Microburst Recovery For Jet Transport Aircraft: A Comparison Between Constant And Variable Pitch Guidance Trajectories

Mark Cadmus

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MICROBURST RECOVERY FOR JET TRANSPORT AIRCRAFT: 
A COMPARISON BETWEEN CONSTANT AND VARIABLE PITCH GUIDANCE 
TRAJECTORIES

by

Mark Cadmus

A Graduate Thesis Submitted to the
Department of Applied Aviation Sciences
in Partial Fulfillment of the Requirements of the Degree of
Master of Science in Aeronautics

Embry-Riddle Aeronautical University
Daytona Beach, Florida
September 2003
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This thesis was prepared under the direction of the candidate’s thesis committee chair,
Dr. Michael E. Wiggins, Department of Applied Aviation Sciences, and approved by the
Thesis Review Committee. It was submitted to the Department of Applied Aviation
Sciences in partial fulfillment of the requirements for the degree of
Master of Science in Aeronautics.

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11/5/03
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ABSTRACT

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The purpose of this research was to compare, in a simulator, the safety of a variable pitch strategy with the established constant pitch strategy in transitioning through a microburst during an abort maneuver in the approach to landing phase of flight. In numerous mathematical and computer studies of microburst penetrations, the variable pitch strategy provided a greater recovery altitude than the constant pitch strategy. A Boeing 737 level C aircraft simulator was employed to evaluate these findings in a dynamic environment. Three appropriately qualified subjects piloted 35 flights through a microburst, while computer generated data were collected. “Safety”, defined as the maximization of the minimum altitude experienced by the aircraft during the recovery phase of the microburst encounter, was statistically greater for the constant pitch maneuver. An improved microburst model and a flight director steering command are recommended for continued studies in a manned simulator.
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CHAPTER 1

INTRODUCTION

Microbursts are a violent form of low-level wind shear and pose a substantial threat to aircraft in flight. Wind in the microburst descends at high velocity and spreads radially outward, forming an area of horizontal and vertical wind shear. Aircraft penetrating this wind shear experience a reduction in climb capability. This performance degradation can be catastrophic when the microburst is encountered at the low altitudes and airspeeds required during the takeoff and approach phases of flight. Low-level wind shear and microbursts are responsible for the deaths of 665 people in 25 airline accidents since 1964 (McCarthy, 1996, p. 9). The preponderance of the fatalities, 512, occurred during the approach to landing phase of flight.

Avoidance of the microburst is the safest measure for arriving and departing aircraft. In recent years there has been considerable improvement in the detection and prediction of microbursts. Despite the sophisticated infrastructure, failures in the system have occurred, resulting in fatalities, and inadvertent microburst encounters are likely to happen again. The escape maneuver is the final defense in surviving a microburst encounter.

A successful escape from an inadvertent microburst encounter might require the maximum performance of the aircraft. The current escape maneuver, keeping “the airplane flying as long as possible in hope of exiting the windshear [sic]” (Federal Aviation Administration [FAA], 1996, p. 1), does not produce an optimum trajectory. An alternate strategy, exiting the wind shear in the minimum amount of time, decreasing the duration of the microburst’s debilitating effects, increases the survivability for
penetrating aircraft in computational evaluations and flight simulator trials of the takeoff phase. Extension of the research to the approach to landing phase is a natural evolution.

Background of the Problem

The advent of the flight data recorder (FDR) led investigators to consider the hazards of low-level wind shear to aircraft. An Iberian DC-10 equipped with an enhanced digital flight data recorder (DFDR) crashed while landing at Boston’s Logan International Airport on December 17, 1973. Investigators were able to construct the approach environment and flight path of this ill-fated tri-jet from the 96-parameter recording. The DFDR clearly illustrated degradation in aircraft performance resulting from the presence of wind shear. Grossi (1988) of the National Transportation Safety Board (NTSB) declared, “there is little doubt that without the DFDR data, this investigation would not have yielded this level of insight into the windshear [sic] phenomenon, and in fact may not have identified it as a factor” (p. 459).

Using the data obtained from the DFDR, five appropriately rated pilots flew 48 simulated approaches. In part, these simulations were conducted to “examine the flight conditions that confronted the flight crew” (National Transportation Safety Board [NTSB], 1974a, p. 12). The flight simulator trials demonstrated the serious problem that wind shear posed to this aircraft (p. 20). “The examination of DFDR data, including the data reproduced in the DC-10 flight simulator, provided more positive evidence of the wind conditions along Flight 933’s final approach profile” (p. 19). The knowledge gained from the data generated by this accident led to the first recommendations on wind shear to aviation safety. (Grossi, 1988, p. 459). These recommendations were directed toward pilot awareness and education.
The prominence of wind shear as a causal factor became more prevalent through the years as sophisticated investigation techniques exposed this insidious phenomenon. Specialists in meteorology and atmospheric science augmented the data generated from FDRs and flight simulators, refining old theories, and developing new theories. The accident investigation of a Boeing 727 in New York became the genesis in the development of a new wind shear theory.

Eastern 66 was approaching John F. Kennedy International Airport (JFK) in heavy rain on June 24, 1975, when it entered a horizontal wind shear coupled with a vertical downdraft. This combination of wind caused the aircraft to crash short of the runway with 113 fatalities. “After an exhaustive analysis of the FDR data and eyewitness accounts, [Fujita] called this windsystem [sic] the ‘downburst’” (Fujita, 1985, p. 2). The downburst, “a localized, intense downdraft with vertical currents exceeding a downward speed of 12 fps or 720 fpm” (Fujita, 1976, p. 50), is strong enough to blow down a jet aircraft (1985, p. 2).

This concept was considered controversial (Rosenfeld, 1999) and not until further research was the downburst accepted by the meteorological community. Fujita’s independent investigation of this accident is the acknowledged origin of microburst understanding and lexicon.

Additional aircraft accidents have been attributed to microburst encounters. Each of these accidents brought new data and new research into the field. Many of the ensuing developments were a benefit to the aviation community, including ground based sensing and forecasting, pilot education, and practical pilot training. In combination, these
improvements have contributed to a decline in the number of microburst related accidents (McCarthy, 1996, p. 6).

Operational considerations limit the ability of scheduled carriers to avoid every area of potential microburst development. In order to judge the probability of an encounter, and make informed decisions, an understanding of microburst meteorology is paramount.

Low-level wind shear is the parent category of downbursts, which are further divided into either macrobursts or microbursts. The classification of microbursts includes dry or wet, depending on the presence of rain at the surface. Dry microbursts occur mostly in the western US where virga-precipitation that evaporates before ground contact–is common due to the large spread between temperature and dew point. In the eastern states, the atmosphere in the summer months tends to have a higher relative concentration of moisture, limiting large-scale evaporation, and leading to a predominance of wet microbursts (Atkins & Wakimoto, 1991, p. 471; see also Nelson & Ellrod, 1997, pp. 262–263).

A number of atmospheric properties have been identified which, singularly or in combination, form microbursts. Vertical pressure gradients differing from the atmospheric hydrostatic pressure can initiate the microburst. This pressure differential contributes significantly to downdraft intensities (Cotton & Anthes, 1989, p. 491). Precipitation drag can also induce a microburst by accelerating the air in the vertical plane. Evaporative cooling provides negative buoyancy to the air, which can cause the formation of both wet and dry microbursts (Stull, 2000, pp. 340–341). Even with the knowledge of microburst inception, forecasting remains a difficult task (National Oceanic
and Atmospheric Administration [NOAA], 2001). The only civilian forecasts available are on an experimental basis via the Internet from the National Environmental Satellite Data and Information Service (FAA, 1999, p. 3-12).

In the initial stages of the microburst air descends from the cloud base creating a vertical shaft of wind. This wind induces a horizontal ring vortex on the perimeter of the wind shaft that descends with the vertical column of wind (Fujita, 1986, p. 56). Several of these horizontal vortices may develop. When the vertical wind contacts the ground it spreads radially into an outflow (see Figure 1). The vortex ring encircling the outflow also expands, increasing the wind velocity near the ground (Caracena, Holle, & Doswell, 1989, p. 12). The outflow front is oftentimes the only visible indication of a microburst, as colloidal particles carried by the outflow wind are distinguished from their surroundings.

![Figure 1. Idealized microburst flow with descriptors. Note. From Pilot Windshear Guide (p. 8), by FAA, 1988, Washington, DC: FAA.](image-url)
The outflow is of particular importance in classifying the downburst phenomenon. Damaging outflow winds extending greater than 4 km are considered macrobursts, while those winds that do not exceed 4 km are microbursts (Fujita, 1985, p. 8). Microbursts have tighter wind shear gradients and are of stronger intensity than macrobursts, and represent the greater threat to aviation (Caracena et al., 1989, p. 1).

Microbursts degrade airplane performance through a decrease in both lift and stability. The combination of horizontal and vertical wind shear reduces lift through a reduction in relative airflow and angle of attack for the aircraft. This loss is compounded by the speed instability that may be present during a microburst encounter. In the region of speed instability the aircraft requires additional thrust to offset the increased drag of the slower speed. Speed instability thus reduces the thrust available for increasing altitude or airspeed.

Longitudinal stability is affected when an aircraft is disturbed from its equilibrium trim state (Cook, 1997, p. 119). Microburst winds excite both the short and long period modes of longitudinal stability. The short period mode is a quick oscillation in the pitch attitude of the aircraft and has little debilitating effect on the flight path. The long period mode, or phugoid, causes oscillations in both the airspeed and the altitude of the aircraft.

The oscillatory nature of the phugoid can cause the airspeed to decay very rapidly. The altitude variations are also impairing and can cause a “premature impact with the ground short of the runway” (McCarthy, Blick, & Bensch, 1979, p. 48). The phugoid is lightly damped in transport aircraft and can be excited by the variable winds associated with a microburst, as documented in numerous studies (e.g., Frost, Turkel, & McCarthy, 1982; McCarthy et al., 1979; McCarthy & Norviel, 1982; Sherman, 1977). Combined
with the performance reducing wind shear, the phugoid oscillation makes the microburst a treacherous phenomenon for jet aircraft (Robinson, 1991, p. 3.18).

In an effort to improve the survivability of aircraft encountering wind shear, the Federal Aviation Administration (FAA) contracted with the Boeing Company to develop an escape profile (FAA, 1988, p. ii). The resultant procedure is known as a constant pitch maneuver as it constrains the initial pitch attitude of the aircraft to 15°. With a high pitch attitude and resultant low airspeed, the FAA procedure increases the exposure of the airplane to the effects of wind shear.

Maneuvers based on a strategy of exiting the shear in the minimum time—so as to reduce the effects of the microburst—have produced promising results in aircraft simulators and mathematical models (e.g. Dogan & Kabamba, 2000; Hinton, 1988; 1989; Miele, Wang, Tzeng, & Melvin, 1987).

Simulators are beneficial in confirming handling characteristics, FDR data, and in testing theories (Ramsey, 1992, p. 11-2). As flight simulators are able to model a microburst’s complex wind—in conjunction with aircraft performance—they have been used as aids to investigation in many of the microburst related accidents. In testing theories, Boeing used aircraft simulators to develop procedures for escape maneuvers (Higgins & Roosme, 1977; FAA, 1987, p. 12), and in developing the *Pilot Windshear Guide* for the FAA (FAA, 1988, p. ii). Researchers at the National Aeronautics and Space Administration (NASA) also used a flight simulator to evaluate potential escape procedures (Hinton, 1989).

The more recent NASA examinations demonstrate an increase in the survivability, during the takeoff phase, of the variable pitch escape maneuver compared
with the FAA recommended constant pitch maneuver. The principle investigator in these simulator trials advised, “extension of the work to the approach-to-landing case is also necessary” (Hinton, 1988, p. 10). Of the 29 air carrier accidents attributable to wind shear, as identified by McCarthy, only 3 were in the takeoff phase (1996, pp. 8–9). With the preponderance of accidents occurring in the landing phase, it follows that the research should be directed toward this area.

A flight simulator study comparing the constant pitch guidance strategy with the variable pitch guidance strategy, in terms of altitude loss during the approach to landing abort maneuver, is the first phase in providing insight into the applicability of the variable pitch procedure to a real world environment. It is desirable to increase the survivability and flight safety of jet transport aircraft exposed to the microburst phenomenon. This objective may be achieved through research and experimentation.

Statement of the Problem

Mathematical models and computer simulations suggest that a variable pitch guidance strategy through a microburst encounter provides for greater safety than the currently employed constant pitch strategy. An aircraft simulator, replicating a jet transport, with a microburst wind field program was employed to test these conclusions in a dynamic environment.

The purpose of this research was to compare, in a simulator, the safety of a variable pitch guidance strategy with the established constant pitch guidance strategy in transitioning through a microburst during an abort maneuver in the approach to landing phase of flight. The safety of the maneuver was statistically evaluated in terms of altitude loss, while other factors of safety were kept in prescribed parameters.
Definition of Terms

Downburst – A localized intense downdraft with vertical currents exceeding a downward speed of 12 fps or 720 fpm at 300 ft above the surface. This value corresponds to a divergence of $4 \times 10^{-2} \text{ sec}^{-1}$ (Fujita, 1976, p. 50).

Macroburst – A large downburst with its outburst winds extending in excess of 4 km (2.5 miles) in horizontal dimension. An intense macroburst often causes widespread, tornado-like damage. Damaging winds, lasting 5 to 30 minutes, could be as high as 60 m/sec (134mph) (Fujita, 1985, p. 8).

Microburst – A small downburst with its outburst of damaging winds extending only 4 km (2.5 miles) or less. In spite of its small horizontal scale, an intense microburst could induce damaging wind as high as 75 m/sec (168 mph) (Fujita, 1985, p. 8).

Outburst Center – The nadir point of a downburst where the vertical air current hits the surface and spreads out violently. The fastest spreading flow is seen in the direction of the cell motion. Environmental flows, such as sea breeze and adjacent cells distort the outburst current. Depending upon the flight path relative to an outburst center, the outburst current is felt by an aircraft as:

a. Crosswind burst – aircraft drifts to the right or left

b. Tailwind burst – indicated airspeed drops and aircraft sinks

c. Headwind burst – indicated airspeed increases and aircraft gains altitude (Fujita, 1976, p. 50).
Phugoid – Lightly damped low frequency oscillation in speed coupling into pitch attitude and height (Cook, 1997, p. 120).

Recovery altitude – The lowest altitude, above ground level, recorded by the simulator computer, of the aircraft during the microburst escape maneuver.

Wind Shear – A change in wind speed and/or wind direction in a short distance resulting in a tearing or shearing effect. It can exist in a horizontal or vertical direction and occasionally in both. (FAA, 2003a, Pilot/Controller Glossary).
Limitations and Assumptions

The research was conducted with the awareness of several limiting factors. Simulators replicate an aircraft to the best that technology has to offer at the time it is built and subsequently upgraded. The simulator response is based on both objective and subjective data, and is hampered by latency, transport delay, and noise in the system. Simulators accurately replicate an aircraft’s response when it is operated well within the performance envelope. As the parameters of the envelope are approached, the response of the simulator loses fidelity and utilizes a more subjective data routine. In microburst research much of the data required are at the edge of the envelope.

Avoidance of the microburst is certainly the safest maneuver, but out of necessity for data acquisition, evasion of the microburst was not practiced in the simulator. Additionally, the element of surprise was neither present nor considered—every approach involved a microburst encounter. Generalized global knowledge of the microburst was assumed, the participating pilots being generally aware of where the microburst began, and where its effects ended.

Flight below glide slope was not penalized; however, the limits of survivability were defined by deviation below the altitude corresponding to field elevation and sustained airspeeds below the stall value.

The simulated microburst included neither turbulence, nor the effects of rain. This does not deviate from the observed environment where quite often the microburst is dry and non-turbulent. Additional limitations and qualifications are presented in chapter three, the methodology section.
CHAPTER II

REVIEW OF THE LITERATURE

Wind shear, a change in wind speed or direction in a short distance, is a tearing or shearing action (FAA, 2003a), the significance to aviation lying in its degrading effect on aircraft performance, and hence flight safety. Low-level wind shear, that which occurs within 500 meters of the surface, is particularly dangerous for departing and arriving aircraft (International Civil Aviation Organization [ICAO], 1987, p. 1). The most violent form of low-level wind shear, the microburst, is “strong enough to blow down a jet aircraft” (Fujita, 1985, p. 2).

Microbursts diminish the lift, stability, and the climb capability of aircraft. The tight wind shear gradients in the microburst lead to rapid changes in the wind vector and may exceed the inertial capabilities of an aircraft to maintain flight (Caracena et al., 1989).

In response to the microburst threat, escape procedures have been developed. Initially, the escape was based on the traditional go-around procedure of holding airspeed and if necessary, allowing a decay to stick-shaker speed to avoid terrain (FAA, 1979, ¶7.a.5). After several microburst accidents, the escape procedure changed from airspeed to pitch control. The pitch attitude of the aircraft is now set at 15° and raised or lowered as required to respect intermittent stick shaker (FAA, 1988, p. 46). The advent of powerful computers allows optimal escape trajectories to be profiled. These optimal maneuvers differ from the FAA escape procedure and, in mathematical and flight simulation, yield less altitude and airspeed loss, providing for a greater probability of survival in the event of an inadvertent microburst encounter (e.g., Dogan & Kabamba, 2000; Hinton, 1988; Miele et al., 1987; Mulgund & Stengel, 1992b).
Historical Context

The history of microburst understanding is intimately tied with a progression of aircraft accidents. It was not until the mid 1970s that the phenomenon was first postulated as a causal factor in the deaths of 113 people (Fujita, 1976). The concept was not well received (Rosenfeld, 1999), and many in the industry clung to previous beliefs, discounting the ferocity of the downburst. As more accidents attributed to these winds occurred, more information became available, and the concept of the microburst took hold. A retrospective analysis indicates that low-level wind shear, the parent category of microbursts, is responsible for the deaths of at least 665 people in 29 American air-carrier accidents (McCarthy, 1996, p. 9).

The sensationalism of aircraft accidents obscures the fact that low-level wind shear has been documented throughout history. In ancient times, Aristotle considered the phenomenon of wind shear in his discourse *Meteorology* (Berlin translation), and during the Renaissance, an Oxford don relayed an accurate description of the microburst and its debilitating effects on maritime activities (Bohun, 1671). The modern era brought a new taxonomy and understanding to meteorology as the physical properties were dissected and understood.

Public and Congressional concern over the spate of microburst induced aircraft accidents released grants to the FAA, the National Science Foundation, the National Oceanic and Atmospheric Administration (NOAA), and others, to initiate the rigorous study of the downburst (National Research Counsel [NRC], 1983, p. 1). These projects carried whimsical titles—NIMROD, JAWS, CLAWS, and MIST—which belied their most serious endeavor, the prevention of aircraft accidents.
Previous aircraft accidents are testaments to the destructive, enigmatic, and dynamic nature of the downburst. Each accident has enlarged the knowledge base and brought about additional recommendations and procedures. The accident of Eastern 66 became the catalyst for the downburst theory, though it was not the first aircraft to succumb to this devastating meteorological phenomenon.

**Eastern 66**

On the summer afternoon of June 24, 1975, an Eastern Airlines Boeing 727-225 was approaching JFK international airport as a scheduled flight from New Orleans. Numerous scattered thundershowers delayed inbound aircraft, and after holding, Eastern 66 was vectored for an instrument landing system (ILS) approach to runway 22L. Slight deviations around rain showers had the 727 intercepting the localizer, while a company flight was executing a go-around from the same approach.

Eastern 902, a Lockheed L-1011, reported to the final controller “…we had … a pretty good shear pulling us to the right and … down and visibility was nil…” (NTSB, 1976, p. 3). The Boeing crew, listening on the same frequency, was incredulous of the pilot report transmitted, a crewmember stating: “I wonder if they’re covering for themselves” (NTSB, 1976, p. 49).

The L-1011 encountered a wind shear that reduced itsairspeed by 24 knots. A positive climb was not established until over 200 feet of altitude was lost and abnormal amounts of pitch and power were employed (Fujita, 1976, p. 23). The wide-bodied jet started climbing just 60 feet above the terrain (Fujita, 1985, p. 37). Eastern 902 was not
the first to encounter or report the wind shear; Flying Tiger 161, a DC-8 aircraft, had just been through it, landing on 22L.

The effect of the wind shear on the DC-8 was witnessed by a Pan Am B-707 captain who “thought that the pilot must have been like a cat on a hot tin roof, trying to save his airplane” (cited in Fujita, 1985, p. 36). The Flying Tiger pilot stated that he estimated conditions to be so severe that he would not have had the performance required to execute a missed approach, hence he elected to carry out a landing (NTSB, 1976, p. 5). As they were taxiing, the captain of Flying Tiger 161 reported to JFK tower, “I just highly recommend that you change the runways and... land northwest, you have such a tremendous wind shear down near... the ground on final” (cited in NTSB, 1976, p. 5).

The tower controller decided no change in landing direction was necessary, as the surface weather report was indicating winds 210° at 7 knots, almost aligned with the runway. The Flying Tiger captain commented, “I don’t care what you’re indicating. I’m just telling you that you have such a dangerous wind shear on the approach that you should change the traffic to land to the northwest” (Bliss cited in Moldrem, 1996, p. 303).

Neither Eastern aircraft, both on approach frequency, were privy to the comments made by the DC-8 captain transmitting on tower frequency. Eastern 902, in the go-around, was asked if they would classify their encounter with the wind shear as severe, to which they responded ‘affirmative’ (NTSB, 1976, p. 52). The next transmission was landing clearance for Eastern 66.

Descending through 500 feet, Eastern 66 entered an area of heavy rain, the windshield wipers were positioned to high, but the visibility remained restricted. At a lower altitude the captain reported the airfield in sight (Fujita, 1976, p. 41), and with a
relatively high indicated airspeed of 150 knots, the jet was only seconds from the runway. Nearing the threshold, the winds changed abruptly, and the flight path and airspeed decayed rapidly. The first officer, who was flying, called for takeoff thrust to arrest the descent. The command was issued too late, and the aircraft continued descending, with the left wing ripping through an approach light stanchion.

The aircraft succumbed to its mortal wound, and sliding through additional lighting towers, disintegrated piece by piece. The main wreckage area came to a rest on Rockaway Boulevard, 1400 feet from the initial contact point and 1000 feet shy of the runway 22L threshold. The official report determined “the accident was not survivable…” (NTSB, 1976, p. 39). In an incredibly gallant effort by fire and rescue personnel, who were on scene within 2 minutes of the aircraft accident, 11 of the 124 persons on board ultimately did survive.

Early in the investigative process the role of weather was speculated in the demise of Eastern 66. *Time* magazine initially reported the accident under the title ‘A Fatal Case of Wind Shear’ (1975, July 7, p. 9). The aviation oriented periodical, *Aviation Week and Space Technology*, proclaimed the NTSB “were pursuing wind shear as one of the most likely factors in the Eastern Airlines Boeing 727 crash…”(1975, June 30, p. 26). Speculating low-level wind shear the most credible culprit, Eastern Air Lines retained an independent and highly acknowledged meso-meteorologist to augment and enhance the findings from the NTSB.

Tetsuya (Ted) Fujita was familiar with aviation accident investigation. A professor of meteorology with unconventional theories, he was commissioned by the British Aircraft Corporation (BAC) as an independent investigator in the accident of
Braniff 250. On the night of August 6, 1966, Braniff 250 attempted to cross a squall line that was pushing through the mid-western states. Braniff 250, a BAC 1-11 aircraft, broke apart in flight after encountering severe turbulence ahead of a line of thunderstorms.

Fujita was able to demonstrate that the BAC 1-11 had just transitioned the fine-line, or wind-shift line, at a time, location, and altitude most favorable for the development of horizontal and vertical vortices (NTSB, 1968, p. 35). In his report to BAC, Fujita advised against flying through this area, and rather prophetically also “against flying through thunderstorms in areas of heavy precipitation where vertical draughts (sic) were bound to be greatest” (cited in Job, 1994, p. 59).

Later, while investigating the outbreak of tornados that occurred on April 3–4, 1974, Fujita documented debris fields that did not have a rotational component, yet were obviously a result of high-speed wind damage. “Some distance away from the tornado paths, trees in the forests were blown over in radial directions, as if they had been blown outward” (Fujita, 1976, p. 44). From these observations the concept of the downburst emerged. This theory, accounting for tangible evidence, postulates that a strong downdraft colliding with the ground spreads in an outburst of damaging winds. Armed with this knowledge, Fujita was provided “with the courage to investigate the Eastern 66 accident” (Fujita, 1985, p. i). To be determined was whether Eastern 66 penetrated one of these downbursts and was subsequently blown into the ground, or if a more benign explanation could account for this tragedy.

In the course of the Eastern 66 investigation, simulator studies were performed based on the data acquired from the FDRs of the penetrating aircraft. These studies were initiated to examine the flight conditions that probably existed at the time, and to
determine the difficulties that a flight crew has in recognizing the development of an unsafe condition (NTSB, 1976, p. 18). The analog flight data recordings of Eastern 66 and the Flying Tiger DC-8 did not provide the detailed information required to determine exact wind velocities. The DFDR from Eastern 902, being digital and recording more parameters, provided the basis for dissecting the wind into vertical and horizontal components (p. 17).

With the derived winds programmed into a B-727 fixed-base simulator, 54 approaches were conducted, of which 18 resulted in impact with the approach lights (NTSB, 1976, p. 19). When applying power, most pilots did not add enough, and they were reluctant to interrupt their scan to verify engine pressure ratio (EPR). Additionally, several pilots used a pitch attitude lower than commanded by the flight director, commenting that the backpressure required on the control column was more than they had anticipated (p. 19).

The simulator studies did confirm the difficult situation in which the flight crew of Eastern 66 found themselves on that summer afternoon; 8 of the 10 simulator pilots “believed they might have crashed during actual flight” (NTSB, 1976, p. 20). Aside from any other issues, the meteorological conditions on approach overwhelmed the ability of the flight crew to save their aircraft or themselves.

The NTSB determined in part, “the probable cause of this accident was the aircraft’s encounter with adverse winds associated with a very strong thunderstorm located astride the ILS localizer course, which resulted in a high descent rate into the non-frangible approach light towers” (NTSB, 1976, p. 39). The Safety Board did not expound on ‘adverse winds’.
Filling this void, Fujita provided an exacting account of the meteorological conditions experienced by Eastern 66. Detailed analysis of the FDRs, along with weather radar plots and meteorological observations, revealed that Eastern 66 encountered a downward gush of air generated by a thunderstorm overhead. On approach, the aircraft sustained two separate headwind gusts of 25 and 28 feet per second (fps) as it entered an area of vertical wind. The headwind then decreased to 7 fps while a vertical wind of 21 fps occurred (Fujita, 1976, p. 41). This caused the aircraft to descend below the glide slope at 300 ft above ground level (AGL) and into the approach light stanchions.

From the mapping of this weather pattern emerged confirmation of Fujita’s new theory, and substantiation of vertical winds greater than previously held possible. Introducing an operative meteorological term into the lexicon of aviation, Fujita coined the word *downburst*: “a localized, intense downdraft with vertical currents exceeding a downward speed of 12 fps or 720 fpm at 300 ft above the surface” (Fujita, 1976, p. 50). This downward velocity corresponds to a descent rate typical of what transport category aircraft experience on a precision approach. A downburst can therefore be viewed as at least doubling the rate of descent of an approaching airliner.

In conjunction with the term downburst came the term *outburst center*: “the nadir point of a downburst where the vertical air current hits the surface and spreads out violently” (Fujita, 1976, p. 50). An aircraft traversing the outburst center experiences a headwind, followed by an increasing downburst, then an increasing tailwind; similar to the experience that befell Eastern 66. Not all were convinced of these unorthodox ideas, and some meteorologists attacked Fujita’s findings (Rosenfeld, 1999, p. 163).
Theory at the time was based on thunderstorm research conducted in Florida in 1946, and in Ohio in 1947. From these studies, downdrafts were hypothesized to decrease intensity from 10 fps at 4,000 ft altitude to zero velocity at ground level (Byers & Braham, 1949). According to this theory, vertical winds dissipated rapidly with height, and a cushion of air existed near ground level. This cushion would prevent an aircraft from being driven into the ground by wind (Melvin, 1986, p. 49).

The accident of Eastern 66 provided a revolution in re-thinking the effect that downdrafts exhibit on aircraft. Significant vertical winds at low altitude could drive a jet airliner into the ground, thus dismissing the fallacy of a cushion of air.

The meteorological findings in the Eastern 66 accident were summarized in Fujita’s paper Spearhead Echo and Downburst near the Approach End of a John F. Kennedy Airport Runway, New York City. This publication, available through the Eastern Airlines Flight Safety Department or the University of Chicago, was popular enough to necessitate an additional printing just six months after the original 2000 were published (Fujita, 1985, p. 45). Many airlines incorporated Fujita’s research and publication into their own flight training departments (NTSB, 1986, p. 52). Slowly the knowledge gained about downbursts and outbursts was being circulated.

In light of the new theories of extreme vertical winds, which have the potential to dramatically degrade aircraft performance, the Air Line Pilots’ Association (ALPA) petitioned the NTSB to reevaluate a previous air carrier accident. The circumstances surrounding the accident of Pan American 806 were similar to those of Eastern 66, and ALPA saw an opportunity to exonerate the flight crew who were held accountable in the initial accident report.
Pan American 806 Revisited

Tutuila, in the South Pacific, is home to Pago Pago International Airport.

Strategically situated, this tiny tropical island became a refueling depot for the early jetliners making the run between Hawaii and New Zealand. Pan American flight 806, a long range 707-321B, was one such aircraft scheduled for the quick stop on the night of January 30, 1974.

Cleared for the ILS approach runway 05, the aircraft captured the localizer some 20 miles out. After being advised of a ‘bad’ rain shower over the airport with winds 030 at 20 gusting 25 knots, Pan Am 806 was given landing clearance (NTSB, 1974b, p.2).

Clipper 806 was unable to establish a stabilized approach, first sinking well below the glide slope, then climbing slightly above, and when briefly on glide slope soon ballooning well above. The stabilizer trim was run nose pitch down at this time and the aircraft descended well below the glide slope, leveling off briefly at 300 ft AGL. The aircraft then lost about 8 knots of airspeed and flew into the jungle environment at 140 knots. Of 101 persons on board, only 4 survived.

The aircraft was determined to be in good operating condition prior to impact, and the investigative team concentrated on human factors issues. The Safety Board reasoned illusions in flight and procedural errors were accomplices in this accident. The initial probable cause, as issued by the NTSB, was “the failure of the pilot to correct an excessive rate of descent after the aircraft had passed decision height” (1974b, p. 19).

There was no mention of weather as a causal factor in the original accident report, it was implied through the statement “visual illusions produced by the environment [rain] may have caused the crew to perceive incorrectly their altitude…” (NTSB, 1974b, p. 19).
ALPA, noticing the references in the accident report to a ‘bad’ rain shower and the
degradation in airspeed and altitude that Pan Am 806 experienced, conjectured that the
new theories of downdraft and outburst center might have played a role in the demise of
the B-707. Just weeks after the publication of Fujita’s findings in the Eastern 66 accident,
and two years after the initial accident report on Pan Am 806, ALPA petitioned the
NTSB to reconsider the probable cause of the Pago Pago accident.

During the second investigation, the FDR was reexamined in conjunction with the
cockpit voice recorder (CVR) and engineering performance data. As was the case with
Eastern 66, any discrepancy between the theoretical performance capability and the
actual performance of the aircraft, as derived from the FDR and CVR, was attributed to
external forces. The second investigation found very little adverse winds encountered
until about 51 seconds prior to impact. The wind, increasing in velocity, was some
combination of head wind and updraft, and this became a decreasing headwind (or
combination downdraft) just seconds later. Another increase in headwind and updraft was
then encountered, followed by a lull in the wind; in the final 4 seconds of flight the
aircraft encountered decreasing headwinds or a downdraft of 1,700 fpm or some
combination thereof (NTSB, 1977, p. 12).

These last winds were severe enough that the aircraft would not have been able to
sustain level flight under the application of full power, about 57,000 pounds thrust
(NTSB, 1977, p. 12). It was during this time that the Boeing 707 experienced a 1,500 fpm
rate of descent only 178 feet above the trees. The Safety Board asserted that the “accident
could have been avoided had the crew recognized, from all available sources, the onset of
the high descent rate and taken timely action” (p. 22).
The new probable cause, as determined from the majority of the board members, changed little from the original. Paraphrasing the 1974 report, the inclusion of why the aircraft experienced an excessive descent rate was the only change. “The probable cause of the accident was the flightcrew’s [sic] late recognition and failure to correct in a timely manner an excessive descent rate which developed as a result of the aircraft’s penetration through destabilizing wind changes [italics added]” (NTSB, 1977, p. 27). While Eastern 66 encountered ‘adverse winds’, Pan Am 806 encountered ‘destabilizing wind’. As before, the obloquy was placed on the flight crew as their late recognition and failure to correct the flight path.

Kay Bailey, the acting chairman of the Safety Board, disagreed with the conclusions drawn by the majority members. Convinced that wind shear was a major factor in the explanation of the accident, his letter of dissent proposes, “the probable cause of the accident was the aircraft’s penetration through destabilizing wind changes and the flightcrew’s [sic] late recognition and failure to correct in a timely manner the resulting excessive descent rate” (NTSB, 1977, p. 29). While not exonerating the flight crew, the Chairman does acknowledge the reduction in performance that wind shear has on aircraft performance.

The NTSB did not conduct simulator studies of this accident. In a rather self-serving statement, they acknowledge the problem is dynamic and “would probably produce a range of results if examined in simulation” (1977, p. 13). Therefore, the difficulties and the ability of the crew to recognize in a timely manner the onset of an excessive descent rate remains extremely speculative.
What is clear, Pan Am 806 flew under a rain shower and through winds that changed direction and velocity in both the horizontal and vertical. From the description of the winds, it is probable that Pan Am 806 entered an area of outburst winds and continued into a downburst. The winds were characterized as (see Figure 2): (1) a headwind and some combination of an updraft, changing in rapid succession to (2) a headwind with downdraft, followed with another (3) headwind and updraft, finally ending with decreasing (4) headwinds and a downdraft of up to 1,700 fpm (NTSB, 1977, p. 12).

![Diagram of Microburst and Series of Horizontal Vortices]

*Figure 2. Probable winds encountered by Pan Am 806. The glide slope at the time of the PAA 806 accident was propagated at 3.25°, with an average airspeed of 150 knots this corresponds to a descent rate of 861 fpm. The downburst was descending almost twice as fast at 1700 fpm. In reference to the glide slope at 150 knots the downburst has a relative velocity of 839 fpm. If the flight time from point 1 to point 4 is one minute, the glide slope will have descended the aircraft 861 feet while the downburst will have descended an additional 839 feet, hence the upward glide slope incline with respect to the downburst in the illustration. Note. Microburst winds from *Pilot Windshear Guide* (p. 10), by FAA, 1988, Washington, DC: FAA.*
The winds experienced by Pan Am 806 were within the parameters comprising Fujita's definitions, though the NTSB did not use the lexicon, downburst or outburst. Reevaluating the accident, and changing the probable cause to include destabilizing winds, the NTSB raised the prospect that previous aircraft accidents may have been induced by downburst type phenomena.

No new wind shear recommendations or initiatives were proposed as a result of the reinvestigation of the Pago Pago accident. The FAA was beginning wind shear research on various fronts in response to NTSB recommendations brought about by the Eastern 66 accident. These included ground and airborne based sensing, and wind shear penetration capability of an airplane (NTSB, 1976, p. 40). This research was still in its infancy and the potential for a wind shear related accident had not diminished.

Allegheny 121

Approaching Philadelphia International Airport during a rain shower, Allegheny Airlines Flight 121 crashed while attempting a go-around maneuver. Witnesses to the accident corroborated the FDR data, both indicating that the aircraft was in a climb attitude prior to and during impact (NTSB, 1978, pp. 4–5).

Flight 121 departed Windsor Locks, Connecticut on June 23, 1976, for the short trip to Philadelphia. After a routine cruise, the crew prepared for an ILS approach to runway 27R. When the DC-9 was still about 15 miles out, the airport visibility decreased from 6 to 2 miles, the captain commented that it was probably due to the small rain shower a few miles west of the field. Assuming they could land before the cell reached the airport, the flight crew continued the approach (NTSB, 1978, p. 2).
The winds at the airport were initially reported on the automatic terminal information service (ATIS) as 260° at 10 knots. When given landing clearance, Flight 121 was issued winds 230° at 25 knots. Three seconds later, tower advised a different aircraft that the winds were 210° at 35 knots. The captain of Flight 121 heard this transmission, and commented to the first officer, “thirty-five, let’s go around” (cited in NTSB, 1978, p. 3).

Activating the go around button on the throttle quadrant, the captain followed the flight director command bars up to a 15° pitch attitude while the JT-8D engines were spooling to the thrust setting requested. Flaps were moved from 50 to 15, and the landing gear was retracted. As the airspeed dropped 5 knots below reference landing speed (V<sub>REF</sub>) the flight director command bars lowered to a pitch setting of about 10° in response. The ground proximity warning system (GPWS) triggered a pull up alert as the aircraft continued descending toward the ground. Allegheny 121, unable to climb through the wind shear, struck the right side of runway 27R four thousand feet beyond the threshold.

An airline captain waiting for takeoff witnessed the event, as did the Philadelphia tower controllers. The observant captain noticed that the DC-9 hit in a nose up attitude of about 10° just 38 feet from his aircraft: “Flight 121 appeared to stop flying, descended to the ground with the nose up, struck the ground to the right of runway 27R, and then slid along the ground…” (NTSB, 1978, p. 4). The air traffic controllers also confirmed a nose up attitude for the DC-9 prior to impact.

There was no post accident fire, the tail section, including the engines, separated from the fuselage shortly after impact, taking away a significant heat source from the
main wreckage area. Though the aircraft was destroyed, as were three taxiway signs, there were no fatalities.

During Allegheny’s approach, the small cell, on which the captain previously commented, had grown into a level 4 intensity thunderstorm with a top of 37,000 feet. The ensuing rains decreased the visibility on runway 27R below approach minimums, the runway visual range (RVR) varying between 1000 and 4000 feet. The winds also were variable, as documented by the NTSB (1978):

The maximum wind speed recorded was 41 knots at 1708. At 1712, the wind speed was 36 knots. The direction of the wind was from the west from 1701 to 1705, from the southwest from 1706 to 1712, from the north from 1716 to 1717, from the northeast from 1718 to 1721, and from the east from 1722 to 1733. (p. 6) The meteorological conditions were highly dynamic and produced an equally dynamic response on the aircraft.

The final flight path of Allegheny 121 was a roller coaster ride of varying altitude and airspeed. The aircraft descended from 551 ft to 88 ft, climbed to 371 ft and then descended to 136 ft, which it held for several seconds before settling. The airspeed was similarly chaotic, increasing from 157 to 162 knots then decreasing to 117 knots and increasing again to 153 knots. The FDR ends the airspeed trace with the aircraft breaking apart at 148 knots (NTSB, 1978, p. 8).

The NTSB proposed various wind models to explain the reduced performance experienced by the DC-9. These models were developed using the established technique of comparing actual performance to theoretical performance, with the difference attributed to the environmental variable, wind (NTSB, 1978, pp. 13–14).
To substantiate the proposed models, the NTSB contracted with Douglas Aircraft to program the derived winds into their Flight Development Motion Base simulator. This simulator, replicating a DC-9, was programmed with the accident aircraft’s equivalent weight and performance. Seven pilots flew the simulator in all but one of the wind models, Model 4b. Most test runs were able to avoid contact with the terrain when following flight director commands. Model 5a was not traversed in 5 out of 9 attempts at the accident EPR setting of 1.83, but when thrust was increased to the maximum setting of 1.93 EPR the runs were successful (NTSB, 1978, pp. 15–17).

The NTSB chose not to evaluate Model 4b, even though it would account for the performance decrement experienced by Flight 121. The rationale: “investigators believed that such high downdrafts so near the ground—which would be required to produce this pitch attitude history—were unrealistic” (NTSB, 1978, p. 16).

Conservative in their statements and research, the Safety Board did not mention the possibilities of either a downburst or an outburst center in their final report, though the meteorological conditions, combined with the performance of the aircraft, and witness statements, suggest that such a phenomenon did influence Allegheny 121 (see Fujita, 1985, pp. 43–44; McCarthy, 1996, p. 9).

The majority of the Board found “the probable cause of this accident was the aircraft’s encounter with severe horizontal and vertical wind shears near the ground as a result of the captain’s continued approach into a clearly marginal severe weather condition” (NTSB, 1978, p. 29). Phillip Hogue, a member of the Safety Board, dissented, stating, “the probable cause of the accident was severe wind shear encountered as the result of a mandatory and unanticipated aborted landing” (p. 32).
Though the flight crew initiated a standard go-around procedure, maximum aircraft performance was not realized. Successful simulator runs were only achieved with strict adherence to pitch attitudes derived through a speed command system, that temporarily sacrificed indicated airspeed below the takeoff safety speed (NTSB, 1978, p. 25). Flight below the takeoff safety speed \( V_2 \) is not a normal airline procedure; accordingly the Safety Board recommended the FAA “establish a joint Government-industry committee to develop flight techniques for coping with inadvertent encounters with severe wind shears at low altitude” (p. 32).

Recommendation A-78-3 resulted, and it became a change to advisory circular AC 00-50 \textit{Low Level Wind Shear} (NTSB, 1986, p. 157). In the event of a downburst encounter, the change instructed the pilot to immediately increase thrust to maximum and trade any airspeed above \( V_2 \) for altitude. If the aircraft continued at an unacceptable descent rate, the pilot was advised to gradually increase the pitch attitude and temporarily trade airspeed below \( V_2 \) for climb capability (FAA, 1979, ¶ 7a-5).

The updated circular, AC-00-50A, was disseminated to all airlines in the United States through their respective FAA principle operations inspector, whose task was to ensure that the new information was reflected in each air carrier’s operations, procedures, and training programs (NTSB, 1986, p. 157). A wind shear escape maneuver demonstration, performed yearly in the training simulator, was mandated for the pilot-in-command. As a demonstration exercise, in which the escape was assured, this training may have instilled a false confidence that all wind shear encounters could be negotiated (p. 53). The training discounted the avoidance principle, and suggested adherence to schedule could be maintained if the prescribed escape procedures were followed.
Long accustomed to the ubiquitous afternoon thunderstorms of the southern United States, the crew of Pan Am 759 prepared for the ensuing takeoff with little hesitation. The weather radar was illuminating areas of precipitation along the departure path, and as a precaution to expected wind shear, a maximum performance takeoff was planned. The air-conditioning packs were turned off to allow for greater engine thrust, the flaps were set at their minimum takeoff setting of 15, and the advice from the captain to the first officer was “let your airspeed build up on takeoff” (NTSB, 1983, p. 103). These measures, outlined in the FAA publication AC 00-50A, were applied to ameliorate the effects of wind shear in a chance encounter.

The Boeing 727-235 was accelerating in a rain shower down runway 10 at New Orleans International Airport on the afternoon of July 9, 1982. Once airborne, the wind quickly changed from a headwind, to a left crosswind, and then into an increasing tailwind. The aircraft rose to an altitude of about 100 feet and then slowly settled, striking tree tops ¼ mile from the runway end before plowing into a residential area at maximum thrust. Along with the aircraft, six houses were destroyed, and five were damaged, 145 persons on board and 8 persons on the ground lost their lives (NTSB, 1983).

The flight was airborne less than two minutes and covered a little over a mile. In that time the crew over-boosted the engines in a desperate attempt to fly out of the wind shear. As the altitude was diminishing the airspeed was increasing. The final command from the captain was “come on back you’re sinking Don—come on back” (NTSB, 1983, p. 112). This action would have traded airspeed for altitude; that is traded kinetic energy for potential energy.
Pan Am 759 did not have an excessive amount of airspeed, about 8 knots over \( V_2 \) (NTSB, 1983, p. 20), though ideally this excess could have been converted into a higher altitude to avoid terrain contact. The escape procedure of the time recommended “if severe wind shear is encountered on takeoff, the pilot should immediately confirm that maximum rated thrust is applied and trade the airspeed above \( V_2 \) (if any) for an increased rate of climb” (FAA, 1979, § 7a-5).

The Pan Am crew applied the appropriate procedures, configuring in anticipation of a microburst encounter and attempting the prescribed escape maneuver. Whether because of insufficient time, or procedures, the flight crew was not able to bring their aircraft through the hostile environmental conditions.

The meteorological conditions present were not abnormal for a summer afternoon. Even though wind shear was anticipated, the NTSB found “the captain’s decision to take off [sic] was reasonable in light of the information that was available to him” (NTSB 1983, p. 72). Confirming a go decision, the low-level wind shear alert system (LLWAS) was not issuing any warnings. However, immediately after the crash, the system warned of a wind shear in the same quadrant as the remains of Pan Am 759 (p. 54).

The LLWAS system is composed of anemometers spaced at intervals around the periphery of an airport. The desired spacing is 3km, however local terrain, zoning laws, or other constraints may dictate different spacing requirements. A wind speed difference of 15 knots between a periphery sensor and the center field sensor will trigger a wind shear alert (Soffer, 1990).
The limitations of LLWAS include the inability to detect winds between or beyond the sensors. As microbursts are relatively small in geographic scale they can occur between sensors, and are only registered when the outflow winds have impinged upon an anemometer. This is an historical alert, as the microburst is well developed and may be several minutes old by the time it is sensed. New systems, combined with terminal Doppler weather radar (TDWR), are known as ‘LLWAS-NE’ (network expansion), and provide a more reliable warning of microbursts (FAA, 2003a, § 7-1-26 2b). This combination of systems is now available at many airports throughout the United States.

The infrastructure in place at New Orleans International Airport was not adequate to warn the Pan Am crew of a microburst. Only after the accident did a warning of low-level wind shear occur.

Two meteorological models of the wind field that influenced flight 759 were developed. Pan Am conducted an independent investigation, led by Fujita. The official government meteorological investigation became the responsibility of NOAA and was conducted by Caracena and Maddox (NTSB, 1983, p. 28). Though differing in some aspects, both investigations revealed the likelihood of a microburst encounter (p. 30).

According to Fujita (1983a), a microburst began just as 759 initiated the takeoff roll and lasted until one minute after the crash. The microburst was centered 700 feet north of the runway and 2,100 feet east of the midfield sensor. The aircraft encountered a 17 knot headwind, followed by a 31 knot tailwind with a 4.1 knot downdraft. The first obstacle, a grouping of trees, was hit at 50.7 feet above the ground with a rate of climb of 384 fpm.
The NOAA report proposed that 759 flew through a weak to moderate microburst with a wind shear of 39 knots and a down flow of 7 fps (4.1 knots) at 100 ft AGL (Caracena, Maddox, Purdom, Weaver, & Greene, 1983). The center of the NOAA microburst was 1,300 feet east of the Pan Am microburst.

In analysis of the takeoff performance for the B-727, the Boeing Company computed a 16-knot headwind at liftoff, followed by a tailwind shear of 35 knots, which diminished to about 10 knots at the point of initial impact. The vertical winds “showed a steadily increasing downdraft from the 35 feet AGL point to about 5 seconds before impact. At this point, the downdraft remained at about 25 fps until tree contact” (NTSB, 1983, p. 57).

The results of the Boeing static engineering analysis suggested that had the pilots held their indicated airspeed, by pitch management, the aircraft could theoretically have maintained a 95-foot altitude, eventually flying out of the microburst (NTSB, 1983).

Survivability was determined purely through the engineering analysis; no simulation was run to determine pilot perception, recognition, or response to a microburst encounter. The Safety Board concedes the difficulty a pilot would face in recognizing this emergency.

The probable cause of the accident was the airplane’s encounter during the liftoff and initial climb phase of flight with a microburst-induced wind shear which imposed a downdraft and a decreasing headwind, the effects of which the pilot would have had difficulty recognizing and reacting to in time for the airplane’s descent to be arrested before its impact with trees. (NTSB, 1983, p. 72)
Inadequacy in the existing infrastructure was also acknowledged. “Contributing to the accident was the limited capability of current ground based low level wind shear detection technology to provide definitive guidance for controllers and pilots for use in avoiding low level wind shear encounters” (NTSB, 1983, p. 72).

The Safety Board felt that though avoidance was the most positive form of prevention, in the form of infrastructure, namely TDWR and LLWAS, training in microburst recovery could prevent a hazardous loss of altitude in a future encounter (NTSB, 1983, p. 61). The Board was critical of previous flight simulator wind shear training, stating it “may tend to instill an unwarranted sense of security to the flightcrews [sic] rather than stressing wind shear avoidance” (p. 67). In demonstration of this casualness with wind shear was the captain’s comment “let your airspeed build up on takeoff” (p. 103), insinuating a technique of penetration and keeping to schedule could replace avoidance and a delayed departure.

The recommendation from the NTSB did little to change the microburst training administered by the airlines. Guidance from the FAA was in the form of Advisory Circular 00-50A, *Low Level Wind Shear*. This document, last updated after the Allegheny 121 accident, did not include the latest microburst findings. According to the FAA, “wind shear is not something to be avoided at all costs, but rather to be assessed and avoided if severe” (1979, ¶ 7a), severity being a qualitative evaluation based on the judgment of the pilot (¶ 7a-4).

The guidelines to identify and escape from a microburst encounter were equivocal and this would be causal in the next air disaster. Indeed, many of the problems that contributed to the demise of PAA 759 would reappear.
Delta 191

The temperatures in central Texas exceeded 100 °F, on the afternoon of August 2, 1985. The high temperature was providing the energy to build several air mass thunderstorms. Delta 191, a flight from Fort Lauderdale (FLL), deviated around one such thunderstorm with a top of 50,000 feet during the arrival to Dallas Fort Worth International Airport (DFW). A much smaller storm, a growing cumulus with a top reaching 23,000 feet, lay between their aircraft, a Lockheed L-1011-385-1, and the landing runway, 17L (Fujita, 1986).

This smaller cell was maturing quickly, the first officer remarked, “lightening coming out of that one.... Right ahead of us” (NTSB, 1986, p. 131). There was no discussion or attempt, at this point, to abandon the approach, and Delta 191 proceeded into this smaller cloud.

Descending below 1,000 ft AGL, the captain advised the first officer, who was the pilot flying (PF), “watch your speed.... You’re gonna [sic] lose it all of a sudden, there it is” (NTSB, 1986, p. 133). The aircraft had entered a microburst and the airspeed, which had been slowly increasing, dropped from 173 knots indicated airspeed (kias) to 120 kias in 20 seconds. The captain commanded a go-around 10 seconds later, but the aircraft never achieved a positive climb gradient. Ground contact occurred at 169 kias, with the aircraft bouncing through a field, over an interstate highway, and onto airport property, finally hitting a water tank and breaking apart (NTSB, 1986).

The aft fuselage separated from the aircraft and escaped the post crash fire. Most of the 29 survivors came from this section. Of the 163 persons aboard, 134 passengers
and crew were killed (NTSB, 1986, p. 6). Additionally, the driver of a pickup truck, struck during the premature touchdown on the interstate highway, perished.

The LLWAS at DFW was operational at the time of the accident; tower controllers noticed a system alert about 10 to 12 minutes after the accident when “all sensors were in alarm” (NTSB, 1986, p. 24). As with Pan Am 759, the LLWAS activated after the accident.

An earlier flight, American 351, entered the area of wind shear and lost 22 kias several minutes prior to Delta’s encounter. This occurrence was not relayed to air traffic control as required per FAR 121.561, the B-727 captain testifying, “a windshear \[sic\] of 20 knots at 2,500 feet at [the] airspeed I was at is negligible and certainly would not interfere with the safety of anyone’s flight” (cited in NTSB, 1986, p. 19).

It is not known whether the presence of either ground advisories or pilot reports would have persuaded the crew of Delta 191 to delay the approach. It appears there was a conviction to continue even when the wind shear was acknowledged. This reluctance to hold until weather conditions were more favorable was also evident with the crew of Pan Am 759.

Attempting to explain this behavior, the NTSB speculated, as early as the Pan Am 759 accident, that wind shear training might instill a false sense of security through repeated successful encounters (NTSB, 1983, pp. 67–68). The Delta Air Lines Systems Manager also held this view; “simulator windshear \[sic\] training might possibly be a subtle form of ‘negative training’ because it could lead pilots to conclude that adherence to the recommended procedures would always result in a successful escape from a windshear \[sic\] environment” (NTSB, 1986, p. 53).
The Delta Flight Training Department’s guidance for a microburst encounter was based on the procedures contained in FAA AC 00-50A *Low Level Wind Shear* (NTSB, 1986, p. 53). If wind shear was anticipated, the pilot was expected to fly a stabilized approach with additional speed added to $V_{REF}$, up to a maximum of 20 knots. Preventing airspeed loss below $V_{REF}$ was attained with thrust application (FAA, 1979). A go-around was recommended, “if the airplane is below 500 feet AGL and the approach becomes unstable” (¶ 7b-1). This guidance had the potential to put the aircraft and crew in a dangerous situation.

Many factors combined to cause this accident. The lack of an LLWAS warning and the lack of pilot weather reports (PIREPs) deprived the flight crew of current information. There were salient clues, however, that foretold of possible microburst development, and it appears that the captain may have been attuned to this as witnessed by his forecast of the dramatic loss of airspeed. The training to continue the approach, rather than hold until conditions improved, ensured that eventually a microburst would be penetrated.

Engineering analysis from Lockheed, the airframe manufacturer, and NASA indicated that the aircraft probably entered a microburst (NTSB, 1986, p. 35). Though the crew of 191 applied the maximum thrust setting possible in an attempt to escape, they were not as aggressive in employing a positive pitch attitude. Unable to extract the performance necessary, the aircraft crashed. In theory, “the airplane physically had the performance capability to fly a path that missed the ground” (p. 37). The discrepancy between reality and theory in escaping from this, and from other accident microbursts, pointed to a deficiency in procedures.
Before the NTSB could establish the probable cause, a segment of the aerospace industry joined to examine the operational implications of wind shear, including mitigation steps (McCarthy, 1996). This symposium was eventually funded by the FAA in 1986 and brought about the Wind Shear Training Aid (WSTA) curriculum. The training aid was preemptive to many of the concerns addressed by the NTSB in their statement of probable cause.

The National Transportation Safety Board determines that the probable causes of the accident were the flightcrew’s [sic] decision to initiate and continue the approach into a cumulonimbus cloud which they observed to contain visible lightning; the lack of specific guidelines, procedures, and training for avoiding and escaping from low-altitude windshear; [sic] and the lack of definitive, real-time windshear [sic] hazard information. This resulted in the aircraft’s encounter at low altitude with a microburst-induced, severe windshear [sic] from a rapidly developing thunderstorm located on the final approach course. (NTSB, 1986, p. 80)

The proposed plan was inclusive enough that the only additional operational recommendations by the NTSB, to the FAA, were for principle operations inspectors to ensure compliance from the various air carriers.

The Integrated Wind Shear Program Plan, drafted in 1986, of which WSTA is a part, was the first comprehensive attempt to mitigate the problems of the microburst. In addition to improving surface and airborne wind shear detection, the plan included training for airline management as well as pilots. The training aid for pilots included operational procedures, classroom curricula, video presentations, written manuals, and
simulator exercises (NTSB, 1986, p. 84). The NTSB found this plan addressed “nearly all of the actions proposed in the Safety Recommendations issued by the Safety Board since 1973” (p. 84).

Appendix I of the WSTA, published as AC 00-54 *Pilot Windshear Guide*, 
“communicates key windshear [sic] information relevant to flightcrews [sic]” (FAA, 1988, front piece). This advisory circular supercedes AC 00-50A *Low Level Wind Shear*, which had not been updated since the Allegheny accident. Microburst information and procedures for escape were introduced with this new publication.

By 1988, the FAA Administrator was urging the use of the non-regulatory WSTA for complying with the requirements of Part 121 of the Federal Aviation Regulations. In 1991 the International Civil Aviation Organization (ICAO) incorporated wind shear training, as outlined in the WSTA, into Annex 5 and 6. Thus, by the early 1990’s, most operators of jet transport aircraft around the world were using the FAA training aid and procedures (McCarthy, 1996, p. 5).

During the 1970s, and into the mid-1980s, wind shear accidents were occurring about every 18 months. After Delta 191, the next microburst accident would be almost 10 years later. The increase in safety was due to a variety of factors, the WSTA was implemented in large scale and there existed standard procedures, endorsed by the major manufacturers, for escaping a microburst encounter. Additionally, the ground infrastructure had expanded to include the ASR-9 radar, which was able to discriminate precipitation intensities and display these areas to air traffic controllers on their radarscopes. The continued implementation of LLWAS-NE, though at a slower pace then
anticipated, was adding to the wind shear defenses. Airborne sensors were also a reality, with the FAA mandating airborne wind shear warning systems per FAR 121.358.

The failure of the infrastructure to provide timely warnings, as in the case of Pan Am 759 and Delta 191, would again surface. While infrastructure chiefly aids in avoidance of the microburst, the escape procedure determines survival. An effective escape procedure extracts the maximum performance from the aircraft.

US Air 1016

The late afternoon flight on July 2, 1994, from Columbia, South Carolina (CAE) to Charlotte, North Carolina (CLT), 80 miles away, required just minutes to complete for US Air 1016, a Douglas DC-9-30 aircraft. Though thunderstorms were not reported on the arrival ATIS, scattered thunderstorms were present in the area. The DC-9’s radar was depicting two separate cells in the terminal area. The cell on the south end of the airport was contouring and moving northward, bringing heavy precipitation; the tower supervisor remarked it was “raining like hell” (NTSB, 1995, p. 3).

Established on a visual approach to 18R, US Air 1016 noticed the rain was now between their aircraft and the runway, the captain commented to the first officer, “chance of shear” (NTSB, 1995, p. 158). This was soon confirmed by the LLWAS alert in the northeast boundary, as reported on frequency by the local controller. Soon after, 1016 entered the rain. The first officer registered an increase in airspeed, the captain observed another increase, and a go-around was commanded. The aircraft was at 200 ft AGL and 147 kias when thrust was increased to 1.82 EPR and a normal go-around was initiated. The flaps were raised from 40 to 15 and the pitch attitude was increased to 15°. The captain, who was the pilot not flying (PNF), instructed the first officer to decrease pitch,
“down, push it down” (p. 164). The aircraft climbed for a few more seconds, to about 350 feet AGL, and then began a steady descent into the ground (NTSB, 1995).

The aircraft broke into four main pieces upon contacting the terrain, less than a half-mile from the airport. Of 57 persons on board, 37 died, 16 received serious injuries, and 4 had minor injuries (NTSB, 1995, p. 8).

The local weather conditions were conducive to microburst development. Before departing CAE, the crew received a copy of the CLT weather, forecasting a thunderstorm (NTSB, 1995, p. 18). When the flight crew arrived in the CLT area they were able to visually identify the storm that appeared as a contouring cell on their radar. Further analysis indicates the cell was of severe enough intensity to form a radar shadow, attenuating the left side of the storm (Smith, Pryor, & Prater, 2000, p. 57). The same area of the storm, on the northeast boundary of the airport, triggered the LLWAS alert. The wind shear alert was responded too on the flight deck with a non-pertinent word (NTSB, 1995, p. 162).

Aircraft on the ground were voluntarily holding for an improvement in the weather; US Air 806 was ‘sitting tight’ (NTSB, 1995, p. 162) and company 797 transmitted, “[departure] wouldn’t sound like a good plan” (p. 162). Aircraft were landing though. The preceding flight, a Fokker model FK-100, reported a smooth ride on approach (p. 161). The NTSB acknowledged in the Eastern 66 accident, “pilots commonly rely on the degree of successes achieved by pilots of preceding flights when they are confronted with common hazards” (NTSB, 1976, p. 34). With clues for and against continuing, US Air chose the former.
The microburst was spawned by a convective air-mass thunderstorm with a top less than 30,000 feet (NTSB, 1995, p. 49). Though small in stature, the storm had a radar reflectivity of 65 Decibels and had generated at least three cloud to ground lightning strikes (Smith, Pryor, & Prater, 2000). The microburst, centered 1.85 km east of the accident site, was 3.5 km in diameter. According to NASA, the maximum wind velocity change was 86 knots along the north-south axis, with a vertical wind velocity of 23 fps (14 knots) along the flight path (NTSB, 1995, p. 48). Douglas Aircraft estimated the vertical winds along the flight path to be initially 10 fps, increasing to 25–30 fps. The DC-9 experienced a 61-knot horizontal wind speed change: a 35-knot headwind shearing to a 26-knot tailwind in 14 seconds (NTSB, 1995, pp. 46–48). Both analyses indicate a very strong microburst.

In determining if this microburst was survivable, the Douglas Aircraft Company performed a mathematical simulation (flight simulation was not performed) using data from the FDR, the NASA derived wind field, and the theoretical aircraft performance. The simulation was able to avoid ground contact with gear retraction, firewall power, and a sustained 15° pitch attitude. Under these constraints the minimum altitude of the aircraft was 335 ft AGL (NTSB, 1995, p. 50). The DC-9 could have successfully flown through the wind shear encounter if the simulated missed approach procedure had been used, or if the wind shear escape maneuver of maximum effective pitch attitude and firewall thrust occurred immediately after the initial airspeed decay (p. 97).

The simulation was optimal, considering timely recognition and immediate action. The reality presented a different situation. During the go-around the EPR had not been set to the maximum 1.93, but was about 9% less (NTSB, 1995, p. 97). This was
cautioned in the Eastern 66 simulation “most of the pilots actually added less thrust than they thought they had added” (NTSB, 1976, p. 19). Also, the pitch attitude was not held at 15° (1995, p. 97). Again, in the Eastern 66 simulation it was noted that the pilots did not rotate to a high enough angle needed to stop the rate of descent (1976, p. 19). The failures of the past were continuing.

Though the LLWAS performed to its design tolerance and issued a wind shear alert, the NTSB concluded that TDWR derived information would have been beneficial to the crew (1995, p. 118). The NTSB also felt that inadequate procedures in the CLT Tower prevented the flight crew from receiving critical weather information (p. 118). The inadequacies of the infrastructure extended into the airplane cockpit as well.

The airborne wind shear alert system installed in the DC-9 was designed to activate a warning to the flight crew when it detected severe wind shear (NTSB, 1995, p. 12). A performance-decreasing shear triggers a red wind shear warning annunciator in addition to an aural message. A performance-increasing shear will illuminate a caution annunciator only. About ten seconds after 1016 initiated the go-around, the system should have gone into warning alert, it did not, and investigators were unable to determine why the on-board wind shear detection system failed (pp. 12–16).

The failure of the infrastructure contributed to the accident. In particular the NTSB found that air traffic control procedures and the airplane’s wind shear warning system were deficient (NTSB, 1995, p. 120).

The accident was a result of the flight crew’s decision to continue the approach into convective activity, their failure to recognize the microburst in a timely manner, and the inability to establish an escape configuration. The lack of real-time wind shear hazard
information from air traffic control was also cited as an element in the probable cause (NTSB, 1995, p. 120).

The flight crew's inability to identify the microburst in a timely manner prompted the recommendation to "reevaluate the Windshear Training Aid based on the facts, conditions, and circumstances of this accident" (NTSB, 1995, p.123). Additional training was suggested for identifying convective activity and microbursts (p. 124). Simulator training was also to be expanded, incorporating an enhancement of scenarios (p. 123). It was also proposed that the escape procedure be used in place of a go-around maneuver below 1000 feet AGL when conditions conducive to wind shear were present (p. 123).

Though the clues were apparent, and acknowledged, that wind shear was a real possibility, the crew continued. The failing of the infrastructure led them into a microburst. Thereafter the escape, theoretically possible, was incumbent upon the flight crew's skill and training.

Additional Accidents

Microbursts are neither a new nor a rare event; nor are they confined to any single geographic locale. With the late acknowledgement of the microburst in 1983 by the NTSB, came the question of whether this overlooked phenomenon might have been responsible for previous accidents. A retrospective analysis, compiled by McCarthy (1996) from the sources of Fujita and others, suggests that many previous accidents display the characteristics of a microburst encounter (see Table 1). Microburst accidents are not limited to jet aircraft. A notable case study by Poellot, Borho and Bassingthwaite (1997) presents the en route accident of a Piper Navajo in North Dakota. However, this table and study concerns large jet transport category aircraft and not general aviation.
Table 1
American Jet Transport Accidents and Incidents as a Result of Wind Shear-Microburst Encounter

<table>
<thead>
<tr>
<th>Date</th>
<th>NTSB #</th>
<th>Airline</th>
<th>Type</th>
<th>Place</th>
<th>Fatalities</th>
<th>Precipitation</th>
<th>Appch</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>07.01.64</td>
<td>Incident</td>
<td>American</td>
<td>B-720B</td>
<td>KJFK</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Thunderstorm</td>
</tr>
<tr>
<td>03.17.65</td>
<td>Incident</td>
<td>TWA</td>
<td>B-727</td>
<td>KMCI</td>
<td>0</td>
<td>Unk</td>
<td>X</td>
<td>Unstable moist air</td>
</tr>
<tr>
<td>06.08.68</td>
<td>Incident</td>
<td>United</td>
<td>B-727</td>
<td>KSLC</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Thunderstorm w/ gust front</td>
</tr>
<tr>
<td>07.27.70</td>
<td>72-10</td>
<td>FlyingTigers</td>
<td>DC-8</td>
<td>ROAH</td>
<td>4</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed on approach</td>
</tr>
<tr>
<td>05.18.72</td>
<td>72-32</td>
<td>Eastern</td>
<td>DC-9</td>
<td>KFLL</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Hard landing</td>
</tr>
<tr>
<td>07.26.72</td>
<td>Incident</td>
<td>National</td>
<td>B-727</td>
<td>KMSY</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Heavy Thunderstorm</td>
</tr>
<tr>
<td>12.12.72</td>
<td>73-11</td>
<td>TWA</td>
<td>B-707</td>
<td>KJFK</td>
<td>0</td>
<td>Light</td>
<td>X</td>
<td>Struck approach lights</td>
</tr>
<tr>
<td>03.03.73</td>
<td>Incident</td>
<td>TWA</td>
<td>B-727</td>
<td>KICT</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Thunderstorm</td>
</tr>
<tr>
<td>06.15.73</td>
<td>Incident</td>
<td>Airlift</td>
<td>DC-8</td>
<td>KORD</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Heavy rainstorm</td>
</tr>
<tr>
<td>10.28.73</td>
<td>74-07</td>
<td>Piedmont</td>
<td>B-737</td>
<td>KGSO</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Long touchdown</td>
</tr>
<tr>
<td>11.27.73</td>
<td>74-13</td>
<td>Delta</td>
<td>DC-9</td>
<td>KCHA</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Landed short thunderstorm gust front</td>
</tr>
<tr>
<td>01.30.74</td>
<td>77-07</td>
<td>Pan Am</td>
<td>B-707</td>
<td>NSTU</td>
<td>96</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed short of runway</td>
</tr>
<tr>
<td>06.24.75</td>
<td>76-08</td>
<td>Eastern</td>
<td>B-727</td>
<td>KJFK</td>
<td>113</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed short of runway</td>
</tr>
<tr>
<td>08.07.75</td>
<td>76-14</td>
<td>Continental</td>
<td>B-727</td>
<td>KDEN</td>
<td>0</td>
<td>Dry</td>
<td>X</td>
<td>Crashed after takeoff</td>
</tr>
<tr>
<td>11.12.75</td>
<td>76-15</td>
<td>Eastern</td>
<td>B-727</td>
<td>KRDU</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Landed short of runway</td>
</tr>
<tr>
<td>12.31.75</td>
<td>Incident</td>
<td>Eastern</td>
<td>B-727</td>
<td>KGSP</td>
<td>0</td>
<td>Light</td>
<td>X</td>
<td>200° wind change rain fog</td>
</tr>
<tr>
<td>06.23.76</td>
<td>78-02</td>
<td>Allegheny</td>
<td>DC-9</td>
<td>KPHL</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed during go around</td>
</tr>
<tr>
<td>06.03.77</td>
<td>78-09</td>
<td>Continental</td>
<td>B-727</td>
<td>KTUS</td>
<td>0</td>
<td>Dry</td>
<td>X</td>
<td>Struck power-lines during t/o</td>
</tr>
<tr>
<td>08.22.79</td>
<td>80-06</td>
<td>Eastern</td>
<td>B-727</td>
<td>KATL</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Engine overboost missed approach</td>
</tr>
<tr>
<td>07.09.82</td>
<td>83-02</td>
<td>Pan Am</td>
<td>B-727</td>
<td>KMSY</td>
<td>153</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed during t/o</td>
</tr>
<tr>
<td>07.28.82</td>
<td>Incident</td>
<td>TWA</td>
<td>B-727</td>
<td>KLGA</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Strong thunderstorm gusty winds</td>
</tr>
<tr>
<td>05.31.84</td>
<td>85-05</td>
<td>United</td>
<td>B-727</td>
<td>KDEN</td>
<td>0</td>
<td>Dry</td>
<td>X</td>
<td>Struck antenna during t/o</td>
</tr>
<tr>
<td>06.13.84</td>
<td>85-01</td>
<td>USAir</td>
<td>DC-9</td>
<td>KDTW</td>
<td>0</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed during landing</td>
</tr>
<tr>
<td>08.02.85</td>
<td>86-05</td>
<td>Delta</td>
<td>L-1011</td>
<td>KDFW</td>
<td>135</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed during approach</td>
</tr>
<tr>
<td>07.02.94</td>
<td>95-03</td>
<td>USAir</td>
<td>DC-9</td>
<td>KCLT</td>
<td>37</td>
<td>Heavy</td>
<td>X</td>
<td>Crashed during go-around</td>
</tr>
</tbody>
</table>

Note: 5 propeller aircraft accidents from 1964 to the present add 126 fatalities to the total.
Sources: NTSB; McCarthy, 1996; Vicroy, 1988.
Approximately 1 in 20 thunderstorms will spawn a microburst. As seen in many of the accident reports, the parent cloud can be relatively small. Microbursts can occur wherever convective activity exists, as such there are few regions immune to this type of meteorological activity.

Around the world, there have been aircraft accidents attributed to microbursts. In May 1976, Royal Jordanian Air Lines encountered a microburst while attempting to land at Doha, Qatar. Ironically, the aircraft slid tail first into the fire station garage (Fujita, 1985). Unfortunately, 45 people perished. In Faro, Portugal a chartered Martin Air DC-10 crashed as the result of a microburst encounter in 1992 (Flight Safety Foundation Accident Prevention, 1996). The aircraft was destroyed and 56 people died. Microburst related accidents have been documented in Africa, Australia, India, Japan, Mexico, and many other countries (e.g., Pan & Liu, 1995).

Case History Conclusions

The substantial loss of life from the microburst provided the stimulus for investigation. While some accidents added to the death toll in large numbers and some people escaped fatalities, all accidents were financially costly. The burden on the aviation industry accelerated the search for a pragmatic solution. The result was a highly sophisticated infrastructure.

Many of the microburst accidents share a commonality beyond the probable cause. Before the accidents clues were available, which in hindsight seem obvious. There was a decision to continue the approach, sometimes when dangerous conditions became increasingly evident. In the attempt to escape, aircraft of different make and model exhibit a similarity in reaction and performance.
Prior to the microburst encounters, clues were available to the flight crews. Eastern 66 had reports from company 902 about wind shear, they had previously deviated around thunderstorms, and were aware of convective activity in the area and on the approach. PAA 806 was advised of a ‘bad’ rain shower on the airport. ALG 121 was following an Eastern flight that executed a missed approach because of high winds. Pan Am 759 anticipated the wind shear as evident in the discussion and actions of the crew. Delta 191 also anticipated the wind shear, when the captain forecast losing speed ‘all of a sudden’. US Air 1016 received an LLWAS alert, was painting the storm on the radar, and anticipated the shear. In all the cases there was an indication of potentially severe wind shear.

The clues were unheeded until too late. Eastern 66, unable to maintain glide slope, initiated the go-around seconds before impact. Allegheny received an update of 35 knot winds before deciding to go around, Delta was also below the glide slope when go-around became evident, and US Air 1016 had two separate airspeed spikes before they attempted a go around.

In the go-around, and even in the takeoff regime, the aircraft exhibited similar performance. Power was applied too little or too late, pitch was sacrificed at some point in the maneuver, and all aircraft contacted the terrain at a speed well above stall. Eastern 66 impacted 33 knots above stall speed, Pan Am 806 at 30 knots, Allegheny 121 at 45 knots, Pan Am 759 at 27 knots, Delta 191 was 64 knots above stall speed, and US Air 1016 was 32 knots above the stall speed when it crashed. Clearly, the full performance capabilities of the aircraft were not being utilized. This performance decrement continued even after the implementation of the WSTA.
Though the same mistakes continued, the frequency of accidents diminished with the progression of microburst understanding and the development of the infrastructure.

The evolution of microburst knowledge is the result of aircraft accidents; starting with the adverse winds of Eastern 66, and continuing through the destabilizing winds of Pan Am 806, the horizontal and vertical wind shears of Allegheny 121, and the microbursts of Pan Am 759, Delta 191, and USAir 1016. Though previous accidents were most certainly a result of inadvertent encounters with microbursts, and dismissed under variegate probable causes, the accident of Eastern 66 changed the understanding of aviation meteorology. This accident provided the catalyst and clues for Fujita to form his theories, and though progressive and unorthodox, they were not conceived in a vacuum.

Microburst History

First through myth, and then science, man has endeavored to understand the chaos of nature and create order in his world. Both methods of understanding describe visible events precipitated by invisible forces; a thunderbolt can be viewed as the wrath of Zeus or as an electrostatic phenomenon (Jacob, 1982). Between these two explanations, Aristotle sought the properties and characteristics of the wind.

Classical

The result of lectures at the Lycaeum around 336 b.c.e., Meteorology describes a coherent world of orderly winds blowing from one of 12 directions. Modern readers can still identify the winds of Aristotle; “Zephyrus is the wind that blows from ... where the sun sets at the equinox” (Aristotle, Berlin Trans. n.d., 363b). This discourse in Meteorology continues with the nature and properties of the wind, informing the reader that contrary winds may not blow while apposing winds can and do. “Winds that are not
diametrically opposite to one another may blow simultaneously,” (Aristotle, 364a) this can be quite advantageous as “... different winds and blowing from different quarters, are favourable [sic] to sailors making for the same point” (Aristotle, 364a).

Renaissance

Not disparaging the authority of Aristotle, Bohun (1671) describes winds that are certainly neither advantageous nor favorable. As documented from his own astute observations and those of contemporary sailors, Bohun notes the existence of variable and most dangerous winds. Describing these tempestuous winds, Bohun uses the colloquial term tornado, which had, since 1625, been in common usage amongst navigators to describe violent thunderstorms of the tropical Atlantic, with torrential rain and sudden and violent gusts of wind (Oxford English Dictionary, 1971).

So variable and unsteady are the tornado-winds, so little obliged to any certain law, that they commonly shift all the points of the compass in the space of an houre (sic), blowing in such suddain (sic) and impetuous gusts, that a ship which was ready to overset on one side, is no lesse (sic) dangerously assaulted on the other; sometimes they shift without intermission ... Let a fleet of ships saile (sic) as near as they can without falling fowl on each other, and they shall have severall (sic) and contrary winds. (Bohun, 1671, pp. 236–237)

Bohun (1671) additionally notes that winds need not be parallel to the ground, “sometimes you shall have a suddain (sic) puffe (sic) of wind, driven from between two clouds, with a violent displosion (sic) of the air; that descends almost perpendicularly to the Earth” (p. 18). This wind, he noted, occurred oftentimes with the onset of rain, “I have oftentimes obsev’d (sic), that stiffe (sic) gusts of wind happen immediately before
rain” (p. 20). With one of three drawings in a book of 302 pages, it is curious to note that Bohun chooses to illustrate a wind remarkably similar to the present understanding of the microburst (see Figure 3). Even if Bohun placed no name on the microburst, he described its effects. “The Portugues [sic] in their discoveries of the Orientall [sic] Indies, lost 9 ships out of 12, which were overset by the prodigious inpetuosity [sic] of these suddain [sic] gusts” (p. 238).

Explaining the formation of microbursts rather clearly, Bohun (1671) states that a tornado-cloud may create a tempest “by its pressure; when the cloud distills not by degrees in pluvious drops, but rushes down impetuously all at once, driving before it a swift torrent of air, which falls as from a precipice, and threatens the oversetting of ships” (p. 249). This is so very similar to the current understanding. “Dry air evaporates rain falling from above, and the cooling caused by evaporation creates a large bomb of cold air that barrels down toward the Earth along with the remaining precipitation. … the descending air spreads out fast” (Rosenfield, 1999, pp. 164–165).

Bohun also states about these winds, “the lesser the cloud appears at first, the tempest will last the longer” (1671, p. 250). Fujita writes “the parent clouds which induce microbursts are not always thunderstorms. Quite often, isolated rain showers spawn relatively strong microbursts” (1985, p. 70). Arguably, Bohun documented the effects and some of the properties of downdrafts and microbursts. While Bohun was able to describe this specific tempest in general terms, he failed to label it discernibly and the years pushed his writings into obscurity. It was then left for Fujita to rediscover and name the downburst and microburst. How Fujita accomplished this would be remarkably familiar to Bohun.
Figure 3 Wind resembling microburst from Bohun’s book of 1671. Note From A discourse concerning the origine and properties of wind With an historicall account of hurricanes, and other tempestuous wind. (p. 19), by R. Bohun, 1671, Oxford, England· W Hall
Modern

In his discourse on wind, Bohun relied on his own astute observations along with the logs and observations of sailors to document the phenomenon of which he wrote. Likewise, Fujita used his own observations and the various logs and observations of others to formulate his theories. Instead of relying on sailors and written logs, Fujita had the opportunity to utilize the electronic logs of aircraft, complex instruments, and meteorologically perceptive observers.

Fujita had the opportunity to investigate many aircraft accidents resulting from wind shear and microbursts. The knowledge gained through the FDRs and aircraft performance painted a physical picture of the environment in a specific place and time. To garner a complete understanding, Fujita spent hours in laboratories and field experiments. Many of these experiments became fundamental to current understanding, providing data for analysis and pragmatic use. Unquestionably, Fujita is the father of the downburst, and its offspring—macro and microbursts.

Many notable scientists refined the downburst theory. Caracena developed the concept of the vortex ring generated by the initial downburst, which accounts for many of the dynamics observed in the microburst (Caracena et al., 1989). McCarthy provided the meteorological expertise for the WSTA, and performed many studies of wind shear effects on aircraft performance (McCarthy, 1996). Wakimoto expanded microburst forecasting techniques (Atkins & Wakimoto, 1991). Indeed, many share in the advancement of microburst knowledge and understanding.

Through research, the microburst was understood, and solutions developed to forecast and mitigate its effects on aviation.
Microburst Research

NIMROD

Rigorous microburst study began with the Northern Illinois Meteorological Research On Downbursts (NIMROD). The initial proposal was submitted to the National Science Foundation (NSF) after the Eastern accident. The additional funding resulting from the accident expanded the project, which became operational in spring 1978. Using new techniques afforded by Doppler radar, the team led by Fujita was able to demonstrate the existence of downbursts. Heretofore there had been considerable skepticism from many scientists that any downward momentum of air could continue below 300 feet.

The NIMROD project uncovered localized and violent downbursts embedded in larger downdrafts; this necessitated a clear division between the localized phenomenon and that of wider reach. From these beginnings came the terms microburst and macroburst. During the course of the investigation, 50 microbursts were observed and recorded (Fujita, 1985, p. 56).

JAWS

Following the success of NIMROD in 1978, Fujita along with McCarthy and Wilson, from the National Center for Atmospheric Research (NCAR), proposed a large-scale project. The moniker chosen by NCAR staff was every bit as creative as the preceding study. Being a collaboration of the University of Chicago and NCAR, and based around the Stapleton Airport in Colorado, the Joint Airport Weather Studies (JAWS) had a fitting and descriptive acronym.
In 1982, from 15 May to 13 August, 186 microbursts were identified and documented (Fujita, 1985, p. 55). Microbursts were in fact quite common. The low probability of encountering a microburst came from their small size and short life span, offsetting their considerable population (McCarthey, 1983, p.21).

The JAWS project was a monumental undertaking involving 3 pulsed microwave Doppler radars, 2 pulsed Doppler lasers, 27 portable automated mesonet (PAM) stations, 21 surface stations, and 5 dedicated research aircraft. Additional instrumentation included a high density LLWAS and a pressure jump sensor array. This structure was placed strategically around Stapleton Airport, then the fourth busiest airport in the United States (McCarthey, 1983).

This extensive arrangement would attempt to meet the researcher’s objectives, which were no less impressive. Three basic areas were to be addressed: low-level convective storm winds, aircraft performance in wind shear conditions, and wind shear detection and warning techniques. The focus remained “to explore quantitatively the nature of the microburst” (McCarthey, Wilson, & Fujita, 1982, p. 20).

Had the researchers any doubt of the significance in their work, it would have disappeared July 9, 1982, in the middle of their field observations. On this day, Pan American Flight 759 crashed in New Orleans. The accident was quickly attributed to a microburst, “as a result the JAWS researchers felt [equally] that the microburst phenomenon should be understood as quickly as possible for the sake of aircraft safety” (Fujita, 1985, p. 53).

Pan Am 759 was the first accident to be formally classified as resulting from an encounter with a microburst. This recognition legitimized the theory and shifted its
acceptance from the fringe into the mainstream, with a resulting increase in credibility and funding for research (Fujita, 1985, p. 53; NASA, 2002, ¶ 5).

The NTSB requested that the information gleaned from the JAWS project be used to quantify the low-level wind shear hazard and to evaluate the effectiveness of the LLWAS. Additional use of the data was to develop training aids to emphasize the peril of convective weather to safe flight, and to develop realistic microburst models for use in flight simulator training programs (NTSB, 1983, p. 75).

NAS

The outcry from citizens, over the Pan Am 759 accident, prompted congress to pass public law 97-369 mandating the FAA contract with the National Academy of Sciences (NAS) to examine ways to mitigate the risk of wind shear (NRC, 1983, pp. ix–x). The blue-ribbon panel recommended near, middle, and long-term solutions, essentially all of which have been implemented to varying degrees (McCarthy, 1996, p.2). This was not a field study but a collection and assimilation of previous research. The National Research Council (NRC) published their findings as *Low-Altitude Wind Shear and Its Hazard to Aviation*. The blue-ribbon panel advocated an integrated wind shear program, which set a course for the FAA, and “was instrumental in coming to grips with a national problem facing the safety of the flying public” (McCarthy, 1996, p. 6).

CLAWS

It was the safety of the flying public that prompted the FAA to request a microburst real-time forecast and warning service at Stapleton Airport (NTSB, 1986, pp.33–34). On May 31, 1984, a United Airlines B-727 encountered a microburst during its takeoff roll, and, after becoming airborne, struck the localizer antenna. The pressure
vessel of the aircraft was breached, fortunately with no injuries, and the aircraft returned to Stapleton (NTSB, 1985).

The Classify, Locate, and Avoid Wind Shear (CLAWS) Project was formed in response to the FAA request (McCarthy & Wilson, 1985). CLAWS was planned, funded, and implemented in just 7 days, and lasted from July 2 to August 15, 1984. Doppler radar was used to issue warnings of microbursts and probable wind shear; 35 microburst advisories were issued for the airport, prompting 7 aircraft to abandon the approach or delay takeoff. In addition to the Doppler radar warnings, a daily microburst probability forecast was issued, achieving an accuracy of approximately 80%. Wind shift advisories and convective initiation advisories were also issued from the data provided by the test instruments.

The success of CLAWS was the ability to quickly implement the research efforts of JAWS into an operational setting. Advanced microburst forecasts and real-time warnings may have prevented an accident. At least one pilot displayed his gratitude; “by just having this available—note we were in a heavily loaded 737 in the critical approach phase—this warning in advance may have just saved an aircraft from being forced into the ground short of the runway” (cited in McCarthy & Wilson, 1985, p. 254).

An important and unanticipated value of CLAWS was the decrease in air traffic delays caused by severe weather. The project also produced effective microburst advisories which improved aviation safety.

Both JAWS and CLAWS, based on the eastern slope of Colorado, primarily studied dry microbursts; those microbursts produced in a dry environment in which the rain evaporates before reaching the surface (Caracena et al., 1989). The two most recent
accidents, PAA 759 and DAL 191, had occurred in moist environments. The
development of the microburst, and the observing techniques required in a moist
atmosphere, differ from the dry environment (Wakimoto & Bringi, 1988).

**MIST**

The Co-operative Huntsville Meteorological Experiment (COHMEX) was a
collection of many different agencies. The FAA component, FLOWS (FAA-Lincoln
Laboratories Operational Weather Studies), tested algorithms for wind shear detection by
Doppler radar. Utilizing the same equipment, meteorological concerns were addressed by
the National Science Foundation (NSF) in the MIST (MIcroburst and Severe

During June and July of 1986, MIST employed 5 Doppler radars, 41 PAM
stations, 30 mesonet stations, 5 LLWAS networks, and 2 rawinsonde sites. With this
extensive array, comprehensive data were collected on the three-dimensional structure of
microbursts in a wet region (Wakimoto & Bringi, 1988). The MIST project
complemented the dry microburst data obtained during JAWS. Scientists now had a full
data set of the microburst phenomenon.

**AWDAP**

Significant public and political focus on the problem of wind shear was generated
by the accident of Delta 191. The Congressional House Committee on Science and
Technology responded by funding wind shear research at NASA. On July 24, 1986, the
Airborne Windshear Detection and Avoidance Program (AWDAP) was absorbed into the
FAA's National Integrated Windshear Plan (NASA, 2002), thus creating a joint research
project between the FAA and NASA.
The purpose of AWDAP was three-fold: to quantify wind shear as a flight safety hazard level, to develop remote sensing of wind shear, and to design and develop a means of conveying the wind shear information to pilots.

The first objective was met with the development of a wind shear hazard index predicting impending flight path deterioration. The index, or F-factor, is based on the total aircraft energy and its potential rate of change through a horizontal and vertical wind (Proctor, Hinton, & Bowles, 2000, p. 482). Hazardous wind shear was determined, through research, to be present when values greater than 0.1 were generated (p. 483).

To evaluate the concept of the F-factor, along with meeting the remaining two objectives, NASA would flight test a variety of sensors and displays. Doppler radar was proving a success in ground instillations, and with substantial modification, NASA was able to develop an airborne Doppler radar. This would be tested on their 737 aircraft along with a lidar system, and an infrared radiometry sensor. Additional enhancements to the 737 included an improved in situ reactive wind shear warning system and a VHF data link from a ground TDWR site (NASA, 2002).

Flight testing and validating the equipment in an operational setting was a major function of the research project. The testing took place in Denver in July of 1991 and 1992 to evaluate dry type microbursts, and in Orlando in June of 1991 and August of 1992 for evaluating wet type microbursts (NASA, 2002). The fully manned and instrumented aircraft was initially guided toward a microburst with the aid of ground based TWDR, several miles from penetration the airborne sensors would be used and internal guidance would commence. The aircraft was flown at a minimum of 750 feet
AGL and 210 kias for storms greater than F-factor 0.1, with 0.15 storms being avoided for safety reasons (NASA, 2002).

The testing confirmed that Doppler radar is the most effective in depicting both types of microburst, with a warning issued 40 seconds or more before penetration (NASA, 2002). Lidar worked well in the dry atmosphere, but was attenuated by the rain and did not provide sufficient warning for wet microbursts. The infrared radiometry system was a disappointment in all cases, being unable to distinguish the necessary temperature changes.

Key successes of AWDAP were the development of the F-factor and Doppler radar. The F-factor, displayed on the sensor screens, provided a crucial quantitative analysis in aiding the decision making process and is now on many new jet aircraft (Procter et al., 2000, p. 485). Doppler weather radar has also made the transition from experimental to operational, and is in many commercial and corporate aircraft. Testing the equipment and theories in a real-world flying laboratory, through actual microbursts with a jet transport aircraft, NASA provided basically unassailable data, and probably unattainable by industry.

**Historical Context Conclusions**

Learning and change is often born from understanding tragedy. The understanding of microburst knowledge and procedures is an evolution following tragedy. The Eastern 66 accident provided the catalyst for the downburst theory, and eventually freed funds for the NIMROD project; Pan Am 759 increased the funding for the JAWS Project, the incident of United 663 prompted CLAWS, and the Delta 191
accident was the catalyst for the FAA to join with NASA in an airborne detection program (NASA, 2002).

Escape procedures are also inexorably tied to the aircraft accidents. Iberian 933, the DC-10 which crashed in Boston, prompted the first publication by the FAA on wind shear (Grossi, 1988). The Allegheny 121 accident added to this advisory circular escape guidance (NTSB, 1986, p. 157). Not until several accidents later, most notably United 663 and Delta 191, were definitive procedures advanced in the form of the WSTA. The NTSB recommended an evaluation of the WSTA after the accident of US Air 1016 (NTSB, 1995, p. 123). Like knowledge, escape procedures were refined through the accidents and research.

Microbursts are not a new phenomenon, but the implications to society are. In a relatively short time span, the theory was postulated, researched, and procedures implemented to mitigate its effects. Many notable scientists contributed to this effort in diverse and creative ways. The data that they collected, the observations made, and the theories presented enhanced the knowledge of microbursts, the safety of aviation, and the science of meteorology.

Microburst Meteorology

The microburst is a small-scale weather phenomenon that easily evades detection. Unlike its cousin the tornado, the microburst is not visible, and telltale signs of dust or rain rings rising from the surface are often the only indication of its existence. Also unlike the tornado, the microburst does not require a storm environment to develop. Summer skies, even those appearing innocent, frequently contain the ingredients to spawn this most deadly wind.
Physical Properties

The microburst is characterized by a vertical shaft of downward flowing air, with or without moisture, which spreads horizontally at surface impact or prior. The downward flow of wind creates a pressure gradient of strong torque which may manifest as a horizontal vortex (Caracena et al., 1989). The outward spread of a microburst is confined to a localized area and signifies the decay of the downburst.

Size

The microburst is a small downburst with its outburst of damaging winds extending only 4 km (2.5 miles) or less (Fujita, 1985, p. 8). It is very difficult to classify downbursts as to size, and to have an arbitrary 4 km size limit confines the term to artificial boundaries (McCann, 1994, p. 532). The term microburst is now colloquially used to convey a small scale but intense downburst.

Microburst winds are generated in the meteorological mid-layer, at about the 500 millibar (mb) level, which corresponds to about 18,000 ft MSL. The core of the microburst is generally less then 1 mile in diameter, with the horizontal outflow 2.5 miles in diameter, the spread beginning 1000 to 3000 ft AGL (FAA, 2003a, ¶ 7-1-26). The depth of outflow is approximately 1 km (3,280 ft) deep (Proctor, 1985, p. 257).

Microburst winds are a localized phenomenon in both space and time. One of the strongest microbursts ever recorded had wind gusts greater than 130 knots, while just 2.3 miles away the winds were light and variable at 5–6 knots (Fujita, 1983b, p. 6). This occurred August 1, 1983, at Andrews Air Force Base, just five minutes after the presidential aircraft had landed, with President Reagan on board (Fujita, 1983b).
**Wind Speed**

While some microburst may produce hurricane strength winds, most have a wind speed of 12–14 m/sec (27–31 mph) (Fujita, 1985, p. 63; Proctor, 1985, p. 257). Peak winds occur about five minutes after the initial horizontal divergence at the ground, typical horizontal differential speeds are 24 m/s (≈ 54 mph) over a distance of 1800 m or about 1 nm (Proctor, 1985, p. 257). The wind at 75 m (≈ 250 ft) AGL contains the highest velocity (p. 257).

The greatest horizontal wind shear and downdraft velocity exists when the core downdraft radius is small (Proctor, 1985, p. 264). The small size and high speed correlates into a tight wind gradient. Downdrafts of 30 m/s (≈ 6,000 ft/min) with shears of 167 km/hr (≈ 90 knots) can occur in the microburst (FAA, 2003a). The maximum down-flow speeds are in the lower levels, below 1 km (3,280 ft) (Proctor, 1985).

**Vorticity and Rotation**

The majority of microbursts are accompanied by a vortex ring (Fujita, 1985, p. 73), which acts to enhance the outflow speed near the ground. The stretching ring vortex generates much faster outflow winds than can normally be accounted for in the downdraft (Fujita, 1983b, p. 28). In fact, maximum outflow speeds occur just as the vortex-ring reaches the ground (Proctor, 1985, p. 258). These vortex rings produce strong shears over a scale of several hundred meters (p. 264). This is particularly dangerous for aircraft, as witnessed when Delta 191 flew through several stretching ring vortices (Fujita, 1986, pp. 35–44).

As the ring vortex stretches, it breaks apart due to expansion. Sections may dissipate, or advance as burst swaths (rotor microbursts). These horizontal rotors,
persisting for 2–3 minutes after the vortex ring fracture, can induce tornado like damage (Fujita, 1985, pp. 73–74).

The streamlines from the majority of microbursts flow outward with little or no horizontal curvature. There are exceptional cases in which downdrafts are observed to have a rotational component. In the regions studied, rotation is predominantly cyclonic, while about 10 % of rotating microbursts are anti-cyclonic (Fujita, 1985, p. 74). This mini-cyclone may act as a hydrometeor funnel to fuel the downdraft (p. 74).

**Pressure and Temperature Variations**

Underneath the downburst, a dome of high pressure exists (Proctor, 1985, p. 258). This dome is induced by stagnation pressure of the outflowing winds. The central high-pressure dome is encircled by a low-pressure ring, which acts as an accelerant for the diverging wind. Beyond the low-pressure ring lies an encircling ring of high pressure, outside of which the pressure drops to the normal atmospheric level. The microburst winds initially accelerate toward the low-pressure ring, and then slow as they approach the high-pressure ring, after which they again accelerate toward the reduced pressure on the edge of the microburst boundary (Fujita, 1983, p. 30).

The relationship between pressure and temperature is intertwined in the ideal gas law. In most microbursts the down-flow wind was observed to be cooler than the environment, and some reactive wind shear alert systems use this heuristic as a warning threshold (NTSB, 1995, p. 13). In NIMROD and JAWS, however, 40% of the microbursts observed were warmer than their environment (Fujita, 1985, p. 65). Evaporation plays a large role in keeping the air inside a microburst cool, and hence
negatively buoyant, however, the downward momentum of the air may drive warm microbursts to the ground (p. 65).

**Duration**

The life of a microburst can be calculated as the duration of \( \frac{1}{2} \) peak wind speed, that is the time from when the wind is half of its greatest value until it drops below this value on its return to the environmental norm. This varies between 1 and 8 minutes with an average of 3 minutes (Fujita, 1985, p. 65). The build up of wind and subsequent dissipation may add considerably to this time. Caracena et al. (1989), notes the periodicity of vortex ring instability may increase the life of the microburst six fold (p.13). Generally, however, rapid growth and decay of the microburst occurs on the order of 10 minutes (Fujita, 1985, p. 90).

This should not lead to a false assumption that once a microburst occurs the event is over. A series of microbursts can take place at a similar location (Caracena et al., 1989, p. 14); they often occur in families (Cummine, 1997, p. 268; FAA, 2003a) and are common during the convective season.

**Frequency**

In the central and southern United States, as many as 100 microbursts a year may occur in a county-size area (McCann, 1994, p. 533). Predominant in spring and summer, an estimated 3,510, with a wind speed of 75 knots or greater, take place in the United States—4 times more frequent than tornados (Fujita, 1985, p. 78). In the 42 days of the NIMROD project, 50 microbursts were observed, while 186 microbursts were observed in the 86 days of the JAWS project, and 62 microbursts occurred in the 61 days of the MIST project (Fujita, 1985; McCann, 1994).
Microburst development is closely related to the time of convective activity in a specific region (Fujita, 1985, p. 68). During the MIST project, peak microburst activity occurred at 15:00 local time with a lesser peak of unknown origin at 12:00 local time (Atkins & Wakimoto, 1991, p. 472). The JAWS project obtained similar results, with wet microbursts peaking between 14:00 and 15:00 local time, and dry microbursts peaking between 14:00 and 16:00 local time (Fujita, 1985, p. 69). Microbursts exhibit this diurnal variation with strong correlation to maximum surface temperatures (Atkins & Wakimoto, 1991, p. 472).

The physical properties of the microburst are dictated by the environmental conditions in which it is born and grows.

**Environmental Conditions**

Though not a rare event, the microburst needs a specific environment in which to emerge. Convective type clouds provide the clues indicating the atmosphere may be ripe for microburst development, however they are not an affirmation that an occurrence is imminent. For a microburst to spawn, the atmosphere must produce motive forces while providing an environment encouraging growth.

**Atmospheric Properties**

Often, microbursts are associated with thunderstorms, but any low or middle layer convective cloud, with the right conditions, is a suitable parent (Fujita, 1985; FAA, 2003a). Altocumuli, and clouds with little vertical development, are able to spawn microbursts as intense and violent as large thunderstorms. The relationship between radar reflectivity of the cloud and the strength of a microburst is not apparent, “weak showers, whose drops evaporated before reaching the ground, sometimes produced intense
microbursts” (Proctor, 1985, p. 257). It was also found that some microbursts “were
induced by relatively weak echoes without thunder” (Fujita, 1985, p. 47).

Of course this does not portend that thunderstorms are not a vehicle for
microburst development. The accident histories, especially Delta 191 and US Air 1016,
clearly demonstrate the ferocity of thunderstorm-produced microbursts. Thunderstorms
contain the conditions conducive to microburst development with a deep mixed layer,
high lapse rate, and precipitation to fuel strong microbursts (Caracena et al., 1989, p. 25).
The presence of these conditions, however, does not guarantee their development.

Thunderstorm outflow boundaries play an important role in the development of
microburst-producing storms (McCann, 1984, p. 538). Microbursts seem to favor storms
that develop from secondary outflow boundaries (McCann, 1984, p. 537, 539), with the
faster moving boundaries more conducive for microburst generation (p. 538). This was
the environment that trapped Delta 191: the 50,000 ft thunderstorm, which was
circumnavigated, was feeding the smaller (23,000 ft) microburst-producing thunderstorm

While the outflow boundary enhances microburst development, specific
atmospheric conditions and forces initiate and support the microburst.

**Motive Forces**

Microbursts have their origin in the precipitation entrained in the mid- and upper-
layer of the atmosphere. In the upper-layer, the precipitation is often in frozen form;
either hail or ice crystals. As the mass of individual particles accumulates, through
various processes, it eventually exceeds the ability to be suspended at that layer. When
the precipitation falls, it creates drag on the surrounding atmosphere, initiating a
downward momentum of air (Stull, 2000, p.340). As the air descends it enters warmer layers, the once frozen particles melt, creating rain. This change of state absorbs the latent heat in the surrounding atmosphere. The cooler air, now much more dense than its environment, becomes negatively buoyant and accelerates downward with the rain. If a layer of dry air exists in a lower level some of the rain will evaporate, further cooling the air and increasing its downward velocity (McCann, 1984, p. 533).

In the mid-layer of the atmosphere, where the temperature may already be above freezing, a downburst can initiate when dry air from the mid to upper atmosphere is entrained into a convective cloud. The dry air mixes with the saturated air in the cloud, cooling off the local air relative to the surrounding air, thus creating negative buoyancy. The entrained dry air initiates a downward velocity (Cummine, 1997, p. 269).

In either the mid level or upper level cloud, negative buoyancy in the downdraft is primarily generated below the freezing level. The freezing level is therefore a measure of the depth of the downdraft. (Hallowell et al., 1996, p. 66).

Radar scans confirm an acceleration of the downdraft at the freezing level (Fujita, 1985, p. 16). It is apparent that the heat required for melting is an important energy source for initiating a large downward acceleration (p. 18). Evaporative cooling is often enough to keep the parcel colder than its surroundings and therefore negatively buoyant (Leech, 1985, p. 308). If a parcel of downward moving air is warmer than its environment, the speed decreases, but if it has enough kinetic energy it can reach the surface before decelerating to zero velocity (p. 307). This may explain the variable temperatures observed inside the microburst.
The primary fuel for the downburst is the amount of upper level-water and ice within the storm, the forcing mechanism is the amount of evaporation and melting of the water and ice as it is pulled down by gravity (Wolfson, 1990). The cooling of the air below the melting level occurs primarily from the evaporation of rain and secondarily from the melting of hail (Proctor, 1985, p. 258), and this is the mechanism for most downburst formations (p. 258).

A relationship between precipitation loading, increasing the weight of air with liquid, and downburst strength does exist, but is less critical than environmental lapse rate for temperature and humidity (Proctor, 1985, p. 258). The lapse rate is a measure of how much negative buoyancy the water-saturated air can gain through melting and evaporation. If the lapse rate is lower than 5.5 °C /km, microburst probabilities are nil (McCann, 1984, p. 533). Thus, temperature inversions with negative lapse rates form a barrier to downdrafts, diminishing the strength of the outflow. It is rare for a microburst to break through an inversion and produce microburst-strength outflows (Hallowell et al., 1996, p. 68).

Two distinct types of microburst exist—dry and wet. Each has a preferred region within the United States. The Dry microburst is predominantly found within the western states, while the wet microburst occurs in the more humid regions of the country, especially in the southeastern states (Atkins & Wakimoto, 1991, p. 471). There is substantial overlapping in the geographical regions, and the microbursts need not be exclusive to any particular locale. Of the microbursts observed in the Denver area JAWS project, 83% were dry, while only 36% of the microbursts in the Chicago area NIMROD project were dry (Fujita, 1985, pp. 4–5).
Dry Microbursts

Regions frequented by warm and dry conditions in the lower atmosphere, with a nearly saturated and well-mixed layer at about 500 mb, favor the development of dry microbursts (Atkins & Wakimoto, 1991, p. 470). This environment is typical during summertime in the intermountain territory of the American West.

The high bases (500 mb) of the convective clouds in the saturated layer sit atop a deep dry adiabatic layer with temperature dew point spreads approaching 30 °C (Caracena et al., 1989, p. 15; Fujita, 1985, p. 71). The high cloud bases and dry lower environment allow time for rain to evaporate (Fujita, 1985, p. 71). The evaporation of falling precipitation droplets causes the subsiding air to become negatively buoyant relative to the environment around it (Cummine, 1997, p. 269).

The strong surface winds associated with the dry microburst are a result of negative buoyancy generated by evaporation, melting, and sublimation of precipitation below the cloud base (Atkins & Wakimoto, 1991, p. 470).

When the lapse rate below 500 mb is approaching, or greater than, dry adiabatic (9.76 °C/km) (Hallowell et al., 1996, p. 67), and conditions are slightly unstable to stable, dry microburst formation is possible (Nelson & Ellrod, 1997, p. 263). The thermodynamic forcing in the dry environment is much greater than in a wet environment (Hallowell et al., 1996, p. 66).

Dry microbursts are usually associated with weakly convective cumulus or altocumulus clouds and are often accompanied by virga (Nelson & Ellrod, 1997, p. 262). However, the anvils of thunderstorms can produce high-level virga resulting in a dry microburst. These dry microbursts occur a distance from the parent hailstorm, and are
difficult to detect because they are not embedded within the large radar echo of the thunderstorm (Caracena et al., 1989, p. 22).

**Wet Microbursts**

Wet microbursts develop in moist conditions, often with heavy precipitation, on days when the environment is potentially unstable; hence these microbursts are frequently associated with severe storms (Atkins & Wakimoto, 1991, p. 478).

The atmospheric profile conducive to wet microburst development has a temperature structure of a dry adiabatic sub-cloud layer from the surface to about 850 mb, topped by a more stable layer. The moisture profile from the surface to 500 mb is nearly saturated, and is capped by a dry layer at mid-level (Nelson & Ellrod, 1997, p. 263; Caracena et al., 1989, p. 16). The precipitation core must interact with the dry layer for microbursts to form, if this precipitation core contains ice, the microburst will be more intense (Atkins & Wakimoto, 1991, p. 481).

The dry layer acts to change the state of the precipitation, absorbing the latent heat in the atmosphere while adding to the negative buoyancy of the air. The strongest downdrafts are associated with very dry air aloft near the melting level (Atkins & Wakimoto, 1991).

The phase of precipitation plays an important role in the generation of microbursts. In more stable environments, precipitation in the form of ice facilitates the strongest microbursts (Atkins & Wakimoto, 1991, p. 480). This can lead to large temperature drops (p. 472) and negative atmospheric buoyancy, which accelerates the air downward.
A strong downdraft conveys rain toward the surface at a much faster rate than it can fall at terminal velocity through still air. As the downdraft approaches the ground it decelerates in the vertical, allowing a heavy load of water to accumulate above the ground. A wet microburst may at first appear as a darkened mass of rain descending through light rain (Caracena et al., 1989) In the humid regions of United States, such as Louisiana and Florida, practically all microbursts are accompanied by heavy rain (Fujita, 1985, p. 70). The precipitation in a wet microburst has high radar reflectivity, as opposed to the dry microburst, which may be undetectable by conventional radar systems.

The cross-section of a microburst shaft is relatively small. The FAA (2003a) states the diameter as less than 1 nautical mile, while Proctor (1985) seems to narrow the diameter down in computer simulation to between 250 m and 4,500 m. Thus the precipitation, though reflective, will be difficult to discern on airborne weather radar. In any event, the relationship between radar reflectivity and microburst strength is not apparent (1985).

Avoidance of the microburst remains the most effective means of survival. At this time, ground based systems surpass airborne systems in detecting microburst events. Though wet microbursts are more easily discerned by remote sensing, all types represent a danger, as witnessed in the accident record. “Wherever and whenever it occurs, and regardless of its type, a microburst can cause an airplane crash, and should be taken seriously” (Caracena et al., 1989, p. 29).

Many similarities, and some differences, occur with both types of microbursts. Table 2 examines and compares some of the more common phenomenon and distinguishing characteristics occurring between the dry and wet microburst.
Table 2

*Qualitative Comparison of Dry and Wet Microbursts*

<table>
<thead>
<tr>
<th>Dry Microbursts</th>
<th>Wet Microbursts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Microburst produced by negative buoyancy, due to evaporation, melting, and sublimation of precipitation below cloud base</td>
<td>1. Microburst produced by combination of precipitation loading, negative buoyancy, momentum transport, and pressure gradients</td>
</tr>
<tr>
<td>2. Little or no rain reaching the surface, virga containing light snowflakes</td>
<td>2. Heavy rainfall; precipitation core composed of melting hail</td>
</tr>
<tr>
<td>3. Weaker convection / updrafts</td>
<td>3. Stronger convection / updrafts</td>
</tr>
<tr>
<td>4. Higher cloud bases</td>
<td>4. Lower cloud bases</td>
</tr>
<tr>
<td>5. Function of solar heating</td>
<td>5. Function of solar heating</td>
</tr>
<tr>
<td>6. Moist at mid levels</td>
<td>6. Dry at mid levels</td>
</tr>
<tr>
<td>7. Relative humidity at 500 mb ≥ 40 %</td>
<td>7. Relative humidity at 500 mb ≤ 40 %</td>
</tr>
</tbody>
</table>

From Nelson & Ellrod, 1997, p. 263, 266
Aircraft Performance Factors

Microbursts are a dynamic occurrence, which produce a dynamic aircraft response. These responses tend to couple, one affecting the other, so a loss of airspeed, for example, will reduce the lift, affect the longitudinal stability, and decrease the total energy. To understand the events that an aircraft experiences when transitioning through a microburst it is beneficial to separate the forces into individual components and undertake a static analysis of the dynamic response.

Flight Instruments

Most aircraft rely on air data, at least in part, to determine altitude, vertical speed, and airspeed (Stengle, 1984, p. 199). In the microburst, pressure varies from atmospheric; the Andrew’s microburst had pressure variations of +0.4 mb (≈ 0.12 inches Hg) to -0.2 mb (≈ 0.06 inches Hg) (Fujita, 1983b, p. 4). This represents a difference in the indicated barometric altitude of 120 ft below actual altitude to 60 ft above actual altitude. Vertical speed indicators (VSI) are primarily pressure driven and can also be susceptible to error (FAA, 1988, p. 27). Airspeed indications also rely on pressure sensations, but are less susceptible to atmospheric variations as they sense a differential between static and dynamic pressure (United States Air Force [USAF], 1983, pp. 4: 15–16).

Non-Pitot-static instruments will also be affected by the microburst. The wind in the microburst may induce sudden gusts which cause rapid fluctuations in the angle of attack sensors (FAA, 1988, p. 28). In modern jet transport aircraft the angle of attack sensors along with the Pitot-static system are inputs into an air data computer (Wild, 1996, p. 10: 21). Thus, a variety of aircraft instrument systems may be influenced by the microburst.
Aircraft Behavior

An aircraft’s response to a microburst will be dependent, not only on the particularities of that microburst, but where in the storm the aircraft penetrates, with what speed and altitude, in what configuration, and other factors. Hence, only a general case is considered here—the NTSB reports are replete with specific case studies.

Transitioning through a microburst (Figure 4), an aircraft will initially encounter an increasing headwind, which will increase the lift and energy of the aircraft. The headwind will give way to a downdraft, which will decrease the lift and energy of the aircraft. As the downdraft is escaped the aircraft will experience a tailwind, which continues the diminution of lift and energy (Bristow, 2003, pp. 262–263). The wind change may be significant enough to cause the wing to stall (McCarthy, Blick, & Bensch, 1979). Two thirds of the microburst is a hostile environment to the lift and energy of the aircraft.

Figure 4. Effect of microburst on flight path. Note. From Influence of wind shear on the aerodynamic characteristics of airplanes (p. 17), by D. D. Vicroy, 1988, NASA technical paper 2827, Washington D.C.: NASA.
When ring vortices are introduced to the microburst (Figure 1), a series of increasing and decreasing up and downdrafts, along with headwind and tailwind components, influence the aircraft (Figure 2). Therefore, depending on the spatial relationship of the aircraft trajectory to the microburst, the initial headwind increase may not be present. This anomaly may hinder the ability to recognize a microburst encounter, with the effect of delaying the escape.

Complicating recognition and aircraft control, microbursts may occur with or without turbulence. The flight crew of US Air 1016 may not have recognized the microburst they were in due to the lack of turbulence (NTSB, 1995, p. 108). Survivors of the Eastern 66 accident recalled minimal turbulence during their approach (NTSB, 1976, p. 4), while Delta 191 reportedly experienced significant turbulence (NTSB, 1986, p. 18). Turbulence complicates aircraft control and may induce unequal span-wise loading on the wings, so that one wing stalls prior to the other (Melvin, 1986, p. 55). The control problems of turbulence, though significant, are not the major factors affecting aircraft performance.

Perturbations by microburst winds on aircraft equilibrium will initiate a response in the dynamic stability of the aircraft (ICAO, 1987, p. 59). Longitudinal stability may be excited, and even resonate, from the upset (McCarthy et al. 1979; Sherman, 1977). Lateral-directional instability may also occur, confounding the control problem. Additionally, negative speed stability can present a control and performance problem during the approach, possibly requiring a descent regardless of the altitude deficit (Higgins & Patterson, 1979).
Lift and stability are the dominant aerodynamic responses affected by the microburst (Vicroy, 1988, p. 13), but aircraft energy will also be affected. The airspeed decrease reduces kinetic energy, and the altitude degradation will decrease the potential energy of the aircraft. Total energy can be increased with added thrust, thereby mitigating the effect of the energy absorbing microburst (Proctor et al., 2000). Thrust may become saturated, however, before the microburst is transitioned, leading to the compromise of trading potential energy for kinetic energy. A base amount of kinetic energy is required to ensure the lift force is adequate to maintain flight.

Lift

Wing lift is an aerodynamic force, produced by the aircraft, which acts in a direction normal to the free stream velocity of the air (AIAA, 1992, ¶ 1.7.2.8). Though engine thrust may act in a direction which enhances lift, particularly at a high angle of attack, the convention is to consider thrust separately.

The classic equation of lift is

\[ L = C_L \frac{1}{2} \rho V^2 S \]  

(1)

where \( C_L \) is the coefficient of lift, \( \rho \) is the air density, \( V \) is the airspeed, and \( S \) is the wing area (Mair & Birdsall, 1992, pp. 3–5).

The coefficient of lift, \( C_L \), is a measure of the lifting effectiveness of the wing, and at subsonic speeds depends mainly on wing geometry and angle of attack (Barnard & Philpott, 1995, p. 20). Angle of attack is often denoted with the Greek letter alpha (\( \alpha \)) and represents the angle between the relative wind and a reference line, usually the chord line.
or the fuselage centerline (Cashman, Kelly, & Nield, 2000, section 1). Increasing the angle of attack will increase the coefficient of lift, the relationship being linear below the stall angle of attack (Anderson, 1997, p. 212). The stall angle of attack is the value of \( \alpha \) for maximum usable lift (Chambers & Grafton, 1977). Larger angles of attack than the stall alpha materially affect lift and may hamper longitudinal stability, to the extent that the aircraft becomes uncontrollable.

The initial headwind in the generalized microburst will increase the airspeed and hence increase the lift. As the headwind diminishes, the lift from airspeed decays. Further decaying the lift is the downward flow. In the downdraft, the relative wind now strikes the aircraft from above, thus decreasing the angle of attack (Figure 5) and reducing the value of \( C_L \).

![Result of downburst on angle of attack](http://www.b737.org.uk/dimensions_737200.gif)

*Figure 5.* Result of downburst on angle of attack. *Note.* Aircraft from *The Boeing 737 Technical Site*, by C. Brady, 2003, http://www.b737.org.uk/dimensions_737200.gif.

The loss of lift due to the change in \( \alpha \) is dependent on the wing design, configuration, and the initial angle of attack. When at high angles of attack, the reduction in \( \alpha \) produces less of a decrement in performance, than when the initial \( \alpha \) is low. This arises from the slope of the \( C_L \) versus angle of attack curve for typical transport category aircraft. For a Boeing 727, with flap 15 at approach speed and 5° \( \alpha \), a one knot down flow
will decrease the lift by 4.5 %, while at an initial $\alpha$ of 15°, a one knot down flow will diminish the lift by 1.3 % (Fujita, 1985, pp. 20–21).

In addition to the loss of lift, the aircraft will become entrained in the downward moving air. The vertical velocity of the downburst will subtract from climb performance an amount at least equal to the downward air velocity.

As the down flow is passed, and the outflow is encountered, the airspeed drops by the magnitude of the tail wind, causing a loss of lift (Higgins & Baker, 1986, p. 43). The airspeed, being a quadratic term in Equation 1, materially affects the lift generated. A change in speed of 10 %, while other variables remain constant, will equate to a 19 % change in the lift force (Fujita, 1985, pp. 20–21). This alleviation in lift is common to all conventional airplanes and is independent of angle of attack.

The aerodynamic effects most influenced by the microburst are rapid changes in lift and pitching moment (Weishaupl & Laschka, 2001, p. 265). Pitching moment translates into the stability of the aircraft and can degrade performance.

**Dynamic Stability**

How an aircraft restores its equilibrium conditions after a disturbance determines the aircraft’s stability. There are five dynamic stability modes: three lateral-directional modes and two longitudinal modes. The lateral-directional modes include the Dutch roll, the spiral, and the roll mode. The longitudinal stability modes are the short period pitch oscillation (SPPO) and the phugoid (USAF, 1980, p. 7.1). Transport aircraft are required, per the airworthiness standards of FAR 25.181, to be highly damped in the SPPO and Dutch roll mode between 1.2 times the stall speed ($V_s$) and the maximum allowable
speed \((V_{MO})\) (FAA, 2003b). The phugoid and spiral mode stability, however, are very lightly damped, and may even be slightly unstable.

Stability modes are excited whenever the airplane is disturbed from its equilibrium trim state (Cook, 1997, p. 119). A microburst encounter will upset the equilibrium trim of an aircraft and may cause a resonant response in the phugoid mode (Stengel, 1984, p. 201).

The phugoid mode is an oscillation about airspeed coupling into pitch attitude and height with a relatively constant angle of attack (Cook, 1997, p. 120). A small disturbance in speed leads to a reduction in lift. As the lift is reduced the aircraft descends and accelerates, when the aircraft accelerates it increases lift and climbs. When the aircraft climbs its speed decays, reducing lift, and causing the sinusoidal series to continue. During the oscillations, drag gradually lessens the amplitude until the motion eventually damps out (p. 121). Jet transport aircraft are designed with minimal drag, so the damping of the phugoid mode is very light.

A reduced-order mathematical model can be used to approximate phugoid properties. It is commonly assumed that the change \((\Delta)\) in angle of attack is zero, that is \(\Delta \alpha = 0\) and that the thrust \((T)\) is equal to the drag \((D)\) of the aircraft, that is \(T = D\) and that compressibility is negligible (Cook, 1997; McCarthy, Blick, & Bensch, 1979; VonMises, 1959). The frequency of the phugoid \((\omega_p)\) in radians per second is given by:

\[
\omega_p = \frac{g\sqrt{2}}{V_0}
\] (2)
Where \( g \) is the gravity constant and \( V_0 \) is the steady trimmed speed (Cook, 1997, p. 126). Through the equation, it can be seen that the natural frequency of the phugoid is inversely proportional to the trim speed.

The phugoid may be stable and damped, or it may be divergent and aperiodic. When damped the oscillations do not continue indefinitely but eventually fade out. The length of time for one cycle divided by the time taken for the total number of cycles to decay is the damping ratio. A heavily-damped oscillation has a damping ratio of 0.3 or greater (Stinton, 1996, p. 429). Mathematically, the phugoid-damping ratio \( (\zeta_p) \) can be expressed as:

\[
\zeta_p = \frac{1}{\sqrt{2}} \left( \frac{D}{L} \right)
\]

(3)

Where \( D \) is drag and \( L \) is lift (McCarthy et al., 1979, p. 11). Thus for any given lift, the less the drag, the less phugoid damping available. A Boeing 737 in the landing configuration has a damping ratio of 0.08 (Gera, 1980, p. 9).

A perturbation in speed brought about by microburst winds can easily excite the phugoid and start the airplane on its “roller coaster” type ride. The efficient design of the modern aircraft lessens the phugoid damping, so that there is a greater deviation from the nominal flight path than would occur with a well-damped mode (Stengel, 1984, p. 201). If the microburst wind occurs at the same, or similar frequency, of the phugoid, a resonant response can occur; causing correspondingly larger airspeed upsets (McCarthy et al., 1979, p. 43).
The phugoid frequency of a Boeing 727 at 140 knots is 0.164 radians/sec (0.026 Hertz), which is a period of about 38 seconds. This period is within the temporal scale of an airplane’s traverse through a microburst. It is probable that a wind gust could initiate a phugoid and then excite it at its resonant frequency (Frost, Turkel, & McCarthy, 1982, p. 1). The velocity perturbation at the resonant frequency for a B-727-200 series aircraft is close to 20 decibels. If such an aircraft encounters a horizontal gust of only 4 knots wind speed, at the angular frequency of 0.026 Hz, the aircraft will respond with an airspeed deviation of approximately 40 knots (McCarthy et al., 1979, p. 10). That is, the speed will be 100 kias at the high point on the phugoid wave, while at the point of minimum altitude the speed will be at its maximum, 180 kias.

Eastern 66 had a fairly constant 10-knot headwind on approach to JFK. At about 600 ft AGL the aircraft, a Boeing 727-200, encountered a headwind gust of 25 knots, which soon subsided to 20 knots and then in four seconds dropped to a 5-knot headwind (NTSB, 1976, p. 17). The time period from initial upset to the steady state was 19 seconds. This is a half sine-wave of frequency 0.026 Hz (McCarthy et al., 1979), with an amplitude of 15 knots. McCarthy et al. (1979) conclude that the JFK accident is “associated with the airplane’s encounter with a horizontal wind containing high energy at the airplane’s critical phugoid frequency, which caused a sudden extreme variation in the airspeed” (p. 45).

Examining the microburst accidents, one predominant theme manifests itself: The question, ‘why would an aircraft trying to climb impact terrain at a speed well above its stall speed, and in many cases, above its go-around speed?’ Eastern 66 hit at about 130 kias, close to its reference speed for the approach (NTSB, 1976, p. 7), but $V_S$ for their
configuration of flap 30 was about 97 kias. Pan Am 806 flew into the jungle at 140 kias while \( V_{\text{REF}} \) was 135 kias (NTSB, 1977, p. 23). Allegheny 121 impacted the ground at 155 kias while the reference speed was 122 kias and \( V_S \) was 110 kias (NTSB, 1978, p. 2, 15). PAA 759 had a \( V_2 \) speed of 151 kias and impacted the trees at 149 kias, following an airspeed increase of 18 knots in about six seconds, while \( V_S \) was still lower at 122 kias (NTSB, 1983, p. 33, 59). Delta 191 had a \( V_{\text{REF}} \) of 137, a \( V_S \) of 105 kias, and impact occurred at 169 kias (NTSB, 1986, p. 7; Fujita, 1986). Finally, USAir 1016 had a \( V_{\text{REF}} \) of 121 kias with flap 40, a go-around target speed of 128 kias with flap 15, and impact occurred at 142 kias (NTSB, 1996, p. 46).

At the top of a phugoid oscillation the aircraft will initiate a descent with increasing airspeed even while flying at the maximum angle of attack (Melvin, 1986, p. 52). Gera found (1980) that even a closed loop system was not damped in phugoid oscillation by the pitch attitude, and that attitude control in stabilizing the divergence was ineffective (p. 11). Melvin (1986) found the phugoid continued after the shear boundary and the oscillation was not preventable by the pilot (p. 52). McCarthy et al. (1979), hypothesized that the phugoid may result in airspeed oscillations of a nature that would be difficult to control, possibly leading to stall, or other disastrous results (p. 29). Sherman (1977) found the phugoid could become aperiodic and unstable from a wind shear encounter (p. 1). In the aperiodic mode, the phugoid continually diverged from the equilibrium, and in the unstable dynamic system the phugoid continued to grow about the equilibrium condition (p. 7).

Control of the airspeed provides an indirect control of dynamic longitudinal stability. Slowing the airplane down increases stability (Sherman, 1977, p. 9).
Alternatively, holding airspeed constant in wind shear decreases changes in airplane stability (p. 15). Both techniques are unfeasible in a microburst encounter.

Changing aircraft configuration has little effect on the longitudinal dynamic stability, however, for wind shearing from tailwind to headwind, the increasing of flap deflection increases system stability (Sherman, 1977, p. 16).

It is difficult to generalize about the atmospheric conditions that constitute a hazard to aviation in general, a wind profile that resonates one aircraft type may not resonate another (Stengel, 1984, p. 201). Sherman (1977) found the wind gradient the most important factor—not the wind speed (p. 13). The higher the speed of the airplane the smaller the wind gradient required for the onset of unstable conditions. Therefore, transport aircraft, with their higher approach speeds, are much more susceptible to the performance restraining effects of wind shear then many other aircraft types (p. 8).

The hazards of the microburst include loss of lift and the effects of the phugoid mode, which can drive an airplane into the ground even with an increasing airspeed. “It is emphasized that it is the combination of the phugoid excitation, and the severe downdraught [sic] that makes the downburst such a treacherous phenomenon for an aircraft” (Robinson, 1991, p. 3.18).

Speed Stability

Speed stability arises from the aircraft’s response to total drag. Total drag, for a subsonic airplane, can be conceptualized as the sum of boundary layer, or profile drag and trailing vortex, or induced drag (Anderson, 1997, p. 73). Profile drag increases with speed, while induced drag decreases with speed. The minimum point in the summation of these two forces is the minimum drag speed and also the point of neutral speed stability.
Neutral speed stability is the point of change between negative speed stability and positive speed stability. That is, speed errors will grow below this speed, but die out at higher speeds (Etkin, 1972, p. 480). From the neutral point, a reduction in speed will increase drag. This increase in drag will grow as the speed decreases until the stall speed is reached and the aircraft stops flying (Barnard & Philpott, 1995, p. 327). In the region of negative speed stability, a change in speed will cause the aircraft to diverge from its trimmed state.

Positive stability occurs at speeds greater than the neutral point. The aerodynamic forces on the aircraft cause the airplane to respond in pitch toward the original trimmed airspeed (Higgins & Baker, 1986, p. 43). The aircraft will pitch down and accelerate to recover a loss of airspeed and pitch up and decelerate to regain the original trimmed airspeed (ICAO, 1987, p. 59). In the region of positive speed stability, a change in speed will cause the aircraft to converge toward its original trimmed state.

Takeoff and landing speeds are close to neutral speed stability for jet transport aircraft. The Boeing 727-200, at 140,000 pounds and flap 30, has a $V_{REF}$ of 128 knots which is the minimum drag speed (Higgins & Patterson, 1979, p. 3). Flight below this speed requires additional thrust to overcome drag. Colloquially this is known as the region of reverse command, as a decrease in speed requires an increase in thrust, whereas in normal flight an increase in speed is attained with an increase in thrust (Hurt, 1965, pp. 353–357). Airspeed degraded by wind shear below $V_{REF}$ will therefore require more thrust to maintain the lower speed then was required to maintain $V_{REF}$. If acceleration back to the landing reference speed is desired, an additional amount of thrust is required. In the region of reverse command, wind shear can quickly saturate the thrust available.
**Performance**

The hazard from wind shear arises from the maximum performance capability of the aircraft being temporarily exceeded by the downdraft environment (Higgins & Roosme, 1977, p. 15). Climb potential and airspeed are important facets of performance that are hampered by microburst winds.

The ability to climb is based on excess thrust (Hurt, 1965, p. 152), and therefore is dependent on the drag curve and the maximum thrust available curve. Two speeds become evident, the speed corresponding to where the difference between thrust and drag is a maximum, and the speed corresponding to where the product of speed and thrust subtract drag is a maximum (Higgins & Patterson, 1979, p. 4). The first speed is the best angle of climb speed and produces the greatest gain in altitude for a given horizontal distance, the second speed is based on time and is the best rate of climb speed, it is the greatest altitude gained in a unit of time (Barnard & Philpott, 1995, pp. 213–218; Dole, 1988, pp. 86–90).

At 140,000 pounds with flap 30 and gear down, the Boeing 727 has a best angle of climb speed of 124 kias with maximum thrust, producing a 1,650 fpm vertical velocity. The best rate of climb is achieved at 140 kias enabling a climb of 1,750 fpm. V\textsubscript{REF}, between these two speeds at 128 kias, generates a rate of climb of 1,690 fpm (Higgins & Patterson, 1979, p. 4).

Climb rates can be increased through a reduction in drag or a conversion of airspeed into altitude through zooming (Dole, 1988, p. 86; Hurt, 1965, p. 150). When flaps are raised the climb ability improves (Higgins & Roosme, 1977, p. 8). For the 727 at 140,000 pounds, the rate of climb at V\textsubscript{REF} increases 500 fpm when transitioning from
flap 40 to flap 30. When the landing gear is raised and the flaps are moved to 25 the rate of climb increases 300 fpm (Higgins & Patterson, 1979, p. 9). This last increase is not as great because the aircraft is configured for higher speed operations, but is being operated at low speed. If the airspeed were allowed to accelerate to 160 kias, the best climb speed in this configuration, the rate of climb would be 2,300 fpm.

Accelerating the aircraft is energy intensive. For the 727 at 140,000 pounds and flap 30 at $V_{REF}$ the climb rate is 1,650 fpm. If an acceleration rate of 2.5 knots per second is desired, the climb capability will be cancelled out completely (Higgins & Patterson, 1979, p. 6). In a wind shear environment, if the pilot wishes to regain lost airspeed, the climb rate must be sacrificed. At $V_{REF}$ and 100% thrust, the 727-200 will lose 650 fpm for each knot per second acceleration (p. 7). Boeing recommends not accelerating in a wind shear because of the great loss in climb rate (Higgins & Roosme, 1977; Higgins & Patterson, 1979; Boeing Windshear Task Force, 1985; Higgins & Baker, 1986).

Just as accelerating the aircraft reduces the climb rate, zooming the aircraft will increase the climb rate, if only momentarily. When the aircraft zooms and uses its kinetic energy it will be left at a low airspeed with a resultant decrease in climb performance (Webb, 1990, p. 206). Once the airspeed has been decayed it is very difficult to regain. The problem arises at speeds below the neutral point, because drag decreases excess thrust (Proctor et al., 2000, p. 484) and consequently impedes climb ability. Though transforming the kinetic energy into potential energy may be beneficial in the short term, there might not be enough climb performance remaining at the lower airspeed to arrest the descent rate in a severe downdraft (Higgins & Roosme, 1977, p. 9).
The role of energy is an important concept in the performance of aircraft—from the kinetic energy that governs lift, to the potential energy of climb, and the trading of the two in the phugoid. Understanding the interrelationship of aircraft energy to the environment allows predictions of aircraft performance to be made.

*F*-factor

The F-factor is an attempt to quantify the microburst hazard for aircraft in flight, it is a numerical index derived from the aircraft total energy and its potential rate change (Proctor et al., 2000). Mathematically this is represented by (p. 482):

\[
F \equiv \left( \frac{dU_x}{g} \right) - \left( \frac{w}{V_a} \right) 
\]

(4)

Where \( U_x \) is the component of atmospheric wind directed along the flight path, and \( dU_x \) is the derivative with respect to time, \( g \) is the gravitational constant, \( w \) is the vertical wind, and \( V_a \) is the airspeed (Proctor et al., 2000).

The equation is based on air mass kinetic energy, as an airplane’s ability to climb is a function of airspeed, and not groundspeed. A descending tail wind will decrease the energy state of the aircraft and so will create larger values of the F-factor. The term \( dU_x \) is a function of the meteorological event and the aircraft trajectory (Proctor et al., 2000, p. 483). The aircraft trajectory is further a function of the thrust to weight ratio of the particular aircraft, which makes the F-factor unique to each make and model. Typically, twin-engine aircraft have the highest thrust to weight ratio in the transport category and so will have a lower F value for a given microburst than will three or four engine aircraft.
To avoid spurious and nuisance warnings the F-factor is averaged over the distance of one kilometer by means of integration. Values greater than 0.1 of the averaged F-factor are considered hazardous by the FAA. A “must alert” threshold is established for aircraft equipped with the F-factor matrix at 0.13 (Proctor et al, 2000, p. 484).

In determining various microburst severities, the F-factor was computed for the Delta 191 and US Air 1016 accidents. The Delta L-1011 experienced the averaged F-factor of 0.23, with an instantaneous F-factor greater than 0.35. The DC-9 of US Air 1016, encountered a similar F-factor value; computer simulation produces a maximum value at 0.27, while the FDR derived winds are greater than 0.3 (Proctor et al., 2000, pp.486–487; NTSB, 1995, p. 48). These microbursts were up to three times greater than what is considered hazardous by the FAA.

The F-factor is a useful tool in determining how a microburst will affect a specific aircraft. Its application lies not so much in constructing past encounters, but in quantifying future events while aiding the flight crew in the decision making process. Aircraft performance is impeded in wind shear and the F-factor combines many of the detrimental effects of the microburst and presents the combination in an unambiguous form.

Aircraft Categories

Each aircraft has different inertial and aerodynamic characteristics; wind fields that are hazardous for one aircraft type may be less hazardous for another type. Aircraft with high airspeed and wing loading (e.g. transport category aircraft) appear to be more sensitive to gradients in head/tail wind, while aircraft with low airspeed and wing loading
(e.g. general aviation aircraft) are more adversely affected by downdrafts (Stengel, 1984, p. 201). General aviation aircraft are also much lighter and have less inertia to overcome performance-wise. The type of power plant also aids in this, as a reciprocating engine will provide very quick acceleration while a jet engine takes time to spool up. The JT-8D turbojet engine requires about 8 seconds to develop full power from an idle power setting. Propellers also develop a localized airflow, aiding lift and decreasing alpha. Additionally, general aviation aircraft have different approach speeds and phugoid values, both in frequency and damping. For a multitude of performance reasons, general aviation aircraft exhibit a different response to microburst encounters, and appear to be less susceptible to microburst phenomenon.

*Performance Factors Summation*

The interrelatedness of the performance variables is apparent, one affecting the other. A change in airspeed will change the lift force, which may excite the stability, affecting the altitude and airspeed, which will further effect the climb performance and handling qualities, ad infinitum. These variables are dependent not only on the type of aircraft, but also the microburst environment. The value in a static analysis allows one to understand the factors and influences affecting one’s aircraft.

Static analysis, while providing insight into the mechanics of a microburst encounter, cannot completely reveal the performance capabilities of the aircraft (Stengel, 1984, p. 200). To counter this limitation, computer simulations, flight simulations, and even real world microburst encounters have been carried out (e.g. NASA, 2002). These simulations and real world experiences have provided additional insights into performance and optimal escape trajectories.
Microburst Escape Maneuvers

The performance impairing effects of a microburst on an aircraft in flight are substantial, and as witnessed through the accident record, can be catastrophic. To counter the threat of the microburst, an infrastructure of prevention has developed. Inadvertent encounters continue though, as the case of US Air 1016 demonstrates, so that the escape maneuver remains the last line of defense.

“While the most prudent approach is to avoid hazardous meteorological conditions whenever possible, there always will be those borderline cases in which pilots are called upon to weigh hazards against mission objectives. Because the future is uncertain, there will be instances when the pilot presses on even though hindsight will prove that to have been the wrong choice.” (Stengel, 1984, p. 198)

The purpose of the escape maneuver is to provide the performance necessary to fly out of a microburst.

Recognizing the microburst is the first action required in commencing the escape maneuver, the Boeing Company Windshear Task Force (1985) found that in a typical low level wind shear encounter about 5 to 15 seconds were available for recognizing a decaying flight path and resolving the situation (p. 7).

From the cockpit, a microburst is identified by an uncommanded change in the flight parameters. A deterioration of the approach path is reason to initiate a go-around, especially when below 1000 feet AGL (United Air Lines [UAL], 1991, p. A-29). An indication of a possible microburst encounter is probable with one or more of the following deviations occurring:
• Airspeed change of 15 kias
• Vertical speed change of 500 fpm
• Pitch attitude change of 5° to hold flight path
• Glide slope displacement of 1 dot
• Throttle position not correlating with normal position for extended period of time

If any of these conditions are noted on the approach, in a convective environment, an escape procedure should be executed without delay (American Airlines [AA], 1990, p. 3A-25).

*Constant Pitch Guidance Maneuver*

In a proactive measure the training department at United Airlines began an independent wind shear study in 1982 (Ireland & Simmon, 1986, p. 27). Commencing after the accident of Pan Am 759 in New Orleans, this two-year research led to the development of the WSTA (p. 28). Eventually funded by a grant from the FAA, the study lost its independence and developed into a consortium including the Boeing Company, United Airlines, McDonnell Douglas, Lockheed California, Aviation Weather Associates, and Heliwell Incorporated (FAA, 1988, ¶ 3). With the three major jet aircraft manufacturers present, it is not surprising that the guidance across the various aircraft models would be similar.

In the event a wind shear is encountered during an approach the recommended procedure is to simultaneously set maximum thrust and rotate to an initial 15° pitch attitude. The flight path is controlled as necessary with pitch, while the configuration of the aircraft remains unchanged during the recovery (FAA, 1988, p. 48; UAL, 1991, p. A-29; AA, 1990, pp. 3A-25–26).
Thrust

The gradual application or reduction of thrust to counter a change in airspeed may mask an impending wind shear (Boeing Company, 1985, p. 7); therefore, a throttle position deviating from normal parameters is a potential clue of a microburst.

Applying thrust introduces energy into the system and mitigates the degrading effects of wind shear (Visser, 1997, p. 5). Engine overboost is permitted to avoid ground contact, but should be discontinued when flight safety has been assured (FAA, 1988, p. 46; UAL, 1991, p. A-29; AA, 1990, p. 3A-25). The JT8D engine (installed on the DC-9, B-727, and B-737) is capable of providing a 10% increase in thrust when firewalled. Though the N1 speed and exhaust gas temperature (EGT) would exceed operating parameters, it is believed that most engines would survive in excess of 5 minutes (Boeing, 1985, p. 04.20.16A). Boeing warns “[this] should only be considered when all other available actions have been taken and ground contact is imminent” (p. 04.20.16A).

Pitch

With the application of thrust, the aircraft should be simultaneously rotated to a pitch attitude of 15° nose up (FAA, 1988, p. 46). The initial attitude may be bound by the lower value of stick shaker or stall buffet, which should always be the upper limit of pitch attitude. When stick shaker or buffet stops, the attitude should be increased in 2° increments up to 15°, and beyond if the flight path is unacceptable (p. 46).

Wanting to prevent premature arrival at stick shaker, United limited the pitch attitude to 15° in their simulator trials (Melvin, 1986, p. 51). Though a range of recovery attitudes provide good performance, the FAA maintained the 15° limit because it is easily remembered, provides good recovery capability, and is prominently displayed on the
attitude indicator (FAA, 1988, p. 45). The 15° limit is not mandatory, however, as operators using target pitch attitudes may use a pre-calculated value in place of the initial attitude (p. 45). The slow 2° change in pitch attitude, when required, replicates a more optimal technique, designed to avoid arrival at the stall too quickly, and it also diminishes the chances of an over-rotation in pitch (Melvin, 1986, p. 51; Boeing Company, 1985, p. 10).

Flight Path Control

The 15° attitude is only the initial target. If the flight path continues to deteriorate it is recommended to increase the pitch attitude, by 2° increments, until either a satisfactory flight path is attained or intermittent stick shaker is reached (FAA, 1988, p. 46; UAL, 1991, p. A-29; AA, 1990, p. 3A-25). As in normal operations, vertical flight path control is maintained with pitch attitude. It is recommended not to use more pitch than is necessary to control the vertical flight path (AA, 1990, p. 3A-25; UAL, 1991, p. A-29). Though jet transport category aircraft have climb capability, in still air, at intermittent stick shaker, the high pitch attitude results in high drag and a minimal climb rate (Higgins & Patterson, 1979, p. 9). Additionally, if all the airspeed is bled off in the maneuver there will be no reserve to soften the impact with terrain if ground contact becomes inevitable (Webb, 1990, p. 206; NRC, 1983, p. 56).

There are a number of difficulties of flying near stick shaker speed, and pilots have had little training in this area (Webb, 1990, p. 206). Problems occur if the airspeed decay rate is too great and the airplane stalls before a pitch change is possible; this may be brought about through aggressive control manipulation or external factors such as turbulence or shear. The effects of heavy rain are also problematic, causing an increase in
the airplane’s stall speed and leading to the stick shaker speed being underrepresented, with a possible stall occurring before warning is given (NRC, 1983, p. 56). Additional performance concerns of flight near the stall angle of attack are the airspeed and altitude, which decay rapidly in this high drag region of flight. Near the stall angle of attack lateral-directional flying qualities may be unfamiliar if not unacceptable (Stengel, 1984, p. 202). It is therefore advised to delay the onset of stick shaker as long as possible and then only when ground contact appears imminent (Melvin, 1986, p. 51).

The stick shaker is generally calibrated per the stall angle of attack. On the Boeing 737-200 “the stick shaker is actuated at a relatively fixed angle of attack for a specific flap setting” (Boeing, 1985, p. 40.40.02). Flying at the stick shaker is a maneuver that excites the phugoid because the angle of attack is held fairly constant. That there is no change in angle of attack ($\Delta \alpha = 0$) is the major assumption for the reduced-order model. Hence, the phugoid is easily propagated in this flight attitude, leading to the problem previously discussed, mainly an oscillation in airspeed and altitude which may cause the aircraft to crash even with an increasing airspeed (Melvin, 1986, p. 57).

Configuration

Recognizing that a microburst encounter is going to be a very busy event, the advice when escaping an encounter is to maintain configuration (FAA, 1988, p. 47). The FAA has acknowledged that a performance increase may be available with the extension of flaps (1988, p. 47). In normal operations flaps are raised during a go-around or departure, this reversal of procedures may lead to confusion. It is felt the risk of moving the flaps in the wrong direction is greater than the risk of encountering a shear so great that a flap change is needed for recovery (UAL, 1991, p. A-29; AA, 1990, p. 3A-26).
A performance increase occurs after landing gear retraction (FAA, 1988, p. 47). However, as the landing gear is in transit, a performance decrement actually occurs through a rise in drag as the gear approaches the body of the aircraft and the gear doors open and close. Therefore, the increase in performance from gear retraction may be offset by the initial decrease in performance and it is recommended to leave the gear in its original position prior to the encounter.

After the escape procedure has been successfully accomplished it is a requirement, per FAR 91.183(b)(c), to report the encounter to air traffic control (FAA, 2003b). As microbursts tend to intensify after ground contact, communication of the event may prevent a subsequent accident. It is also advisable to land at the nearest suitable airport in point of time if the engines have exceeded their design tolerances (Boeing, 1985, p. 04.20.16a).

The constant pitch guidance maneuver is a straightforward procedure to mitigate the effects of the microburst, it was chosen partly for simplicity and ease of recall (FAA, 1988, p. 45). More complex techniques may make better use of airplane performance, admits the FAA in their publication AC 00-54, *Pilot Windshear Guide* (p. 45). This is born out in a number of independent studies demonstrating optimal and near optimal procedures increasing the altitude of penetrating aircraft (e.g. Dogan & Kabamba, 2000; Hinton, 1988; 1989; Miele, Wang, Tzeng, & Melvin, 1987; Mulgund & Stengel, 1992a).

The advent of digital computers enabled the evaluation of optimal trajectories as interrelated and coupled influences could be accurately modeled. Optimal trajectories seek to minimize the altitude loss in a microburst encounter while keeping the airspeed above stall.
Alternate Guidance Maneuvers

The emphasis of industry, science, and government has been concentrated on microburst detection and avoidance. Escape procedures have not had the benefit of equivalent scrutiny. United's wind shear efforts from 1982 to 1984 may have unintentionally led to this shortfall in research. It was United's feeling that differences of opinion within the industry were impeding development of wind shear training and that a consensus was required for a training package to be developed (Ireland & Simmon, 1986, p. 28). With the endorsement of the major airframe manufacturers, and subsequently the FAA, there has been little incentive to develop alternate procedures. As such, this area of study has become the realm of individuals in university settings, and to a much lesser extent the research arm of NASA (e.g., Hinton 1988; 1989).

Obtaining the theoretical best performance from the aircraft is achieved by optimizing the flight path. Optimization is often characterized, in microburst studies, as minimizing the altitude loss within the constraints of airspeed (Visser, 1996; 1997; Mulgund & Stengel, 1992b; Miele et al., 1987). Optimization requires a global knowledge of the microburst winds; that is the wind components at all points in the aircraft's trajectory must be known in advance (Mulgund & Stengel, 1992b, p. 2). Guidance studies and laws assume only local information (Miele et al., 1987, p. 485). The state of art of microburst detection limits the knowledge of the wind field so that optimization is currently not practical in a real world environment. Guidance laws, developed through optimization techniques, are useful and demonstrate an increase in performance over the constant pitch maneuver in simulated cases (Miele et al., 1987; Visser, 1996; 1997; Mulgund & Stengel, 1992a; 1992b).
The research into microburst escape has concentrated on three main areas: penetration landing laws, lateral escape maneuvers, and longitudinal maneuvers.

Penetration landing laws attempt to maintain an approach profile, and land the aircraft in the microburst winds. This strategy uses varying thrust and pitch. Lateral escape maneuvers use a global knowledge of the microburst and avoid the most severe winds through steering commands in a three dimensional environment. Abort landing trajectories evaluate the performance of the aircraft in the vertical plane, with global, or local knowledge of the wind field being used depending on the study.

Penetration landing makes sense only if the wind shear encounter occurs at lower altitudes (Miele, Wang, & Melvin, 1988, p. 153). At low altitude the aircraft may only have to traverse a section of the microburst, whereas an aborted landing may lead to greater hazard, traversing the whole of the shear region at low airspeed and altitude (p. 154).

Penetration landing guidance uses pitch control to maintain the nominal glide path while thrust control augments the approach by keeping the aircraft from running out of airspeed (Psiaki & Park, 1989, p. 1131). When the control laws are used with global knowledge of the microburst, full thrust is commanded at the headwind section (p. 1132). Though this is an unlikely response if the microburst is not recognized, it does demonstrate the need to apply power as quickly as possible.

There are a number of practical problems with the penetration maneuver; certainly the accident case histories bear out the dangers of trying to land in a microburst wind. If the initial altitude is high enough the abort landing is clearly a safer maneuver (Miele, Wang, & Melvin, 1988, p. 153).
Lateral maneuvers are very desirable as they steer the aircraft away from the most adverse conditions, however, global knowledge of the microburst is not yet available and there is a danger of steering into the core rather than away (Melo & Hansman, 1990, p.1). An incorrect turn towards the microburst core is more hazardous than straight flight; lateral maneuvers are therefore limited to the availability of precise information about the microburst (p. 6). If lateral maneuvering is employed, the optimum bank angle, per computer simulations, is limited to 10° (Melo & Hansman, 1990, p. 3; Visser, 1996).

The lateral escape is especially effective in improving the recovery performance if advance warning is provided (Visser, 1996, p. 115), in which case the most adverse microburst winds can be avoided. As yet, the obstacles include the uncertainty of the core location and possible traffic conflicts with parallel approaches.

Longitudinal maneuvers are less complex than either penetration or lateral maneuvering, and though global knowledge is an aid to any escape procedure, longitudinal maneuvers are not dependent on prediction or forward look sensors. Longitudinal maneuvers constitute a practical reality with current technology. The two basic longitudinal maneuvers are the constant pitch maneuver, previously discussed, and the variable pitch maneuver, which seeks to optimize the flight path.

The basic philosophy of the variable pitch guidance maneuver is the minimization of the time spent in the shear environment and thereby the reduction of the effects of wind shear on aircraft performance. Minimizing the time in the shear is accomplished by sacrificing altitude for speed (Bray, 1986, p. 13). This differs from the constant pitch guidance maneuver philosophy of keeping the airplane flying as long as possible, by trading speed for altitude, in hope of exiting the shear (FAA, 1988, p. 45).
Variable Pitch Guidance Maneuver

Maximizing the terrain clearance is the objective in optimizing the go-around procedure (Visser, 1996, p. 110). The type of problem is known as a Chebyshev or minimax equation; this term being derived from minimizing the maximum value of altitude loss (Visser, 1996, p. 108; Miele et al., 1987, p. 483).

Though differing techniques have developed to minimize altitude loss, the procedure of directing the aircraft towards a target altitude constitutes a promising longitudinal guidance strategy (Visser, 1997, p. 1). The maneuver is robust with respect to uncertainty in microburst strength, with little sacrifice in altitude (p. 11). This guidance easily outperforms constant pitch guidance in terms of both altitude and energy management (p. 7), while climb rate guidance was found to be minimally useful (p. 6).

The target altitude maneuver incorporates three phases; a descending flight phase to a target altitude, the maintenance of horizontal flight, and ascending flight after the aircraft has passed through the shear region (Miele et al., 1987, p. 483). In providing uniformity with the constant pitch guidance strategy this technique is referred to herein as the variable pitch guidance strategy, as pitch attitude continually changes throughout the maneuver.

Similar to the constant pitch maneuver, when the wind shear is acknowledged, the thrust setting is commanded to a maximum value (Miele et al., 1987, p. 485) introducing energy into the system. Thereafter, the only control variable available to the pilot is angle of attack, which is manipulated indirectly by pitch attitude. Controlling pitch, the pilot is able to alternately trade altitude for airspeed, or potential for kinetic energy.
Descent Phase

The Chebyshev solutions of optimal control trade altitude for airspeed in the initial phase of the microburst (Visser, 1996, p. 117; Visser, 1997, p. 4). This may appear counterintuitive, however, descending to a low altitude is a beneficial procedure in terms of energy management (Visser, 1997, p. 5). Optimized escape procedures initially decrease the angle of attack at the outset of a microburst (Dogan & Kabamba, 2000; Melvin, 1986; Bray, 1986). The constant pitch technique fails to exploit the energy gain when the aircraft is in the region of increasing headwind.

The initial altitude represents an energy component that can be converted to speed with which to extend endurance in the shear (Bray, 1986, p. 16). The aircraft is guided to a descent in the computer simulations through a pitch controller, as in Dogan and Kabamba (2000) or by flight path or angle of attack as in Miele et al. (1987). Optimally these controllers take into account the microburst winds with pitch attitude being changed accordingly. The rate of descent is very high for the dive portion of the flight, averaging 2300 fpm. The descending flight path is flown entirely in the shear portion of the trajectory (Miele et al., 1987, p. 493), thus maximizing the airspeed and minimizing the time spent in the shear. The aircraft is leveled out at a predetermined optimal altitude and attempts to maintain this altitude through the remaining shear.

Level Phase

The horizontal branch is flown partly in the shear and partly in the after shear portion of the trajectory (Miele et al., 1987, p. 493). After the dive phase, the aircraft is at a relatively high airspeed and uses this kinetic energy to maintain the target altitude. As the airspeed decays, the pitch is adjusted to maintain altitude until the shear boundary,
which is ideally at the point of minimum airspeed. In the event that stall $\alpha$ is reached prior to the shear boundary, the altitude is allowed to decay. In optimized studies this does not happen, as the extent of the microburst is known and altitude and speed are judiciously controlled.

The less time spent at the stall angle of attack, the better the performance (Bray, 1986, p. 18). Flight at maximum $\alpha$ is not efficient, and “it is very bad to use up available airspeed too soon” (Melvin, 1986, p. 57).

The optimal altitude is chosen through the solution of the Chebyshev equation. Miele et al. (1987) reformulated this as a Bolza type integral, and using the velocity of a strong, but realistic shear of 140 ft per second, simplified the equation for the target altitude, $h_{\text{mm}}$, leading to the approximate solution (p. 493):

$$h_{\text{mm}} = 0.4 h_0 + 6 \Delta W_x - 840$$  \hspace{1cm} (5)

Where $h_0$ is the initial altitude of the encounter, and $\Delta W_x$ is the change in the horizontal component of wind velocity, or wind shear. Units are in feet, so that a shear on the order of 140 feet per second at an altitude of 1000 feet will yield a target altitude of 400 feet. From Equation 5 it is apparent that the target altitude is a function of the microburst severity and the altitude of the encounter. Greater microburst intensities lead to higher target altitudes. Higher initial altitude also leads to higher target altitude, and it provides greater opportunity to convert potential energy into kinetic energy; hence, identifying the microburst at the earliest time remains beneficial.
Using the assumption of one of the strongest shears ever recorded, the Andrew's microburst being the strongest to date, a simplified target altitude equation emerges. By keeping the target altitude slightly higher than the optimal altitude, Miele et al. (1987) introduced a simplified guidance strategy. Assuming the worst-case scenario, the aircraft is commanded to the target altitude (p. 498):

$$h_{\text{min}} = 0.4 \, h_0 + 100$$

(6)

With Equation 6, neither global nor even partial knowledge of the shear is required. This near optimal guidance works well for moderate to severe microbursts, but is overly conservative for weaker wind shears.

The simplified case of using one of the most intense wind shears provides a conservative value for the majority of encounters. The preponderance of microburst shears are between 37 fps and 43 fps (Fujita, 1985, p. 63), the frequency of a greater wind decreasing exponentially as the wind speed increases. The relationship between the probability of an encounter and the wind speed for the JAWS data indicate (p. 64):

$$\log P = 0.216 - 0.0902 \, W$$

(7)

Where $P$ is the probability, and $W$ is the wind shear in meters per second. Equation 7 suggests that a velocity of 140 fps ($\approx 46 \, \text{m/s}$) has a probability of $0.000116627$. This low value, of 1 occurring per 8,574 microbursts, translates into a robust altitude floor for the variable pitch guidance strategy.
In an open-loop Chebyshev solution, the target altitude is such that angle of attack just reaches its limit as the high shear region is exited (Visser, 1997, p. 2). When the aircraft regains sufficient energy it is allowed to climb on a predetermined nominal flight path.

*Climb Phase*

Once the aircraft has transitioned through the shear it is desirable to gain altitude. Miele et al. (1987) use a flight path corresponding to the steepest climb condition in quasi-steady flight for their modeled aircraft, a B-727-200 advanced, giving a path inclination of $7.431^\circ$ (p. 481). Dogan and Kabamba (2000) use a pitch attitude of $15^\circ$ once the energy drain has abated (p. 421). Visser (1997) considers a climb from target altitude in terms of an aircraft’s instantaneous available climb performance (p. 6). As the danger of the microburst is past, the technique for climb-out resides with the discretion of the operator.

*Evaluation*

In the studies examined, no dramatic altitude excursions occur during an escape maneuver based on altitude guidance. Visser (1997) maintains “large altitude excursions tend to raise the anxiety levels experienced by pilots” (p. 9). Additional benefits of the variable pitch maneuver include the reduction of the probability of the phugoid mode, controls less likely to saturate, and improved control of the flight path.

Bray (1986) found that the constant altitude, variable pitch attitude demonstrates improved performance compared with constant pitch (p. 18), and that superior performance in low-level wind shear involves controlling the flight path of the aircraft to minimum altitudes (p. 20). This conclusion was supported recently in Dogan and
Kabamba (2000); “even if pitch guidance is used with the intention of immediately increasing altitude, the minimum altitude reached during the escape maneuver is very likely to be lower than it would be if dive or altitude guidance [variable pitch] were used” (p. 425).

**Takeoff Case**

The benefit of the variable pitch maneuver is also apparent in the examination of the takeoff phase. Similar to the approach to landing case, the takeoff case commands a constant altitude through the wind shear with a climb-out when the shear’s boundary has been traversed (Bray, 1986; Hinton, 1988; Melvin, 1986). Unlike the approach case, the altitude to trade for an increase in airspeed may not be present.

Optimal trajectories for the takeoff case are characterized by an initial decrease in angle of attack (Melvin, 1986, p. 53) with a push-over to a linear flight path (Bray, 1986, p. 18). The linear, or horizontal flight path, is controlled with pitch, and as airspeed decays a gradual increase in angle of attack occurs, similar to flaring, until the shear ends (Melvin, 1986, pp. 53–54). These flight paths are superior in survivability when compared to the constant pitch maneuver. As demonstrated by Bray (1986) in a severe microburst simulation, the constant pitch maneuver was not survivable when the variable pitch recovered at 60 feet (p. 18). Hinton (1988) produced similar results, with a constant pitch maneuver impacting the terrain, while the enhanced flight-path-angle strategy (variable pitch) lost only 4 feet during the microburst encounter (p. 8).

If the aircraft is above the minimum altitude, a dive should be initiated. The minimum altitude used for the studies varied from 200 feet (Bray, 1986, p. 17), to 100 feet (Hinton, 1988, p. 4). Diving the aircraft and then maintaining a level altitude
minimizes the time in the shear and the time spent at stick shaker speed. The activation of stick shaker should be postponed because the airplane phugoid mode is excited in this realm and a descent cannot be prevented (Hinton, 1988, p. 10).

Though the minimal altitude is different in the takeoff case, the flight phases and the philosophy of exiting the shear in the minimum amount of time are similar to the abort landing case. Each maneuver ideally contains a descent phase, which is completely in the shear, a level flight phase, which is partly in the shear and partly beyond the boundary, and a climb phase, which occurs outside of the microburst. Since thrust is at a maximum the only control available to effect a flight path change is pitch attitude. From the control perspective, there is no difference in the variable pitch guidance strategy between the abort landing case and the takeoff case.

Comparison of Guidance Strategies

As optimal studies take into account the whole of the microburst, comparing them to a maneuver which does not, provides little insight. Since optimization in a real world environment is not yet realized, the value resides in the development of simplified guidance, which approximates the optimal trajectory (Miele, Wang, & Melvin, 1988, p. 154). The more functional comparison of safety is between the constant pitch guidance maneuver and the variable pitch guidance maneuver, which does not take global knowledge into consideration.

Qualitative Assessment

The constant pitch maneuver is an acknowledged compromise between other maneuvers (FAA, 1988, p. 45). The initial pitch to 15° does not exploit the energy possibilities of the aircraft and may lead to premature arrival at the stick shaker. Flight at
stick shaker speed is inefficient and ALPA’s Airworthiness and Performance Committee opposes early arrival at stick shaker speed (Melvin, 1986, p. 51). “Deliberately flying to the stick shaker angle of attack when ground impact is not imminent is extremely dangerous” (p. 58). Melvin additionally reports that “many pilots have been encouraged to rapidly increase the angle of attack to its limiting value in hopes of magically escaping a wind shear. In reality it reduces their chances for escape” (p. 54).

The variable pitch guidance maneuver is optimized for one wind shear intensity; below this value it will be too conservative and allow a lower altitude than the constant pitch maneuver, while greater intensities will cause a pitch-up to the stick shaker prior to escaping from the microburst. Greater shears than the optimized value of 140 fps ($\approx 46$ m/s) have been recorded; the Andrew’s microburst generated wind speeds greater than 190 fps ($\approx 62$ m/s) (Fujita, 1983b, p. 6), and the US Air 1016 microburst was calculated to have a maximum wind velocity change of 145 fps ($\approx 47.6$ m/s) along the north-south axis (NTSB, 1995, p. 48). From Equation 7 it can be inferred that though these strong microbursts are rather anomalous, they are present and constitute a great hazard to aviation.

A limiting assumption of the variable pitch guidance maneuver is that all low-level wind shear is a microburst. A sea-breeze front, for example, may prompt the aircraft to descend and accelerate into relatively still air at a low altitude. Though this is not a great problem, it may increase the damage of a bird strike or violate noise abatement procedures.
Quantitative Assessment

In Miele et al. (1987), the survival capability of various guidance strategies, in terms of efficiency, was computed using the optimal trajectory as the criterion. The guidance trajectories all used the variable pitch maneuver, though target altitude and pitch were controlled differently depending on the extent of the wind shear knowledge—global, local, or none. With the optimal trajectory set at 100% efficiency, the guidance trajectories with some local knowledge of the wind shear were 90% to 99% effective, while the escape maneuver without local knowledge was 82% to 90% effective, and the constant pitch maneuver was 73% to 79% effective (p. 500). A maximum angle of attack maneuver was also evaluated, which produced an efficiency of 42% to 51% (p. 500), demonstrating that premature arrival at the stick shaker is not an efficient strategy (e.g. Melvin, 1986).

In evaluating three different escape strategies Dogan and Kabamba (2000) confirmed trading altitude for airspeed in the initial phase of the escape maneuver reduced the risk of crashing (p. 425). Their version of the variable pitch maneuver, which they termed h-guidance, was similar in concept to the maneuver described in Miele et al. (1987), the chief differences being the dive controller and the climb phase. In a computer simulation, the constant pitch guidance cleared the ground by 102 ft (33.45 m) in a moderate to severe microburst, while the variable pitch maneuver generated a minimum altitude greater than 183 feet (60 m) (p. 422). When the microburst intensity was increased by 25% the constant pitch guidance caused a crash, while the variable pitch guidance cleared the ground by more than 90 ft (30 m) (p. 422).
It was found that the variable pitch guidance was robust against changes in microburst strength, when the command altitude (target altitude) was low (Dogan & Kabamba, 2000, p. 422). The probability of a crash was computed using the Monte Carlo method with variable pitch having less probability of a crash than other maneuvers when command altitudes were between 30 and 75 ft (10m–25m) (p.424). The probability of a crash, with confidence parameter δ at .05, is about .25 with constant pitch guidance and as low as .12 with variable pitch guidance (p. 423). The variable pitch guidance maneuver provides greater authority over the minimum altitude reached during the escape maneuver than do other strategies (p. 425).

The special case of propeller driven aircraft was investigated by Mulgund and Stengel (1992a), and an increase in performance was demonstrated with a variable pitch maneuver. The minimum altitude for the variable pitch maneuver was 52 feet higher than the altitude generated by the constant pitch maneuver (p. 7), which in this study was 17° rather than 15°, as it was found to provide better performance (pp. 5–6). Though the minimum airspeed of the variable pitch maneuver was lower by 2 knots, the total energy was higher by 5.7% and the maximum angle of attack was lower by 1.5° (p. 7). The performance increase for different aircraft types demonstrates the robustness and value of the variable pitch strategy.

The same authors, Mulgund and Stengel, examined a jet transport aircraft’s performance through a microburst in a later work (1992b). Again they found that an optimal maneuver of varying pitch attitude provided a higher minimum altitude than the constant pitch strategy. For the Boeing 737-100, the minimum altitude was 400 ft for the variable pitch maneuver and 350 ft for a 15° constant pitch maneuver (p. 7).
When lateral escape was considered, the variable pitch maneuver still outperformed the constant pitch maneuver in altitude by about 80 ft (25m) (Visser, 1997, p. 8). The specific energy of the variable pitch maneuver also was greater than the constant pitch maneuver during the microburst encounter in which the core was not penetrated (p. 8). Visser’s study (1997) demonstrates that the variable pitch maneuver is superior in conserving altitude and energy whether the microburst core is penetrated or avoided.

The abort landing case is demonstrative for computer simulated microburst encounters—the variable pitch maneuver out performs the constant pitch maneuver in these scenarios. The takeoff case is similar. Hinton (1988) compared five recovery strategies and found the variable pitch strategy (his enhanced flight-path-angle strategy) commanding the best overall performance (p. 10). In a strong shear, of 84 knots, the variable pitch maneuver cleared the ground by 52 feet, while the constant pitch strategy caused an impact with the ground (p. 25). In weaker shears, the variable pitch was not as good as some other strategies, but it always out performed the constant pitch maneuver (p. 20; 25).

**Simulator Assessment**

To validate his earlier findings, Hinton (1989) conducted a flight simulator trial of the strategies examined, using NASA’s Visual Motion Simulator, replicating a Boeing 737-100 aircraft (p. 6). The performance of the piloted simulation was generally less than that of the batch computer simulation for any given recovery strategy. The constant pitch strategy was 36 to 57 ft less in the real-time simulation than that of the computer simulation (p. 8). The variable pitch strategy was the most irregular, being 100 to 104 ft
in the computer simulation and varying in the flight simulation from 114 ft to 29 ft (p. 8).
The poor correlation was attributed to errors in pilot tracking, variations in aircraft and microburst state parameters, and a slightly lower performance of the simulator computer (p. 9).

The average minimum altitudes during the flight simulation were 79.8 ft for the constant pitch strategy, 82.2 ft for an acceleration strategy, and 86.9 ft for the variable pitch strategy (Hinton, 1989, p. 7). These takeoff case scenarios were not statistically different, as determined by an analysis of variance at a level of significance of .05 (p. 29). A statistically significant difference in minimum altitude was found between pilots at p ≤ .01 (p. 29), and also in the root mean square (RMS) of the pitch error between pilots at the same level (p. 31).

With a 10% increase in the wind shear velocity, a significant difference in escape strategies was present at p ≤ .01 (Hinton, 1989, p. 30). In this analysis, the constant pitch maneuver mean altitude was 4 ft with a standard deviation of 9.3 ft. The acceleration guidance altitude was 0 ft with a standard deviation of 0 ft, while the variable pitch maneuver performed the best, with a mean altitude of 29.2 ft and a standard deviation of 36.2 ft (p. 28).

Flight simulation is an important element in microburst escape studies. The value of simulators is that they allow pilots to experience dangerous wind shears in a safe environment, ideally with the knowledge and skills transferring to a real world environment. Simulated microburst encounters can help crews coordinate their escape efforts in critical situations (Treviño & Laituri, 1989, p. 6). As a research tool, simulators provide a unique insight by introducing the human element, which often points to the
limits of a system. Escape maneuvers, which appear promising in a computer simulation, might be of only marginal improvement when evaluated in a flight simulator. Simulators are unique in evaluating conditions of flight and their utilization for such endeavors is appropriate.

In Hinton’s preliminary study (1988) he recommended the approach to landing case be considered (p. 10). The mathematical models and computer simulations suggest that a more favorable strategy than the constant pitch maneuver exists for escaping from a microburst encounter. “Static analyses are not necessarily conservative, nor do they reveal the full potential for successful wind-shear penetration” (Stengel, 1984, p. 200). A simulation of the variable pitch guidance strategy may therefore be beneficial. “Enough proposing of, analysis of, and simulation of microburst encounter guidance strategies has been carried out. The time has come to test these strategies in a real aircraft or, at least, in a manned simulator” (Psiaki & Park, 1989, p. 1138).

Statement of the Hypothesis

The variable pitch guidance maneuver through a microburst exhibits a greater factor of safety than the constant pitch guidance maneuver through the same microburst as examined in a flight simulator of a large jet transport category aircraft. In this context, safety is defined as a maximization of the minimum altitude above ground experienced by the airplane during the microburst recovery.
CHAPTER III
RESEARCH METHODOLOGY

Evaluating whether the variable pitch guidance maneuver exhibits a greater factor of safety than the constant pitch guidance maneuver was determined, in this study, through statistical significance of the difference in recovery altitude between these two escape maneuvers. Qualified pilots flying an FAA approved airplane simulator performed the maneuvers. The test runs involved a simulated flight along an ILS approach path through a microburst wind shear. Recovery altitude was recorded by the simulator computer and was the primary measure of safety. The data were evaluated by an analysis of variance (ANOVA) technique to determine the difference in the safety of the maneuver.

Simulation was the key method in this study, as the aerodynamic factors that are involved in microburst encounters are confounding and numerous; while the safety aspects in using a simulator are obvious.

Design

This comparative study examined the difference in recovery altitude between the constant pitch maneuver and the variable pitch maneuver. Recovery altitude was defined as the lowest altitude, above ground level, recorded by the simulator computer, of the aircraft during the microburst escape maneuver. The escape maneuver was that flight phase from initiation at 800 ft AGL until the aircraft’s airspeed stabilized beyond $V_{\text{REF}} + 10$ out of the microburst environment, or until the completion of data recording for that run, whichever occurred first. In practice, the escape maneuvers were completed prior to the cessation of data collection by the computer.
The planned number of experimental trials was based on findings in Hinton’s study (1989) of microburst penetration in the takeoff phase. Hinton found the standard deviation of the pitch-hold strategy to be 58.4 feet, while the flight-path angle strategy (variable pitch maneuver) produced a standard deviation of 58.3 feet (p. 28). Assuming the difference between the means of the maneuvers is significant at one standard deviation, and specifying an alpha value of .05 and a beta value of .20, the group sample size is estimated, by the power of F Test, to be 17 runs per maneuver (Neter, Wasserman, & Kutner, 1990, p. 1151). Any difference larger than one standard deviation would require fewer trials. The estimation necessitates the sample size be equal across groups.

With 4 pilots initially scheduled to participate, it was desired to maintain an even group size, and 16 trials per maneuver for a total of 32 trial runs were planned for the experiment. One pilot subject dismissed himself prior to data collection, and so 15 runs were substituted for each maneuver, 5 per individual to maintain symmetry in the cell frequency. With 15 trials per maneuver, the minimum difference between means to generate a statistically significant value at the .05 level increased by less than 15 feet (Neter, Wasserman, & Kutner, 1990, p. 1151). This compromise was deemed acceptable for the experiment; though more trial runs were desirable they were not thought attainable in the scheduled time.

The approaches flown for this study amounted to 42. Of these, 4 were flights through the microburst wind shear terminating with a landing on the runway, 15 were constant pitch maneuvers through the microburst wind shear, 3 were training maneuvers, and the remaining 20 were variable pitch maneuvers through the same microburst as the constant pitch and landing maneuvers.
Prior to performing the escape maneuvers, the individual pilot subject flew an approach through the wind shear to a landing. This enabled the subjects to familiarize themselves with the effect of the microburst on the aircraft performance and response. Each subject flew one of these approaches prior to the experimental procedures for that day, with the result that the pilot who flew two days also performed two landings in the shear. The other maneuvers that were not statistically evaluated were the training maneuvers. The practice maneuvers were supervised, but no data recording occurred.

The constant pitch maneuver was performed a total of 15 times, though symmetry was not attainable due to time constraints. The difference was 1 trial per pilot subject. The variable pitch maneuver was performed a total of 20 times with the breakdown of 5, 6, and 9 trials per subject. Statistical procedures accounted for the discrepancies in cell frequency, which were a result of time and scheduling parameters.

Generally, the smaller the difference to be determined, the larger the sample size required. The difference in means between the two maneuvers studied was assumed to be similar to the study conducted by Hinton (1989). In actuality, the difference in means was much greater, so the sample size, though less than desired, was greater than required. In the context of the type and scope of the experiment, the statistics generated are robust to evaluations of sample size.

The statistics employed to evaluate the data were selected to reduce the error inherent in unequal cell frequencies. The difference in recovery altitude between maneuvers was determined through an ANOVA with significance predefined at the .05 level.
The escape maneuvers and pilots were the independent variables; trajectories from the escape maneuver produced specific values of the dependent variable: altitude. An ancillary dependent variable, airspeed, was also recorded for regression analysis with altitude. The lower limit of altitude was considered ground contact, while the upper limit was not confined. The lower limit of airspeed was the stall speed for the particular aircraft configuration, and no upper limit was imposed. In all cases the simulator controlled the lower limit of altitude, and generated a stall for the lower limit of airspeed. It appears that sustained ground contact, that is, the lower limit of altitude, did not occur in the maneuver trials.

Internal validity was controlled using the same flight simulator with the same wind data as each previous run. Pilot subjects were also compared within the group for each maneuver type to determine significant difference between individuals as measured by recovery altitude.

External validity was enhanced with the use of an independently certified flight simulator and a realistic microburst model derived from the analysis of the Delta 191 microburst accident.

Reliability was evaluated through the examination of the data. The variance of recovery altitude for each pilot subject was compared, through a test of significance, within the group. No significant difference between pilot subjects in recovery altitude strengthens the assumption that the variance in the data was due to the escape maneuver and not the individual. The demographics of the pilot group increases the reliability, as each pilot subject had different training and experience levels, yet performed similarly in the maneuvers; indicating that the data were not dependent on time nor place.
Participants

Airline transport pilots, type rated on equipment, and with operational airline experience, performed the maneuvers from the left hand seat. Support pilots occupied the right hand seat and performed PNF duties. Support pilots held the same qualifications as the left seat participant for the type aircraft used. Crew coordination was observed to ensure the PF received the necessary assistance.

The three pilot subjects were drawn from qualified instructors, employed by Flight Training International, who were available during the slotted simulator times. They were paid their normal contractual rate for the duration of the flight, whether acting as PF or PNF. In the interest of confidentiality the pilots are represented by number, identifying characteristics have been removed from the simulator plots.

The simulator engineering manager for simulator 737 # 4 at United Airlines set the required simulator parameters, repositioned the flight, initiated the computer subroutines, monitored systems operations, and ensured no mechanical interruptions occurred during data collection. After each approach, the aircraft was repositioned and configured for the next maneuver.

Experimental Device

The use of simulators to explore aircraft performance in wind shear has been well established by internationally recognized institutions. The NTSB used flight simulators in their investigations of various microburst related accidents to examine flight conditions and appropriate corrective action (e.g. NTSB, 1976, p.18; NTSB, 1977, p. 15). The Royal Aeronautical Society (1995) contends “the fidelity of windshear [sic] modelling [sic] has developed significantly in the last few years such that simulators are very effective tools
for training flight crews in the techniques necessary to combat these phenomena” (¶ 2H.2). In addition, the FAA mandates flight simulator training of wind shear encounters under part 121.409 for air carriers with turbine-powered airplanes (FAA, 2003b). With endorsements from the NTSB, the Royal Aeronautical Society, and the FAA, it is assumed that a simulator is the appropriate device for exploring aircraft performance in a microburst environment.

A level C airplane simulator housed at United Airlines Training Facility (TK) in Denver, Colorado was used for this investigation. Replicating a Boeing 737-291 with JT8D-17 engines, simulator 737 # 4 was specifically qualified for wind shear training by the National Simulator Program Manager (NSPM). The simulator was re-certified 15 days prior to data collection.

The simulating platform, an electrically actuated, hydraulically controlled six-degree-of-freedom system, was engaged during all flights. The simulator was fully functioning with no outstanding corrective maintenance items occurring during the maneuver trials or practice periods.

The FAA classifies the aircraft chosen, a Boeing 737-200, as a large jet transport category aircraft. This model, powered by the Pratt and Whitney JT8D-17 turbofan engine, produces 32,000 foot-pounds of thrust at sea level. The maximum take off weight is 117,000 pounds and in high-density configuration accommodates up to 133 passengers. The wing loading is 119.38 pounds per square inch at take off, and the thrust to weight ratio is 0.27. The aircraft is a typical twin-engine short-range airliner with conventional handling characteristics. Figure 6 illustrates the dimensions and three view drawing of the Boeing 737-200.
Flight instrumentation on the 737-200 is primarily electromechanical. To enhance situational awareness of the flight crew, an Allied Signal Mark 5 Enhanced Ground Proximity Warning System (EGPWS) has been incorporated into the avionics. This computer-based system with geographical database warns of controlled flight into terrain (CFIT) and low-level wind shear conditions. The reactive wind shear system includes both aural, and visual warnings of a performance-decreasing shear. Activation of the warning occurs when the computer senses that a difference between the aerodynamic acceleration and the inertial acceleration has exceeded a threshold value.

Reactive systems place the aircraft within the microburst before a warning is issued to the flight crew. In this study, the warning occurred slightly after the PF initiated the microburst recovery, and well after the effects of the microburst were apparent to a well-trained crew.

To meet the requirement of wind shear and microburst training, United Airlines has developed models representative of known accident scenarios. These wind shear models “must be supported or properly referenced in the ATG [Approval Test Guide]” (FAA, 1991, Appendix 1, p. 6).

One of the most investigated microbursts in aviation history occurred on August 2, 1985. Colloquially this has become the Delta microburst, in reference to the accompanying accident, Delta 191. The winds derived from analysis were representative of a severe microburst as defined by the F factor. The analysis of the accident (Fujita, 1986) indicates a 27-knot headwind changed to a 40-knot tailwind in about one mile, and the maximum downdraft was about 2880 feet per minute (28.4 knots). The aircraft transitioned the downburst and then entered a roll vortex. This changed the vertical
component of wind to include both up and down drafts. A crosswind changing direction and intensity further affected the flight.

It was calculated that the center of the parent microburst, which spawned these winds, was located 1000 feet to the left hand side of the aircraft, and 12,000 feet before the runway threshold (NTSB, 1986, p. 59). The outflow from the thunderstorm was about 11,000 feet (3.4 km) in horizontal diameter and was assumed symmetrical. The NTSB (1986) concluded that based on the outflow diameter, the winds met the criteria of a microburst (p.59). The L-1011 passed close to the center of the microburst, and was in the outflow for only 38 seconds before crashing.

The Delta microburst is modeled for use in the simulators at United Airlines per the ATG and is labeled UAL–7, severe on approach. Table 3 represents the computer wind plots for UAL–7, the microburst used in this research study. The microburst is initialized when the aircraft descends through 1,200 feet AGL, and the wind effects continue for 21,000 feet horizontally thereafter. The wind, as modeled, is independent of altitude; each approach will experience the same wind, regardless of vertical displacement. Values between datum points are derived by linear interpolation.

Only the UAL–7 severe on approach microburst model was used in this experiment, as was only one simulator, 737 # 4, thus providing internal consistency in the experiment.

In Table 3, a negative value for headwind indicates a tailwind, a negative value for vertical wind corresponds to a downdraft, and a negative crosswind value is indicative of a wind from the left, while a positive value is from the right. Headwind and crosswind are in knots, while vertical wind is in feet per minute.
Table 3

*United Airlines Seventh Shear: Wind Profile*

<table>
<thead>
<tr>
<th>Distance (feet)</th>
<th>Headwind (knots)</th>
<th>Vertical wind (feet per minute)</th>
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<td>0</td>
</tr>
<tr>
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*Note.* Distance is in feet beyond the trigger point of the microburst.
Instruments

The test instruments included two separate maneuvers: the constant pitch maneuver and the variable pitch maneuver. The constant pitch maneuver represents the current authorized procedure, while the variable pitch maneuver has shown promise in computer simulations (see Bray, 1986; Dogan & Kabamba, 2000; Hinton, 1988, 1989; Melvin, 1986; Miele, et al., 1987; Mulgund & Stengel, 1992a, 1992b; Psiaki & Stengel, 1988; Visser, 1997).

The constant pitch maneuver, published by the FAA (1988) in Advisory Circular 00-54, *Pilot Windshear Guide*, delineates the approval of the maneuver for specific aircraft. Boeing’s model 737 is in this list of approved aircraft (p. ii). The constant pitch maneuver dictates the thrust being set to go-around EPR, the pitch attitude positioned to 15° at a rate of 3°/second, while respecting stick shaker, and configuration maintained. If the stick shaker does not activate and the aircraft is descending, the pitch attitude is increased in 2° increments until either the descent is arrested or intermittent stick shaker activation. If at 15° pitch attitude the stick shaker is operating, the pitch is decreased until intermittent activation. Intermittent stick shaker activation is always considered the upper limit of pitch. To maintain consistency in the data, go-around thrust was set at 2.00 EPR.

The variable pitch escape maneuver, described by Dogan and Kabamba (2000) and Miele et al. (1987), was adapted for this study. Figure 7 is a graphical representation of the variable pitch maneuver as briefed to the flight crews. Optimization was not considered a factor, as it remains unattainable in the real world environment. A near optimization of a microburst escape maneuver occurs with an initial decrease in pitch to a target altitude, which is maintained until energy is available for initiating a climb.
Variable Pitch Escape Maneuver

1 Dive Phase
- Microburst recognized
- Thrust set to maximum
- Pitch attitude decreased to 0°
- ROD 2,000–2,500 fpm

2. Level Phase
- Altitude Maintained
- Thrust Maintained
- Respect stick shaker

3. Climb Phase
- Airspeed $V_{REF} + 10$
- Microburst end
- Normal climbout

The dive flight path angle used by Dogan and Kabamba (2000) was employed for this study. This differed somewhat from the optimized dive presented in Miele et al. (1987), which was dependent on a feedback loop. Maintaining an optimized dive would require reprogramming the flight director, and was deemed out of scope for this research. The simplified dive guidance was used instead. At the first indication of a microburst, the pitch angle ($\theta$) was decreased to $0^\circ$, generating a flight path angle ($\gamma$) of about $-7^\circ$. The pitch attitude change was accomplished at a rate of $3^\circ$/second. The $0^\circ$ pitch attitude was maintained until transition to the target altitude.

The target altitude is a function of the initial altitude (Equation 6), being 40% of the initial altitude rounded up 100 feet and bound by the lower limit of 200 feet above ground level. The initial altitude was set at 800 feet AGL and was only several seconds prior to the point corresponding to wind shear annunciation by the EGPWS, Mark V. For ease in flight technique, the target altitude was rounded to the nearest 100-foot level. The target altitude used was thus 400 feet AGL, not 420 feet as computed through Equation 6. Target altitude was maintained through pitch control. Similar to the constant pitch maneuver, the upper limit of pitch was the activation of intermittent stick-shaker. The flight path trajectory changed to the climb phase as the airspeed stabilized past $V_{REF} + 10$, with the aircraft out of the microburst environment.

The climb phase was left to the discretion of the PF; some chose to fly at high speed and low level while others performed high-speed pitch up maneuvers. No data were analyzed in this phase, as the microburst effects were no longer present and the altitude was not at a minimum.
The maneuver was considered complete 100 seconds after initially passing through 1,400 feet AGL. This was a limit imposed by the test equipment, in practice, however, it did allow enough time for all escape trials to exit the microburst wind shear with the aircraft in a stabilized climb for all test maneuvers. The recording window opened when the aircraft initially descended through 1,400 feet AGL and continued thereafter for 100 seconds, after which time the simulator froze in data and motion output; the simulator was then reset to the initial conditions for the next trial.

Data

The subject of examination was the safety, in terms of altitude, of the variable pitch escape guidance trajectory. Comparison of the safety of the individual escape maneuvers was achieved by noting the minimum altitude of each maneuver while ensuring ancillary flight parameters remained within limits.

Data are reported in the form of English Standard Units. Altitude is measured from the center of gravity (CG) location of the airframe and represented in feet and decimals thereof. Airspeed is in knots indicated, and thrust is presented as EPR.

Real time data recorded by the simulator system computer were attained. A subroutine was written to capture the altitude data at a rate of 5Hz during the recording window of 100 seconds. This program was then tested and operated by the simulator engineer during the experiment trials. Simulator 737 # 4 is run from a VAX computer using a VMS language. Graphical data output to the printer included height above ground, indicated airspeed, average EPR, stick force in pounds, body attitude in degrees, and angle of attack in degrees (see Appendix A through C).
To document that a minimum set of trials in each maneuver were complete before proceeding to the next phase, a paper form was filled out (Figure 6) for each pilot flying. Simulator, aircraft configuration and performance, along with environmental and approach parameters were noted to confirm consistency in settings for each pilot subject. A running tally was kept of each trial phase and coordinated with the simulator plots, graphical and numeric, to ensure correct record keeping.

The simulators at UAL TK are equipped with video cameras installed for contract crews to use if part of their training curriculum. Simulator training is not currently videotaped at UAL, per agreement with the pilot’s union. As this was an independent study, the cameras were run to facilitate and backup record keeping. After data reduction, any and all individual or identifying characteristics were removed from the data sets.

Procedures

The participating pilots were briefed on the maneuvers to be performed, the microburst, and the data collection devices. They were also accordingly debriefed and informed of relevant findings at the conclusion of the study.

The simulator was set for a landing gross weight of 90,000 pounds and a representative CG of 25% mean aerodynamic chord. The aircraft was in landing configuration with gear extended and flaps set at 15 for all maneuvers. A positioned on the extended centerline, 9nm from the runway threshold above 2000 ft AGL, served as the initiation point. This position closely corresponds to the international recommended practice in validating simulators for wind shear training (ref: Royal Aeronautical Society, 1996, p. 101) and is similar to the FAA Piloted Flight Simulator Study of Low-level Wind Shear (Gartner, 1977, p. 26).
**MET Study – Simulator Data**

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<td>TVPM</td>
<td>VPM</td>
</tr>
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</table>

| Notes             |       |       |       |

*Figure 8. Researcher’s data collection form.*
The flap setting was chosen to provide ease of operation and good maneuverability throughout the speed range anticipated. At flap 15, the flaps extend mainly aft and only slightly down, increasing drag very little (Boeing, 1985, p. 04.60.02). Flap 15 is the setting used in a go-around maneuver until the aircraft accelerates to flap speed schedule. In practice, the flaps remained at 15 and a flap overspeed condition was not penalized. The airspeed never exceeded 10% of the upper limit of flap speed.

Reference airspeed for this configuration and weight was computed to be 132 kias. Approaches are traditionally flown at $V_{REF} + 5$ knots, and the target approach speed was set at 137 kias for every trial run. Each approach was hand flown, and it was the discretion of the PF whether or not to use a flight director.

The peculiarities of the simulator program required that approaches be set to runway 26 at Denver International Airport (KDEN). Each approach was initiated 9 miles from the runway threshold on the ILS course (Figure 9). The aircraft was in landing configuration and trimmed for 161 kias with all checklists complete. The approach began when the pilot subject advised ready. Normal airline procedures and callouts were given by the PNF during approach. Additionally, two non-standard callouts were annunciated by the PNF; an 800 foot call to advise the PF to initiate the selected maneuver, and a 400 foot call (target altitude) when the variable pitch escape maneuver was flown.

Environmental conditions used were pre-programmed into the simulator and included a barometric pressure (QNE) of 29.92 inches, a temperature of 28 °C, a visibility of 49.9 statute miles, and surface wind 190° at 8 knots. Turbulence was set to zero for all approaches, as this was considered noise introduced into the system and would further randomize the results.
During the escape maneuver phase, the microburst model was positioned at a constant point along the approach path. Data acquisition began as the aircraft descended through 1,400 feet AGL, and the microburst winds began as the aircraft descended through 1,200 feet AGL. The pilot subjects were instructed to continue flying as normal an approach as possible until reaching 800 feet AGL, at which point they performed either the constant pitch escape maneuver or the variable pitch escape maneuver.

The constant pitch escape maneuver was familiar to all the pilot subjects and was the first sequence in the trial runs. Upon reaching 800 feet AGL the pilot subjects commanded go-around thrust and pitched initially for 15° on the attitude deviation indicator (ADI). Stick shaker was respected with pitch and the aircraft continued on its trajectory until the recording window closed, 100 seconds after opening, and the simulator stopped.

The next maneuver in sequence was the variable pitch escape training maneuver. This was conducted in the absence of the microburst to demonstrate the procedure and to train the participating pilots. The aircraft was pitched to $\theta = 0^\circ$ from 800 to 400ft AGL, at which point altitude was maintained. A reduction in thrust mimicked the variable pitch nature of holding altitude with decreasing airspeed. At stick shaker speed ($V_{SS}$) the thrust was returned and the aircraft allowed to climb. After the demonstration and a practice session, the microburst was introduced onto the approach path.

After the training exercise, the pilot subjects flew the variable pitch escape maneuver through the same microburst as used during the constant pitch escape maneuver. At 1,200 feet AGL the microburst wind shear began, and at 800 feet AGL the pilots commanded go-around thrust while decreasing pitch to $0^\circ$ on the ADI, accelerating
to the target altitude of 400 feet AGL. The pilot subjects then attempted to maintain this altitude with pitch control. The wind shear ended 21,000 feet after it began, and the recording window closed shortly thereafter.

Thrust was limited to 2.00 EPR immediately after recognition of the microburst. This setting, 10 % less than the normal take off go-around (TOGA) EPR for the JT8D-17 engine at that pressure and temperature, was used to enhance the effects of the microburst and limit the aircraft from powering out at a relatively high altitude prior to data collection. In previous trials it was found that the aircraft was not entering the microburst core in the recording window.

After each run, the simulator was positioned back to the initiation point; the pilot subjects prepared for the next run on the flight deck, and the simulator supervisor set the required parameters at the simulator console and computer. The flying was segmented to minimize fatigue and the crossover of maneuvers. Each pilot subject flew about 5 maneuvers before trading position with the accompanying crewmember. The variable and constant pitch maneuvers were separated into these 5 run sequences when possible, so that constant pitch trials for the day were completed prior to the introduction of the variable pitch trials for that day.

The total escape maneuvers flown by the pilot subjects during the trial phase of the study amounted to 35. The constant pitch maneuver was performed 15 times, while the variable pitch maneuver accounted for the remaining 20 trials. Further time was not available to add to the constant pitch maneuver tally. The disparity in cell frequency would be mitigated by the application of statistical measures.
In addition to the 35 escape maneuvers, 4 approaches were flown through the shear to a landing on the runway, and 3 practice variable pitch maneuvers were performed, for a total of 42 approaches in the simulator during two days of trials. The approaches through the microburst with a landing on the runway provided the pilot subject an opportunity to feel the effects of the microburst on the handling qualities and performance of the aircraft. The practice maneuvers were necessary because this was a new technique for the pilots, and their understanding of the procedure was important to perform the maneuver. These 7 approaches were not statistically evaluated, and the 3 practice approaches were not recorded.

The minimum number of approaches planned per maneuver was 15. This was determined as a compromise from data supplied in Hinton’s study (1989) and the desire to retain symmetry of data. Increasing the trial runs to 18 was considered untenable in the time allotted. The opportunity to perform additional maneuvers was deemed more important than cell frequency, this accounts for the disparity in trial runs between the constant pitch maneuver and the variable pitch maneuver.

Altitude data, recorded by the simulator computer at a rate of 5Hz, generated 500 individual readouts for each run. The individual readouts were extracted from the host computer via a subroutine and deposited into files. The files for each run were labeled consecutively and transferred to the mainframe computer at United TK, they were then relocated to a server and emailed to the researcher for reduction and statistical analysis. Data were also captured on graphical output (Figures 15 through 53). The graphs were printed from the simulator computer at the conclusion of the day’s trials and include those parameters deemed important by the training department at United Airlines.
Treatment of Data

Recovery altitude is the primary quantitative value in this study. A difference in recovery altitude between maneuvers answers the hypothesis of which escape maneuver provides for greater safety. A difference in recovery altitude will also determine the homogeneity of the sample group within the escape maneuver. Two techniques in analyzing the recovery altitude are employed, as required by differing independent variables.

Determining the difference in recovery altitude between escape maneuvers is performed by a $3 \times 2$ analysis of variance (ANOVA) with pilot subject and maneuver type as the factors and minimum altitude as the criterion. Significance is demonstrated at a $p$ value corresponding to less than .05.

The difference in recovery altitude between pilots for the same maneuver is evaluated via a single factor ANOVA, with pilots as factor and altitude as criterion. This analysis is performed to determine any outliers in data, and validate that a difference in recovery altitude is due to the escape maneuver rather than the individual.

Pragmatically safety is a multivariate function. Two factors that play a dominant role in the safety of flight for conventional aircraft are the altitude and airspeed. It was of interest to determine if a relationship between these factors existed for the individual escape maneuvers. The relationship between altitude and airspeed is examined with a regression analysis and scatter plot for each maneuver type.

The data for recovery altitude and airspeed for each maneuver are displayed in numerical form in Chapter IV, the graphs of the trial runs are provided in Appendix A through C. Statistical analysis is presented in Chapter IV and discussed in Chapter V.
CHAPTER IV

RESULTS

The data were collected on two separate days and involved simulated flights of two hours duration each day. In the time apportioned, three pilots flew a total of 42 approaches. The 7 familiarization approaches, 4 through the microburst wind shear to a landing on the runway and 3 variable pitch training maneuvers with no shear present, did not contribute to the data output. These maneuvers were provided for training purposes. The approaches providing data for analysis were 15 constant pitch maneuvers through the microburst wind shear and 20 variable pitch maneuvers through the same wind shear. The number of maneuvers completed was dependent on the ability to perform as many grouped trials as possible in the time scheduled.

Data acquisition began as the flight descended through 1,400 ft AGL and continued for 100 seconds. All trial runs were completed within the data time frame. The microburst, UAL-7 “severe on approach” (Table 3), began when the aircraft initially descended through 1,200 feet AGL and it continued horizontally for 21,000 feet thereafter. The pilots proceeded into the microburst, on approach, until 800 feet AGL, as determined by the barometric altimeter. At this point, the PNF called “800 feet” and the PF performed either the constant pitch maneuver, or the variable pitch maneuver, as briefed prior to the approach.

Altitude data were collected at 5Hz from the simulator host computer via a subroutine providing numerical output to seven decimal places. Graphical data were produced by a dot-matrix printer on 11 inch by 15 inch paper, the reduced images of which are provided in the Appendices as Figures 15 through 53. The recovery altitude
derived from the computer subroutine, and the airspeed interpreted from the graphical output, is provided in Table 4 for each pilot subject, maneuver, and trial run.

Prior to the escape maneuvers, each pilot flew an approach through the microburst wind shear to a landing on the runway to familiarize themselves with the handling and performance of the aircraft in a microburst wind shear. The pilot subjects then flew the constant pitch maneuver through the shear; each run increasing the individual’s tally for the particular maneuver. The pilot subjects then profiled a training maneuver, with no microburst wind shear present. Data for the training runs were not recorded. The subjects finally performed the variable pitch maneuver through the microburst wind shear. At the end of day two, time remained for additional approaches, and though this caused a larger disparity in cell frequency it provided additional data for examination.

The data in the appendices are presented with landing approaches in Appendix A, followed by Appendix B with the constant pitch maneuver (Figures 19 through 33), and Appendix C housing the variable pitch maneuver data (Figures 34 through 53). The data are not presented in the order in which collected.

A compilation of the data is provided in Table 4. The pilots were assigned a number after the data collection to provide a level of confidentiality to the individual. The maneuvers flown by the pilots are only those that represent the experimental procedures, the maneuver column does not include any training maneuvers or familiarization flights. The run number is reported in sequence by maneuver for the individual. Altitude was recorded in feet AGL to seven decimal places, but in this table is given to a hundredth of a foot. The next column, airspeed, is reported to the whole number only. The last column, Figure #, indicates the graph in the appendix that corresponds to the data presented.
Table 4

**Altitude and Airspeed of Simulator Trials for Constant and Variable Pitch Maneuvers**

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Maneuver</th>
<th>Run</th>
<th>Altitude</th>
<th>Airspeed</th>
<th>Figure #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CPS</td>
<td>1</td>
<td>264.48</td>
<td>107.00</td>
<td>19</td>
</tr>
<tr>
<td>1</td>
<td>CPS</td>
<td>2</td>
<td>632.21</td>
<td>109.00</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>CPS</td>
<td>3</td>
<td>500.39</td>
<td>109.00</td>
<td>21</td>
</tr>
<tr>
<td>1</td>
<td>CPS</td>
<td>4</td>
<td>409.75</td>
<td>110.00</td>
<td>22</td>
</tr>
<tr>
<td>1</td>
<td>CPS</td>
<td>5</td>
<td>389.38</td>
<td>108.00</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>CPS</td>
<td>1</td>
<td>517.86</td>
<td>106.00</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>CPS</td>
<td>2</td>
<td>444.91</td>
<td>111.00</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>CPS</td>
<td>3</td>
<td>560.91</td>
<td>111.00</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>CPS</td>
<td>4</td>
<td>493.81</td>
<td>109.00</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>1</td>
<td>633.96</td>
<td>102.00</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>2</td>
<td>388.40</td>
<td>102.00</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>3</td>
<td>560.70</td>
<td>102.00</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>4</td>
<td>498.55</td>
<td>101.00</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>5</td>
<td>555.56</td>
<td>102.00</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>6</td>
<td>341.91</td>
<td>99.00</td>
<td>33</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>1</td>
<td>220.67</td>
<td>123.00</td>
<td>34</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>2</td>
<td>283.16</td>
<td>114.00</td>
<td>35</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>3</td>
<td>131.30</td>
<td>117.00</td>
<td>36</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>4</td>
<td>93.97</td>
<td>116.00</td>
<td>37</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>5</td>
<td>153.74</td>
<td>109.00</td>
<td>38</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>6</td>
<td>251.51</td>
<td>119.00</td>
<td>39</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>7</td>
<td>190.26</td>
<td>116.00</td>
<td>40</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>8</td>
<td>196.13</td>
<td>117.00</td>
<td>41</td>
</tr>
<tr>
<td>1</td>
<td>VPS</td>
<td>9</td>
<td>208.57</td>
<td>114.00</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>VPS</td>
<td>1</td>
<td>53.22</td>
<td>124.00</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>VPS</td>
<td>2</td>
<td>11.37</td>
<td>125.00</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>VPS</td>
<td>3</td>
<td>207.08</td>
<td>116.00</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>VPS</td>
<td>4</td>
<td>132.48</td>
<td>116.00</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>VPS</td>
<td>5</td>
<td>165.22</td>
<td>117.00</td>
<td>47</td>
</tr>
<tr>
<td>3</td>
<td>VPS</td>
<td>1</td>
<td>261.56</td>
<td>114.00</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>VPS</td>
<td>2</td>
<td>263.66</td>
<td>113.00</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>VPS</td>
<td>3</td>
<td>173.13</td>
<td>108.00</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>VPS</td>
<td>4</td>
<td>199.85</td>
<td>107.00</td>
<td>51</td>
</tr>
<tr>
<td>3</td>
<td>VPS</td>
<td>5</td>
<td>271.69</td>
<td>115.00</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>VPS</td>
<td>6</td>
<td>225.96</td>
<td>108.00</td>
<td>53</td>
</tr>
</tbody>
</table>

1. CPS = Constant Pitch Strategy, VPS = Variable Pitch Strategy
2. Run is individual tally for that pilot in that particular maneuver
3. Altitude is lowest recorded by computer in feet AGL
4. Airspeed is lowest interpreted in knots indicated (KIAS)
The recovery altitude was the primary measure of safety and was defined as the lowest altitude, above ground level, recorded by the simulator computer, of the aircraft during the microburst escape maneuver. The descriptive statistics in Table 5 are delineated by pilot subject and maneuver, while the totals are provided in the text of the discussion section. The reported values are given to four decimal places, but were computed to seven, the last digit being rounded per conventional accounting methods. The mean \( (M) \), standard deviation \( (SD) \), and total number of trials \( (N) \) are provided for each pilot subject per maneuver.

Descriptive statistics are used to compute inferential statistics. The inferential statistics, ANOVA, regression analysis, and post hoc procedures follow in Tables 6 through 11. A discussion of the descriptive statistics, along with the measures of central tendency, including kurtosis and skewness follow in Chapter V.

Table 5

\textit{Descriptive Statistics for Recovery Altitude}

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Maneuver</th>
<th>( M )</th>
<th>( SD )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CPS</td>
<td>439.2421</td>
<td>136.8153</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>VPS</td>
<td>192.1456</td>
<td>58.8717</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>CPS</td>
<td>504.3727</td>
<td>48.3918</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>VPS</td>
<td>113.8744</td>
<td>80.3992</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>CPS</td>
<td>496.5126</td>
<td>111.4382</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>VPS</td>
<td>232.6423</td>
<td>39.9623</td>
<td>6</td>
</tr>
</tbody>
</table>
In comparing the recovery altitude between pilots and maneuver, a two-factor ANOVA was employed. The ANOVA compares group means. The independent variables, or factors, were the pilots and maneuver type: With three pilot subjects and two different escape maneuvers a 3x2 ANOVA was formed. The data indicate no significant difference between pilot subjects and no interaction effect between maneuver and pilot. A significant difference does occur between maneuvers. The probability that the null hypothesis is true, that no difference in recovery altitude exists between maneuvers, is extremely low, below one in one thousand or $p < .001$.

Table 6 reports the source of the inferential statistic followed by the degrees of freedom (df) and the F-factor (F). Mean square error is reported in parenthesis at the bottom of the table.

Table 6

*Analysis of Variance for Altitude with Pilots and Maneuver as Factors*

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between subjects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maneuver</td>
<td>1</td>
<td>104.753*</td>
</tr>
<tr>
<td>Pilots</td>
<td>2</td>
<td>1.467</td>
</tr>
<tr>
<td>Maneuver x Pilots</td>
<td>2</td>
<td>2.145</td>
</tr>
<tr>
<td>Error</td>
<td>29</td>
<td>(7088.258)</td>
</tr>
</tbody>
</table>

*Note. Value enclosed in parenthesis represents mean square error.*

*p < .001*
Determining a relationship between the lowest airspeed encountered, during the constant pitch microburst escape maneuver, and the recovery altitude was examined through the use of a regression analysis, Table 7. All 15 constant pitch runs were examined and no significant relationship was observed. The variable is presented first, followed by the regression coefficient (B), the standard error of the regression coefficient (SE B), and then the beta value (β). The multiple correlation (R²) is given at the bottom of the table.

Table 7

Regression Analysis of Constant Pitch Maneuver: Airspeed Predicting Altitude (N = 15)

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspeed</td>
<td>0.462</td>
<td>7.141</td>
<td>.018</td>
</tr>
<tr>
<td>Constant</td>
<td>430.557</td>
<td>756.483</td>
<td></td>
</tr>
</tbody>
</table>

Note. $R^2 = 3.24 \times 10^{-4}$

Similar to the constant pitch maneuver, a regression analysis was performed for the variable pitch maneuver. Five more trials were performed in the variable pitch maneuver, bringing the total runs to 20. Table 8, the regression analysis of the variable pitch maneuver is consistent in layout to Table 7, the regression analysis of the constant pitch maneuver. The data in Table 8 indicate that a relationship does exist between the lowest airspeed and recovery altitude, and it is significant at the $p < .05$ level. The multiple correlation, here 19.9, is the percent of variance in the dependent variable explained by the independent variable.
Table 8

*Regression Analysis of Variable Pitch Maneuver: Airspeed Predicting Altitude (N = 20)*

<table>
<thead>
<tr>
<th>Variable</th>
<th>$B$</th>
<th>$SE B$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspeed</td>
<td>-6.475</td>
<td>3.063</td>
<td>-.446*</td>
</tr>
<tr>
<td>Constant</td>
<td>931.917</td>
<td>353.807</td>
<td></td>
</tr>
</tbody>
</table>

*Note. $R^2 = .199$*

*p < .05*

Evaluating the difference in recovery altitude between pilots for each maneuver was accomplished via a one-factor ANOVA. For the constant pitch maneuver, Table 9, the factor, or independent variable is the pilot subject. Three pilot subjects participated, so the degrees of freedom (df) is two, while the F-factor (F) is reported as 0.513. This value does not meet the level of significance established, and therefore the null hypothesis is accepted. No significant difference in recovery attitude exists between pilot subjects for the constant pitch maneuver. The error is reported in the lowest row with mean square error in parenthesis.

Table 9

*Analysis of Variance for Altitude in Constant Pitch Maneuver with Pilots as Factor*

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilots</td>
<td>2</td>
<td>0.513</td>
</tr>
<tr>
<td>Error</td>
<td>12</td>
<td>(11999.282)</td>
</tr>
</tbody>
</table>

*Note. Value enclosed in parenthesis represents mean square error.*
A comparison of the mean recovery altitudes for the variable pitch maneuver is reported as a one-factor ANOVA in Table 10. The degrees of freedom (df) is two for the pilot group and the F-factor is significant at the .05 level. There was a significant difference in recovery altitude for one or all the pilots in the variable pitch maneuver. Error is reported in the last row with mean square error in parenthesis.

Table 10

_Analysis of Variance for Altitude in Variable Pitch Maneuver with Pilots as Factor_

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilots</td>
<td>2</td>
<td>5.436*</td>
</tr>
<tr>
<td>Error</td>
<td>17</td>
<td>(3621.653)</td>
</tr>
</tbody>
</table>

*Note. Value enclosed in parenthesis represents mean square error.

*p < .05.

Determining where the difference lies within the pilot subject group was accomplished by a Tukey-Kramer post hoc analysis; a conservative test, likely to minimize Type I errors and not likely to reject the null hypothesis. The values, as provided in Table 11, indicate a significant difference in recovery altitude exists only between pilot subject 2 and pilot subject 3 at the p < .05 level. No other statistical differences manifest themselves in the table.

In Table 11, the pilot subject to which comparison is made is presented first (i), followed by those subjects to which compared (j). The mean (M) is provided along with the standard deviation (SD) and the significance probability (p).
Table 11

Post Hoc Comparison between Pilots for Altitude in Variable Pitch Maneuver

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>M</th>
<th>SD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>78.2711</td>
<td>33.5669</td>
<td>.078</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-78.2711</td>
<td>33.5669</td>
<td>.078</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-118.7679*</td>
<td>36.4409</td>
<td>.012</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>40.4968</td>
<td>31.7177</td>
<td>.427</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>118.7679*</td>
<td>36.4409</td>
<td>.012</td>
</tr>
</tbody>
</table>

Note. Tukey-Kramer Analysis

*p < .05.

The data collected represent graphical and numeric output from the simulator computer. Though provided to seven decimal places, the recovery altitude is only reported to four decimal places in the statistical analysis, and is discussed to two decimal places in the text. This level of precision represents about an eighth of an inch in altitude for an aircraft that is 100 feet long. The altitude was determined from the CG location of the aircraft, which was established at the 25% MAC position.

Airspeed was derived from the original graphical plots and is not accurate below a one-knot distinction. As an ancillary value, this provides adequate accuracy for the calculations imposed. Stall speed was generated by the computer, and a stalled condition is provided in the graphical plots of angle of attack versus time. The reported value of stall in the discussion section, Chapter V, was derived from graphs furnished by Boeing.
CHAPTER V
DISCUSSION

In every approach flown through the microburst, the effects of the wind field on the aircraft are apparent. A characteristic trace of the altitude plot is the portrayal of a ‘W’ starting around the 50-second time hash, a result of the vortex modeled in the microburst. The wind had an affect on the altitude, the airspeed, and the handling of the aircraft in all the phases flown.

Three different maneuvers through the microburst were performed; a landing approach, a constant pitch strategy, and a variable pitch strategy. With the landing approach, each pilot was in a position to put the aircraft in the touchdown zone at the conclusion of the run, and confidence was gained that the shear was navigable. This introductory run provided the pilot subject a point of reference to compare with non-wind shear approaches in how the aircraft would respond.

Constant Pitch Maneuver

The constant pitch escape maneuver, familiar to all the pilot subjects, followed the landing approaches. The pilot subjects were instructed to fly as normal an approach as possible until the commencement of the escape maneuver. At 800 feet AGL the maneuver was initiated—the aircraft was about a third of the way into the microburst at this point, with a headwind of 23.5 knots and a downdraft of 705 fpm.

Attempting to maintain glide slope to 800 feet AGL, the pilot subjects had the thrust levers at idle and used pitch for flight path control. When the aircraft arrived at 800 feet AGL the engines were spooled up to 2.00 EPR, concurrent with an increase in pitch attitude to 15°, or beyond as needed. The time required between idle power and go-
around power was about six seconds. A review of the simulator plots in Appendix B shows the response in pitch attitude slightly lagging EPR. With thrust applied, and a positive pitch, the aircraft continued to descend below the initiation point.

The lowest altitude attained in the constant pitch maneuver was generally in the second valley of the aforementioned W. Just 2 of the 15 trials exhibited the lowest altitude in the first valley (Figure 20 & 24). For the majority of trials, the low altitude point follows the highest peak in angle of attack and the lowest level in kinetic energy. This second valley in the altitude trace is initiated by a downburst of 2,520 feet per minute occurring 14,800 feet beyond the start point of the microburst (Table 3). Though this second downburst is not as great as the preceding downburst, the aircraft is in a lower kinetic energy state and so is more vulnerable to environmental effects.

As the aircraft reaches it’s low point, and begins climbing, it is aided by a vertical wind change from a downburst to an updraft of 1,080 feet per minute. Combined with the thrust and positive pitch of the aircraft, this updraft allows for climb rates exceeding 3,000 fpm while accelerating.

Descriptive Statistics

Mean recovery altitude attained for the constant pitch maneuver was 479.52 feet with a standard deviation of 105.66 feet. The highest recovery altitude for the constant pitch maneuver was 633.96 feet, while the lowest altitude was 264.48 feet. No outliers or extreme values were observed in the altitude data. Individual mean recovery altitudes and standard deviations are provided in Table 5. The data do not contain any zero values, as no crashes occurred during the trials of 15 total runs.
An examination of the boxplot (Figure 10) for altitude versus pilot, in the constant pitch maneuver, shows a similarity among groups. The heavy line in the box is the median altitude attained by that pilot, while the box itself represents the interquartile range, that is from the 25\textsuperscript{th} percentile at the bottom of the box to the 75\textsuperscript{th} percentile at the top of the box. Whiskers protruding from the bottom and top of the box are the observed lowest and highest values respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{boxplot.png}
\caption{Boxplot of pilot versus altitude for the constant pitch maneuver.}
\end{figure}

In the graph, the boxes are roughly located at similar altitudes for all pilot subjects, indicating little difference among groups. The median line shows skewness in the distribution of altitude for pilot subjects 1 and 3. The difference of the median from the mean for pilot 1 is 29.50, for pilot 2 the difference is 1.46, and for pilot 3 the
difference is -30.54. When the data from the pilots were combined, the constant pitch maneuver had a median of 498.55. When compared with the mean altitude of 479.52, the skewness is relatively small.

An investigation into the skewness and kurtosis shows that the data do not violate the assumption of normality. For this test, the skewness (-0.390) was divided by the standard error (0.580) to give a value (-0.672) within an acceptable range (-2 < -0.672 < 2). The heuristic for kurtosis is similar, and the computed values for the Fisher kurtosis were -0.338 with a standard error of 1.121, giving a value of -0.302 which falls within the conservative guidelines of ±2.

**Analysis of Variance**

The ANOVA procedure assumes a normal distribution, though it is robust when moderate departures from normality occur. Equal variance of the dependent variable across the independent variables is an additional postulate of the ANOVA. In this study, homogeneity of variance was established through Levene’s test, which clearly established (p = .251) that the error variance of the dependent variable was equal across groups.

Scheduling restrictions dictated the trial runs of the participating pilots, causing an unequal sample size. In performing the ANOVA, this unequal sample size was relegated by a Type III sum of squares. As there were no missing cells in the data, merely unequal trials, the Type III sum of squares provided a linearly unbiased estimate of the marginal means, giving the most traditional value for the ANOVA.

The ANOVA (Table 9) confirms that there is no significant difference (p = .611) in the dependent variable recovery altitude when compared among groups for the constant pitch maneuver.
Regression Analysis

The microburst is energy absorbing for aircraft performance; it was therefore surmised that trading the greater amount of potential energy would relieve the burden on the kinetic energy. Pragmatically, lower recovery altitudes were thought to be accompanied by higher airspeeds. To test this ancillary hypothesis, a regression analysis was computed (Table 7) for airspeed predicting altitude in the constant pitch maneuver. A scatter plot (Figure 11) of the 15 datum points for recovery altitude versus minimum airspeed in the constant pitch maneuver shows no apparent relationship. The nearly horizontal line midway in the graph is the plot of the regression equation.

![Regression plot of constant pitch maneuver: Airspeed predicting altitude.](image)

Figure 11. Regression plot of constant pitch maneuver: Airspeed predicting altitude.
The resulting equation from the analysis shows that altitude and airspeed do not greatly affect each other.

\[ \text{Altitude} = 0.46 \text{(Airspeed)} + 430.56 \] (8)

In Equation 8, altitude is in feet AGL and airspeed in knots indicated. A one-knot change in airspeed will change the altitude by 0.46 feet. Though the slope is relatively flat, it is opposite to the direction expected.

The \( R^2 \) value, the multiple correlation coefficient, is the percent of variance in recovery altitude induced by airspeed, in this analysis, \( R^2 = 3.24 \times 10^{-4} \). Basically, none of the variance in the recovery altitude is attributed to airspeed. It is thus apparent that recovery altitude and minimum airspeed are not intertwined in the constant pitch maneuver.

The escape maneuver was initiated at 800 feet AGL, but the aircraft continued to descend in the microburst to a mean altitude of 479.52 feet AGL. The pilot subjects did not demonstrate a significant difference between themselves in recovery altitude for the constant pitch maneuver. Though some of the recoveries occurred at a lower altitude, and some at a higher altitude, there was no relationship between recovery altitude and minimum airspeed in the constant pitch maneuver.

Variable Pitch Maneuver

The variable pitch maneuver was a new concept to the pilot subjects, and some were vocal in their skepticism. Nonetheless, the maneuvers were flown to the best of the crew’s ability. Similar to the constant pitch maneuver, the PF attempted to adhere to the
glideslope until 800 feet AGL, at which point the pitch was lowered to zero on the ADI, and the aircraft accelerated to 400 feet AGL. Thrust was simultaneously increased to 2.00 EPR while configuration was maintained.

Leveling at 400 feet AGL proved to be difficult, and the roll vortices in the microburst are apparent in the altitude plots presented in Appendix C (Figures 34 through 53) for the variable pitch maneuver. Most of the low altitude conditions, 14 out of 20, occurred in the first segment of the ‘W’, as opposed to the constant pitch maneuver, which had low altitudes predominantly 13 out of 15 in the second segment of the ‘W’.

Climb-out from the low altitude condition commenced when the energy level had increased and the speed was acceptable to the PF. Some of the pilot subjects chose to maintain the 400-foot level and let the airspeed build. The climb phase was 20–30 seconds after recovery altitude and did not affect the data.

Though the lowest altitude recorded occurred during the variable pitch maneuver, there appeared to be greater altitude control overall, airspeed was generally higher, and less time was spent above stick shaker angle of attack.

Descriptive Statistics

Altitude control was more definitive in the variable pitch maneuver, and pilot standard deviations were generally less. The total standard deviation of recovery altitude for the variable pitch maneuver was only 72.89 feet with a mean altitude of 184.73 feet. The highest recovery altitude was 283.16 feet, while the lowest was 11.37 feet. This low value does not constitute a statistic outlier; all the datum points were valid with no zero entries occurring in the 20 trial runs. Individual mean recovery altitudes and standard deviations for the variable pitch maneuver are shown in Table 5.
The boxplot (Figure 12) for altitude versus pilot in the variable pitch maneuver is slightly staggered, suggesting there might be a difference among the groups. There is overlapping between highest and lowest values for each pilot subject, but the medians do show some disparity. The median for pilot 1 was 196.13, the median for pilot 2 was 132.48, and pilot 3 had a median of 243.76. The difference in medians between pilot 2 and pilot 3 was 111.28, while the difference in means was 118.77. When all pilot subjects were combined, the total median for recovery altitude was 197.99 feet, while the mean was a bit less at 184.73 feet. This indicates a negatively skewed distribution; where the extreme scores are at the minimum altitudes, while most of the recoveries were at altitudes higher than the mean.

Figure 12. Boxplot of pilot versus altitude for the variable pitch maneuver.
There is negative skewness in the distribution of altitude for pilot subjects, but overall the data do meet the assumption of normality. Skewness for the variable pitch maneuver is -0.840, and when divided by the standard error of 0.512, gives a -1.641 value, which falls inside the normality guidelines of ±2. Testing of the kurtosis gives a more conservative value. The Fisher kurtosis (0.394) divided by the standard error (0.992) results in 0.387, close to the mid-point of the ±2 limit for normality. The positive value of the kurtosis suggests that most of the recovery altitudes centered around each other with few datum points occurring outside the grouping.

*Analysis of Variance*

Whether a statistical difference in recovery altitude existed between pilot subjects was examined through a one-factor ANOVA. The precondition of normality was met through the skewness and kurtosis tests, while homogeneity of variance was computed using Levene’s test. The error variance of recovery altitude was similar across pilot subjects with $p = .245$.

As the groups were of unequal sample sizes, it was considered important to minimize Type I errors by adhering to conservative statistical practices. While Levene’s test of homogeneity of variance is robust when examining departures from normality, and ANOVA is fairly accurate with deviations in homogeneity of variance, these assumptions were ensured to provide a sound statistical basis. Accounting for unequal trials, a Type III sum of squares was used, as it was in the constant pitch maneuver ANOVA, to estimate the marginal means.

The one-factor ANOVA for the variable pitch maneuver (Table 10) does show a significant difference in recovery altitude between pilot subjects at the $p < .05$ level.
Post Hoc Analysis

A Tukey-Kramer post hoc analysis (Table 11) was performed after the one-factor ANOVA for the variable pitch maneuver rejected the null hypothesis. The Tukey-Kramer is a conservative test, which minimizes the likelihood of Type I errors. Homogeneity of variance is a requirement, but unequal sample size is allowed and controlled using a harmonic mean.

The difference in recovery altitude for the pilot subjects, as reported by the ANOVA, occurred between pilot 2 and pilot 3. The mean difference was significant at the \( p < .05 \) level. Other differences in recovery altitude between pilot subjects were not significant in the post hoc analysis.

One possible explanation for the disparity between pilot 2 and pilot 3 is the amount of practice given to the participants. Prior to data collection, pilots 1 and 3 had the opportunity of flying the simulator through the various maneuvers while data collection anomalies were rectified. This increased training time was not afforded pilot 2, who was scheduled for a later session. There were no significant differences in recovery altitude for the constant pitch maneuver, which had been familiar to all the pilot subjects, lending credence to the hypothesis that the amount of practice time increased recovery altitude in the variable pitch maneuver.

An inequality in the means between pilot 1 and 2, though not a significant difference, can be seen in Table 11 and Figure 12. The departure in means was 78.27 feet between pilots 1 and 2, compared to the significant difference of 118.77 feet between pilots 2 and 3. It is therefore plausible that the additional practice time was beneficial, to pilots 1 and 3, by increasing recovery altitude.
Regression Analysis

The ethos of the variable pitch maneuver is the trade of potential energy for kinetic energy to minimize the time the aircraft spends in the microburst. A lower recovery altitude should translate into a higher minimum airspeed for the maneuver. A scatter plot (Figure 13) of altitude versus airspeed depicts the spread of the datum points, while the heavy line is a projection of the regression equation, showing the relationship between altitude and airspeed.

![Figure 13. Regression plot of variable pitch maneuver: Airspeed predicting altitude.](image)

The relationship between altitude and airspeed is not as strong as theory would seem to indicate. Percent of variance in the recovery altitude, accounted for by airspeed, was about 20% ($R^2 = .199$). The $\beta$ weight was significant at the $p < .05$ level and was
computed as -.446. In this analysis, $\beta$ is the amount that the standard deviation of the recovery altitude changes with a one-standard deviation change in airspeed. The standard deviation for airspeed in the variable pitch maneuver was 5 kias.

Data derived from Table 8 give the equation for airspeed predicting altitude.

$$\text{Altitude} = -6.48 \text{ (Airspeed)} + 931.92$$

(9)

Again, airspeed is in knots indicated, and altitude in feet AGL. A one-knot decrease in airspeed represents an increase in recovery altitude of 6.48 feet. Using Equation 8, the maximum recovery altitude achievable can be computed by minimizing the airspeed. As the upper limit of pitch was set at the stick shaker speed, this would also correspond to the minimum usable airspeed. The stick shaker speed for the 737-200 advanced with flap 15, gear down, wings level, and at 90,000 pounds is 112 kias ($V_s = 103$ kias). At stick shaker speed, the computed maximum recovery altitude is 206.72 feet AGL.

In practice, almost half of the trials, 9 out of 20, had recovery altitudes above the computed maximum, while only 4 of 20 runs had indicated airspeeds below calculated stick shaker speed. Equation 9 might be representative of a trend, but it is not an accurate predictor of the data.

All trials in the variable pitch maneuver descended below the target altitude, of 400 feet AGL, as a consequence of the microburst wind. The mean altitude attained was 184.73 feet with a standard deviation of 72.89 feet. Within the pilot group, there was a statistical difference in recovery altitude between pilot 2 and pilot 3. This was possibly a result of proficiency in the maneuver afforded by prior training.
Combined Analysis

The purpose of this study was to compare the safety of the current microburst escape procedure with an alternate maneuver. Safety was quantified as the maximization of the minimum altitude attained by the aircraft during the escape. Altitude data were supplied by the simulator computer to seven decimal places at a rate of 5 Hz, the lowest value from this output became the recovery altitude and provided the data for the statistical analysis.

The constant pitch maneuver was performed 15 times during the data acquisition phase. Pilot subject 4 dismissed himself prior to the start of the experiment, and so pilot 1 performed the trials slotted for number 4. This created unequal datum cells, though steps have been employed in the statistics to mitigate the errors this may impose. In the variable pitch maneuver, 20 trials were performed. Again, unequal cells surfaced, and pilot 1 has three more trials than pilot 3, and four more trials than pilot 2; totals are provided on the right hand side of Table 5.

At 800 feet AGL the pilot subjects initiated the constant pitch maneuver; regardless of the climb attitude, the aircraft continued to descend an average 320.48 feet. The mean minimum airspeed in the recovery was 105 knots indicated—this is below stick shaker speed, but above stall speed. Climb-out was at a high deck angle.

In the variable pitch maneuver, the pitch attitude was zeroed at 800 feet AGL, and the aircraft dove to the target altitude of 400 feet AGL. It was intended that the target altitude be maintained, but this was not possible. The microburst influenced the flight path and the aircraft descended to an average altitude of 184.73 feet before recovering to the target altitude.
Though the altitude was lower in the variable pitch maneuver, it was maintained to tighter tolerances than in the constant pitch maneuver, as graphically depicted in Figure 14. The standard deviation for the variable pitch maneuver was 72.89 feet, while the constant pitch maneuver standard deviation was 105.66 feet. The closer confine of altitude in the variable pitch maneuver might be a result of greater airspeed, which aids in aircraft control. The minimum airspeed was higher in the variable pitch maneuver by an average of 10 knots.

The lower altitude of the variable pitch maneuver is apparent in an examination of the combined boxplots (Figure 14). In some cases, the recovery altitudes overlapped for maneuver type, but the interquartile range of recovery altitude for the variable pitch maneuver is distinctly lower than the constant pitch maneuver.

*Figure 14.* Boxplot of combined altitude versus maneuver type.
3 x 2 Analysis of Variance

Determining a statistical difference between maneuvers for recovery altitude was performed via a 3 x 2 ANOVA. The pilot subjects and maneuvers were the factors, and recovery altitude the criterion. Homogeneity of variance was assumed with a non-significant p value (.074) reported through Levene’s test of equality of error variances.

Though interpretation of main effects can be confounded by unequal sample size, in a two-way ANOVA the interaction effects are free from this influence. Mitigating the problem of unequal sample size for the main effects was the use of a Type III sum of squares, which provides a good linearly unbiased estimate of the marginal means.

The two-way ANOVA is reported in Table 6. The analysis indicates that interaction between pilot subject and maneuver is not significant. That is, the pilot subjects do not modify the effect of the maneuver on recovery altitude. The main effect for pilot subjects on recovery altitude is also not significant. Pilot subjects, by themselves, did not alter the recovery altitude to a significant level.

Significant main effects for maneuver type were established in the 3 x 2 ANOVA. There is a difference in recovery altitude for maneuver type at the p < .001 level. The constant pitch maneuver had a total mean recovery altitude of 479.52 feet with a standard deviation of 105.66 feet. The variable pitch maneuver generated a total mean recovery altitude of 184.73 feet with a standard deviation of 72.89 feet. There was a little overlap between the low recovery altitudes of the constant pitch maneuver and the high recovery altitudes of the variable pitch maneuver, but this was not extensive enough to bring the two maneuvers to congruency.
CHAPTER VI

CONCLUSIONS

The variable pitch maneuver generated a significantly lower recovery altitude than the constant pitch maneuver through the same microburst. The research hypothesis must therefore be rejected: The constant pitch maneuver, and not the variable pitch maneuver, exhibits the greater factor of safety as determined through the maximization of the minimum altitude attained during the escape maneuver.

The mean altitude for the constant pitch maneuver was 79.52 feet higher than the target altitude of 400 feet AGL adopted for the variable pitch maneuver. The target altitude came from a previous study (Miele, Wang, Tzeng, & Melvin, 1987) and was not increased during the course of the research. Hence, the variable pitch maneuver started at an altitude lower than the mean recovery altitude of the constant pitch maneuver. Even with the increased airspeed, the aircraft sank an average 215.27 feet below the target altitude. To generate the same mean altitude, the variable pitch maneuver would require a target altitude 100 feet below the initiation altitude, not enough of a height difference to materially increase airspeed and effect the maneuver.

As might be expected, the variable pitch maneuver did have a higher average minimum airspeed than the constant pitch maneuver. The difference of 10 knots, coupled with the reduction of time spent at stick shaker angle of attack, probably contributed to the better altitude control demonstrated in the variable pitch maneuver. However, this control, and airspeed increase, was gained at the expense of recovery altitude, the determinant of safety in this study.
The constant pitch maneuver, which immediately brought the airplane into a climb attitude, economized the recovery altitude and so outperformed the alternate escape maneuver. Though there was less altitude control, greater altitude loss from initiation altitude, and slower airspeeds, it must be concluded, by the original definition, that the constant pitch maneuver demonstrated a greater factor of safety than the variable pitch maneuver.

In some flight parameters the constant pitch maneuver may be less than ideal, however, no crashes occurred in the trials, and a higher altitude was maintained. In regard to airspeed, there was altitude to recover from a stall if necessary, and 6 of the trials were successfully completed with minimum speeds below the one g stall speed of 103 kias.

Pilot subjects felt more comfortable with the prompt establishment of a climb attitude, as in the constant pitch maneuver, rather than initiating a recovery by pitching toward the ground, as in the variable pitch maneuver. As disclosed by the subjects, the variable pitch maneuver was not instinctual.

Airline pilots have trained to proficiency in the constant pitch maneuver and they seem comfortable with the philosophy and performance of immediately initiating a climb attitude. The WSTA established the curriculum and the escape maneuver, which is endorsed by the major manufacturers and employed by the airlines of the United States. There is, for the time being, minimal motivation to change maneuver strategy.

Avoidance remains the safest maneuver of all. Until a more robust strategy is found, the constant pitch maneuver will be employed as a last ditch effort for unintentional microburst encounters.
CHAPTER VII

RECOMMENDATIONS

Computer simulations indicate the variable pitch maneuver does increase recovery altitude. The research presented herein is contrary to many of these studies. Not disparaging the experience and knowledge of the previous researchers, it is felt that additional trials in a manned simulator should be conducted with improvements.

The flight simulator used for the research is a training device. As such the environment programmed into the flight simulator is optimized for training, and this includes the microburst. Any flight descending through 1,200 feet AGL would experience the same microburst wind shear, regardless of altitude. In the atmosphere, a microburst has a varying wind with height; higher vertical winds with less horizontal wind shear at altitude and lower vertical wind, but greater horizontal wind shear at low-levels. One of the benefits of the variable pitch maneuver that could not be tested is escaping this high vertical wind at altitude and using the increase in airspeed to mitigate the horizontal wind shear. A more realistic microburst model, with varying wind, would increase the validity of transferring the data to the real world environment.

The microburst required positive control of the aircraft; airspeed, pitch attitude, roll, yaw, and displacement continually changed in the microburst wind. During the variable pitch maneuver, the pilots found that upon arriving at the target altitude, it was easier to try and maintain a pitch attitude of about 11° on the ADI, rather than holding, or trying to hold, altitude. A flight director steering command programmed for the variable pitch maneuver may provide for even tighter altitude tolerances. Any future maneuver should consider reprogramming the flight director for pilots to follow. It is felt that this
would greatly aid in reducing variance between and among pilots while providing a more accurate representation of maneuver performance.

A program sub-routine can be written to capture the difference between the pitch attitude commanded by the flight director and the actual airplane attitude. This might be a better indication of pilot performance than recovery altitude. The use of recovery altitude as a determinant of safety is an over simplification, a more sophisticated equation taking into account airspeed and other aircraft parameters would increase relevancy.

Aircraft performance and response tends to be well modeled in approved simulators, however, the phugoid presents several problems. McCarthy and Norviel (1982) report the long period mode phugoid frequency exhibits an overdamped response in standard training flight simulators (p. 29). Frost, Turkel and McCarthy (1982) concur with this finding that low-frequency response is overly damped in the simulator (p. 10).

The phugoid influences the altitude, airspeed, and controllability of the aircraft as it transitions through a microburst. The nature of the constant pitch maneuver excites this mode, thus decreasing aircraft performance. If not accurately modeled, the constant pitch maneuver will produce artificially high recovery altitudes.

The simulator evaluation handbook (Royal Aeronautical Society, 1995) allows the same tolerances as the FAA. The wavelength of the phugoid in the simulator should be ±10 % of the flight test value. Time to half amplitude is equally controlled at ±10%, while damping ratio is ±0.02. Variance between flight test data and simulator data is acceptable in evaluating the phugoid. “The purpose of this test is not to obtain a perfect match of all plotted parameters for the entire length of the manoeuvre [sic]” (¶ 2C.33).
The test is performed in cruise flight and should include 3 full cycles of the phugoid, or time to half-amplitude, whichever is less (FAA, 1991, Appendix 2 p. 11).

Prior to conducting a simulator study, the phugoid mode should be examined for amplitude, frequency, and overdamping in all flight phases to be encountered. Adjustments should be made and documented as required.

The investigation of microburst escape strategies, using a manned simulator, will provide data only as reliable as the input. Knowledge about the mechanics of microburst wind has grown substantially since the accident of Eastern 66, however, any simulation is a reflection of what should happen, and not necessarily of what does happen. Good decisions are based on good information, and there might come a time when actual microburst data are required.

To meet the potential requirement of real world data, Psiaki and Park (1989), advise that escape maneuvers be tested in remotely piloted vehicles (RPV). “The danger of flight testing can be avoided by using relatively cheap RPVs. Flying them in thunderstorms under the automatic control of some of the suggested guidance schemes should provide a wealth of data by which they can be evaluated” (p.1138).

Improving the data of microburst escape procedures is the underpinning recommendation. If a manned simulator study is to provide relevant findings it must employ a more realistic microburst, one with varying wind at altitude, a guidance system for the pilots to follow, without substantial training, and an accurate phugoid mode oscillation that is not overly damped. Real world data, obtained by RPVs will enhance the simulation model and current knowledge and understanding.
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Montreal: Author.


APPENDIX A

GRAPHICAL DATA OF LANDING IN SHEAR TRIALS
Figure 15. Pilot 1, landing in shear, run 1.
Figure 16. Pilot 1, landing in shear, run 2.
Figure 17. Pilot 2, landing in shear, run 1.
Figure 18. Pilot 3, landing in shear, run 1.
APPENDIX B

GRAPHICAL DATA OF CONSTANT PITCH MANEUVER TRIALS
Figure 19. Pilot 1, constant pitch maneuver, run 1.
Figure 20. Pilot 1, constant pitch maneuver, run 2.
Figure 21. Pilot 1, constant pitch maneuver, run 3.
Figure 22. Pilot 1, constant pitch maneuver, run 4.
Figure 23. Pilot 1, constant pitch maneuver, run 5.
Figure 24. Pilot 2, constant pitch maneuver, run 1.
Figure 25. Pilot 2, constant pitch maneuver, run 2.
Figure 26. Pilot 2, constant pitch maneuver, run 3.
Figure 27. Pilot 2, constant pitch maneuver, run 4.
Figure 28. Pilot 3, constant pitch maneuver, run 1.
Figure 29. Pilot 3, constant pitch maneuver, run 2.
Figure 30. Pilot 3, constant pitch maneuver, run 3.
Figure 31. Pilot 3, constant pitch maneuver, run 4.
Figure 32. Pilot 3, constant pitch maneuver, run 5.
Figure 33. Pilot 3, constant pitch maneuver, run 6.
APPENDIX C

GRAPHICAL DATA OF VARIABLE PITCH MANEUVER TRIALS
Figure 34. Pilot 1, variable pitch maneuver, run 1.
Figure 35. Pilot 1, variable pitch maneuver, run 2.
Figure 36. Pilot 1, variable pitch maneuver, run 3.
Figure 37. Pilot 1, variable pitch maneuver, run 4.
Figure 38. Pilot 1, variable pitch maneuver, run 5.
Figure 39. Pilot 1, variable pitch maneuver, run 6.
Figure 40. Pilot 1, variable pitch maneuver, run 7.
Figure 41. Pilot 1, variable pitch maneuver, run 8.
Figure 42. Pilot 1, variable pitch maneuver, run 9.
Figure 43. Pilot 2, variable pitch maneuver, run 1.
Figure 44. Pilot 2, variable pitch maneuver, run 2.
Figure 45. Pilot 2, variable pitch maneuver, run 3.
Figure 46. Pilot 2, variable pitch maneuver, run 4.
Figure 47. Pilot 2, variable pitch maneuver, run 5.
Figure 48. Pilot 3, variable pitch maneuver, run 1.
Figure 49. Pilot 3, variable pitch maneuver, run 2.
Figure 50. Pilot 3, variable pitch maneuver, run 3.
Figure 51. Pilot 3, variable pitch maneuver, run 4.
Figure 52. Pilot 3, variable pitch maneuver, run 5.
Figure 5.3: Pilot 3, variable pitch maneuver, run 6.