	5	1	1	12%
235	35	5	0.9	1.5	13206%
236	77	5	0.9	1.4	12313%
237	120	5	0.9	1.3	6114%
238	161	5	0.9	1.2	198%
239	200	5	0.9	1.1	19%
240	250	5	0.9	1	12%
241	39	5	0.8	1.5	13205%
242	82	5	0.8	1.4	12294%
243	124	5	0.8	1.3	6051%
244	167	5	0.8	1.2	193%
245	206	5	0.8	1.1	19%
246	251	5	0.8	1	12%
247	42	5	0.7	1.5	13203%
248	84	5	0.7	1.4	12276%
249	126	5	0.7	1.3	5992%
250	169	5	0.7	1.2	188%

251	212	5	0.7	1.1	19%
252	254	5	0.7	1	12%
Current	170	Current	Current	Current	100%

REFERENCES

Abbott, K., McKenney, D., & Railsback, P. (2013). Operational use of flight path management systems—Final report of the Performance-based operations Aviation Rulemaking Committee (PARC)/Commercial Aviation Safety Team Flight Deck Automation Working Group (CAST). *Commercial Aviation Safety Team Flight Deck Automation Working Group*.

Boeing. (1998, July). 777-200/300 airplane characteristics for airport planning. Boeing Commercial Airplanes.

Boeing. (2014). Boeing submission for Asiana Airlines (AAR) 777-200ER HL7742 landing accident at San Francisco - 6 July 2013 (M. E. Bernson, Comp.).

Carbaugh, D. (2007, Q1). Tail strikes: Prevention. *Boeing Aeromagazine*, 6-13.

de Boer, R. J., Coumou, T., Hunink, A., & van Bennekom, T. (2014). The automatic identification of unstable approaches from flight data. In *6th International Conference on Research in Air Transportation, ICRAT* (pp. 26-30).

Federal Aviation Administration (FAA) (1971) 14 C.F.R. § Chapter I, Subchapter C, Part 33.73(b) (1971).

Federal Aviation Administration (FAA) (2013). *Safety Alert for Operators: Manual Flight Operations.* Retrieved from: https://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/safo/all_safos/media/2013/SAFO13002.pdf

Federal Aviation Administration (FAA) (2017). *Safety Alert for Operators: Manual Flight Operations Proficiency*. Retrieved from: https://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/safo/all_safos/media/2017/SAFO17007.pdf

Flight Safety Foundation. (2000). FSF ALAR briefing note 7.1—Stabilized approach. *Approach and landing accident reduction toolkit*.

Hansman, R. J., Wanke, C., Kuchar, J., Mykityshyn, M., Hahn, E., & Midkiff, A. (1993). Hazard alerting and situational awareness in advanced air transport cockpits.

Haslbeck, A., & Hoermann, H. J. (2016). Flying the needles: flight deck automation erodes fine-motor flying skills among airline pilots. *Human factors*, *58*(4), 533-545.

Lambregts, A. A. (1985). *U.S. Patent No. 4,536,843*. Washington, DC: U.S. Patent and Trademark Office.

McFadden, K. L., & Towell, E. R. (1999). Aviation human factors: a framework for the new millennium. *Journal of Air Transport Management*, *5*(4), 177-184.

Merritt, S. R., Cliff, E. M., & Kelley, H. J. (1985). Energy-modeled climb and climb-dash - the Kaiser technique. *Automatica*, *21*(2), 319-321.

National Transportation Safety Board. (2013). Descent below visual glidepath and impact with seawall: Asiana Airlines Flight 214.

Pritchett, A. R. (2001). Reviewing the role of cockpit alerting systems. *Human Factors and Aerospace Safety*, *1*(1).

Puranik, T. G., Harrison, E., Min, S., Jimenez, H., & Mavris, D. N. (2016). Energy-Based Metrics for General Aviation Flight Data Record Analysis. In *16th AIAA Aviation Technology, Integration, and Operations Conference* (p. 3915).

Rutowski, E. S. (1954). Energy approach to the general aircraft performance problem. *Journal of the Aeronautical Sciences*, 187-195.

Shish, K. H., Kaneshige, J., Acosta, D. M., Schuet, S., Lombaerts, T., Martin, L., & Madavan, A. N. (2015). Trajectory Prediction and Alerting for Aircraft Mode and Energy State Awareness. In *AIAA Infotech@ Aerospace* (p. 1113).

Shish, K., Kaneshige, J., Acosta, D., Schuet, S., Lombaerts, T., Martin, L., & Madavan, A. N. (2016). Aircraft mode and energy-state prediction, assessment, and alerting. *Journal of Guidance, Control, and Dynamics*, *40*(4), 804-816.

van den Hoven, M., de Jong, P., Borst, C., Mulder, M., & van Passen, M. (2010). Investigation of energy management during approach - evaluating the total energy-based perspective flight-path display. *AIAA Guidance, Navigation, and Control Conference*. https://doi.org/10.2514/6.2010-8401

Williams, D., Oseguera-Lohr, R., & Lewis, E. (2004). *Design and testing of a low noise flight guidance concept*. NASA.